Ground Motion Inputs for the Seismic Shake Table Test

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology
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APPENDIX E

NFCSC DOCUMENT COVER SHEET[1]

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This deliverable was prepared in accordance with ______________________ *(Participant/National Laboratory Name)*

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1 ☐ Other

This Deliverable was subjected to:

☒ Technical Review ☐ Peer Review

Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet
or,	
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s)
below	

Name and Signature of Reviewers

Douglas Ammerman

NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the NFCSC Document Cover Sheet.*

- *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone.*

NOTE 2: *If QRL 1, 2, or 3 is not assigned, then the QRL 4 box must be checked, and the work is understood to be performed using laboratory QA requirements. This includes any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

NOTE 3: *If the lab has an NQA-1 program and the work to be conducted requires an NQA-1 program, then the QRL-1 box must be checked in the work Package and on the Appendix E cover sheet and the work must be performed in accordance with the Lab's NQA-1 program. The QRL-4 box should not be checked.*

EXECUTIVE SUMMARY

Currently, spent nuclear fuel (SNF) is stored in on-site independent spent-fuel storage installations (ISFSIs) at seventy-three (73) nuclear power plants (NPPs) in the US. Because a site for geologic repository for permanent disposal of SNF has not been constructed, the SNF will remain in dry storage significantly longer than planned. During this time, the ISFSIs, and potentially consolidated storage facilities, will experience earthquakes of different magnitudes. The dry storage systems are designed and licensed to withstand large seismic loads. When dry storage systems experience seismic loads, there are little data on the response of SNF assemblies contained within them. The Spent Fuel Waste Disposition (SFWD) program is planning to conduct a full-scale seismic shake table test to close the gap related to the seismic loads on the fuel assemblies in dry storage systems. This test will allow for quantifying the strains and accelerations on surrogate fuel assembly hardware and cladding during earthquakes of different magnitudes and frequency content.

The main component of the test unit will be the full-scale NUHOMS 32 PTH2 dry storage canister. The canister will be loaded with three surrogate fuel assemblies and twenty-nine dummy assemblies. Two dry storage configurations will be tested – horizontal and vertical above-ground concrete overpacks. These configurations cover 91% of the current dry storage configurations.

The major input into the shake table test are the seismic excitations or the earthquake ground motions – acceleration time histories in two horizontal and one vertical direction that will be applied to the shake table surface during the tests. The shake table surface represents the top of the concrete pad on which a dry storage system is placed. The goal of the ground motion task is to develop the ground motions that would be representative of the range of seismotectonic and other conditions that any site in the Western US (WUS) or Central Eastern US (CEUS) might entail. This task is challenging because of the large number of the ISFSI sites, variety of seismotectonic and site conditions, and effects that soil amplification, soil-structure interaction, and pad flexibility may have on the ground motions.

The ground motion development work was divided into two phases. Phase 1 focuses on the development of the free-field ground motions and an approach to the soil-structure interactions. It will be completed at the end of FY21. Phase 2 will be devoted to the soil-structure interactions and will be based on the approach developed in Phase 1. This phase will begin in FY22.

Sections 1 and 2 of this report provides brief information on the shake table test, background information describing the dry storage systems used at the different ISFSI sites, site-conditions, and site-specific ground motion data. It also discusses an approach to developing ground motions. This approach leverages a recent extensive study of the CEUS "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" documented in NUREG-2115. In NUREG-2115, seven test sites were selected to represent the seismic hazards in 7 different seismotectonic regions in the CEUS. In addition to the sites from NUREG-2115, four representative sites were selected in WUS.

Section 3 summarizes the major results related to the development of the spectral shapes and amplitudes (peak ground acceleration scaling factors) that cover the range of seismotectonic and site conditions at the CEUS and WUS NPP (ISFSI) sites. The work was performed by Nicholas Gregor and Linda Al Atik (Consultants to SC Solutions) and reviewed by Norman Abrahamson (SC Solutions). The report documenting this work is included as Appendix A to this report.

Section 4 provides the summary of the ISFSI survey. The structural parameters, soil parameters, and ground motion response spectra are discussed.

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ACKNOWLEDGEMENTS

The authors would like to express their appreciation to Dr. Norman Abrahamson for providing invaluable expertise for this work. The authors would also like to thank the SC Solutions team for the excellent work and on-time completion of the report.

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REVISION HISTORY

Revision	Date	Description of Revision
0	06/28/21	Initial Issue

ACRONYMS

6DF	6 degrees of freedom
AHSM	Advanced Horizontal Storage Module
CEUS	Central Eastern US
DBE	Design-Based Earthquake
DOE	US Department of Energy
EPRI	Electric Power Research Institute
ESEP	Expedited Seismic Evaluation Process
ESP	Early Site Permit
FSAR	Final Safety Analysis Report
FY	fiscal year
GI-199	Generic Issue 199
GMRS	Ground Motion Response Spectrum
HF	High Frequency
HSM	Horizontal Storage Module
ISFSI	independent spent fuel storage installation
LF	Low Frequency
LHPOST	large capacity high-performance outdoor shake table
MMTT	multi modal transportation test
MTU	Metric Tons of Uranium
NCT	normal condition of transport
NEUP	Nuclear Energy University Program
NGA-East	Next Generation Attenuation for Central and Eastern North
NHERI	national hazards engineering earthquake research infrastructure
NPPs	Nuclear Power Plants
NRC	Nuclear Regulatory Commission
PEER	The Pacific Earthquake Engineering Research Center
PGA	peak ground acceleration
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
SFWD	Spent Fuel Waste Disposition
SNF	spent nuclear fuel
SONGS	San Onofre Nuclear Generating Station
SPID	Screening, Prioritization and Implementation Details
SSC	Seismic Source Characterization
SSE	Safe Shutdown Earthquake

TTCI	Transportation Technology Center, Inc.
UCSD	University of California in San Diego
UHRS	Uniform Hazard Response Spectra
WUS	Western US

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SPENT FUEL AND WASTE DISPOSITION

GROUND MOTION INPUTS FOR THE SEISMIC SHAKE TABLE TEST

1. INTRODUCTION

Currently, spent nuclear fuel (SNF) is stored in onsite independent spent-fuel storage installations (ISFSIs) at seventy-three (73) nuclear power plants (NPPs). Only three NPPs do not have on-site dry storage. However, two of them are considering building on-site ISFSIs in the near future. The SNF inventory stored on sites either in pools or dry storage was 84,500 MTU [1] in 2020. The inventory stored in on-site dry storage facilities was 39,207 MTU (46% of total). The on-site dry storage inventory is projected to increase by approximately 3,500 MTU every year until the SNF is transported to a geologic repository for disposal. Alternatively, the on-site SNF might be transferred to a consolidated dry storage facility, if such facility (federal or private) is licensed, where it will be stored until geologic repository becomes available. Figure 1-1 reproduced from the NRC site (*https://www.nrc.gov/waste/spent-fuel-storage/map-fuel-storage-facilities.pdf*) shows the locations of the existing (in November 2020) on-site ISFSIs and the locations of two sites pursuing private consolidated storage facilities.

Because a site for geologic repository for permanent disposal of SNF has not been constructed, the SNF will remain in dry storage at many locations in the US longer than planned. During this time, the ISFSIs and consolidated storage facilities may experience earthquakes of different magnitudes. The dry storage systems are designed and licensed to withstand large seismic loads. When dry storage systems experience seismic loads, there are little data on the response of SNF assemblies contained within them.

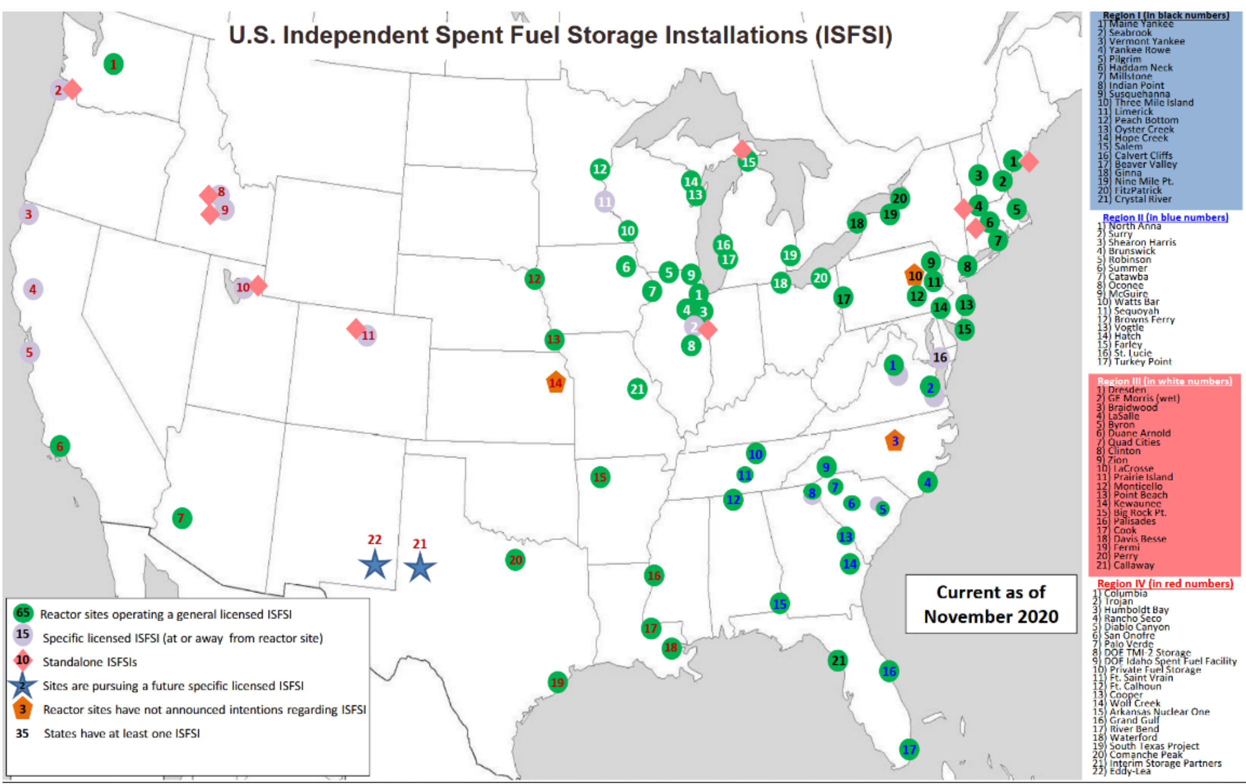


Figure 1-1. Locations of the Independent Spent-Fuel Storage Installations in the US.

The only full-scale experiment that considered all the components of the dry storage system, including surrogate fuel rods, was performed in Japan in 2007 [2]. The test unit consisted of a full-scale concrete cask (simplified model, not an actual cask), dry storage canister, 20 dummy and one surrogate Pressurized Water Reactor (PWR) fuel assemblies and a concrete pad. The test was conducted using a three-dimensional shake table in E-Defense, a 3-D full-scale earthquake testing facility. The scaled ground motions recorded during two actual earthquakes and one artificial ground motion were used as inputs to the shake table.

A series of shake table experiments with scale-model representations of the free standing vertical dry storage systems (a scaled dry storage cask with a scaled canister) were conducted under the Nuclear Energy University Program (NEUP), 2016 final NEUP report "*Seismic Performance of Dry Casks Storage for Long-Term Exposure"* [3]. The scaled canister in these tests did not contain surrogate fuel assemblies. Instead, additional mass was added to the test units using 16 lead panels.

The Spent Fuel Waste Disposition (SFWD) program is planning to conduct a full-scale seismic shake table test to close the gap related to the seismic loads on the fuel assemblies in dry storage systems. This test will allow for quantifying the strains and accelerations on surrogate fuel assembly hardware and cladding during earthquakes of different magnitudes and frequency content.

The SFWD program has recently closed the gap related to the SNF integrity during the normal conditions of transport (NCT). The data on the accelerations and strains on the fuel rods due to shock and vibration were collected during the multi-modal transportation test (MMTT), the heavy haul, ship, and rail transport, including specialized rail tests at the Transportation Technology Center, Inc. (TTCI) [4] and during the 30 cm drop test [5]. These tests demonstrated that SNF will maintain its integrity during NCT.

Figure 1-2 shows the MMTT acceleration shock response spectra in the middle of the transportation platform during the largest registered shock events (the ones that resulted in the maximum strain on the fuel rods) during different transport modes and during the Single Bump Test at TTCI (the test with one of the largest accelerations among the specialized rail tests). Also shown in Figure 1-2 are examples of a rock and soil acceleration (ground motion) response spectra for Vogtle NPP site based on the seismic hazard with 1E-05 annual frequency of exceedance. These response spectra were plotted using data from Vogtle Unit 3 and 4 Updated Final Safety Analysis Report (FSAR) [6]. The expected seismic site response spectral accelerations are higher in the low frequency band (0 to 10 Hz) than the spectral accelerations observed in MMTT during the largest shock events. The seismic shake table test will provide the data on how the fuel assemblies will respond to these different types of excitations.

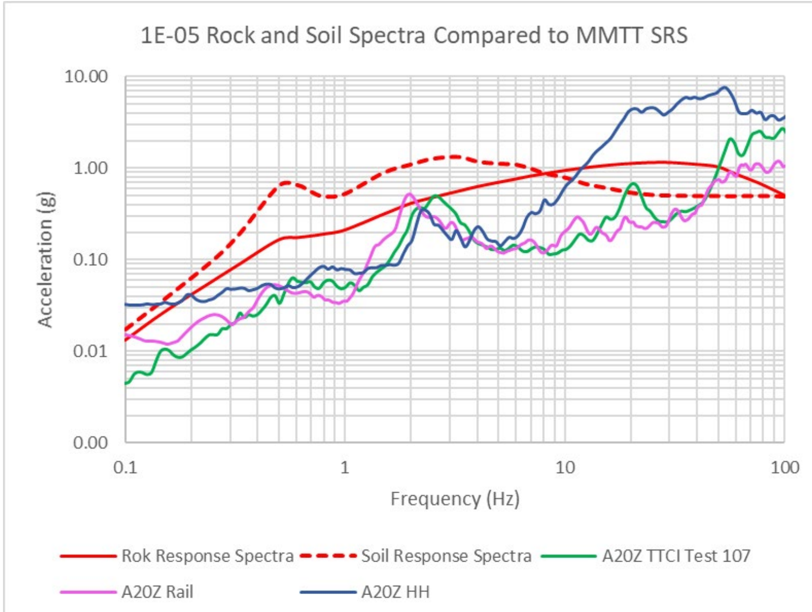


Figure 1-2. Maximum Event Transportation Platform Acceleration Response Spectra in MMTT Compared to Rock and Soil Response Spectra for a NPP Site.

The test unit in the MMTT was the full-scale dual purpose ENUN 32P storage and transportation cask loaded with 3 surrogate and 29 dummy assemblies (Figure 1-3). The data from the MMTT demonstrated that all the elements of the transportation system behaved differently. This did not corroborate the common assumption that the cask content experiences the same accelerations as the cask itself. Most importantly, the accelerations were amplified from the cask to the surrogate assemblies. Similar effects were observed during the 30 cm drop test. Based on these results, it is anticipated that the elements of the dry storage system will respond differently to the seismic loads with possible amplification of the fuel assembly response.

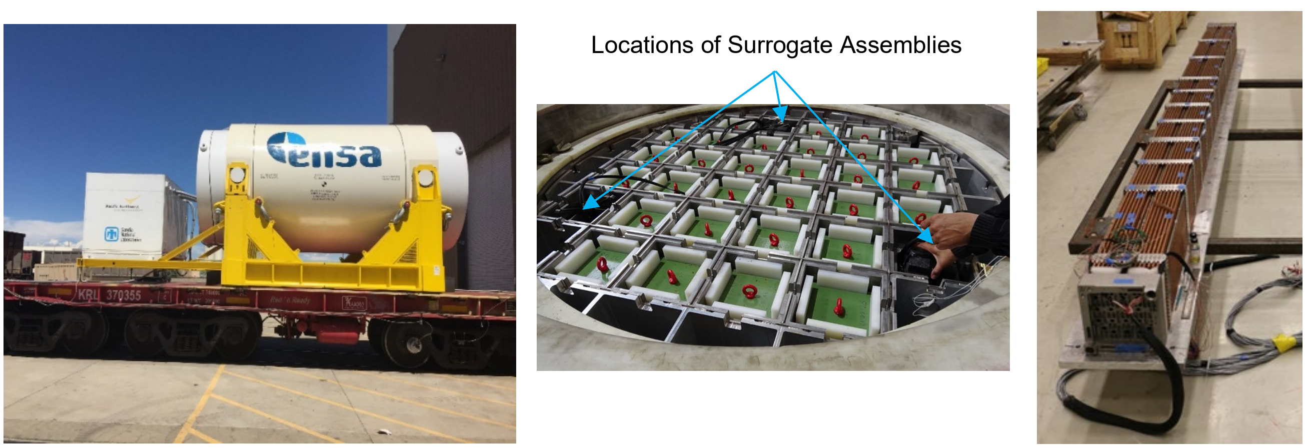


Figure 1-3. ENUN 32P cask (left), Basket inside the Cask (middle), and Surrogate Fuel Assembly (right).

Note that a dry storage system is a highly nonlinear system making it hard to predict (model) the responses. The non-linearity arises from the multiple gaps in the system – between the fuel rods and the basket, between the basket and dry storage canister, between the dry storage canister and the storage cask (overpack), and ventilation gaps. The non-linearities pose significant limitations on the value of tests with scaled systems.

The seismic shake table test will be a full-scale dry storage system test. This only became possible because the SFWD program gained access to the NUHOMS 32 PTH2 dry storage canister and NUHOMS Advanced Horizontal Storage Module (AHSM) through the San Onofre Generating Station (SONGS) at no cost to the project.

The main component of the test unit is the full-scale NUHOMS 32 PTH2 dry storage canister. The canister will be loaded with three surrogate fuel assemblies and twenty-nine dummy assemblies. The surrogate assemblies will be similar to the ones used in the MMTT.

Two dry storage configurations will be tested – horizontal and vertical above-ground concrete overpacks (Figure 1-4). These configurations cover 91% of the current spent fuel in dry storage configurations. The current dry storage inventory in vertical configuration makes up 66% of this inventory. Table 1-1 provides information regarding the type of dry storage at the different NPPs. Note that a few NPP sites have both vertical and horizontal systems.

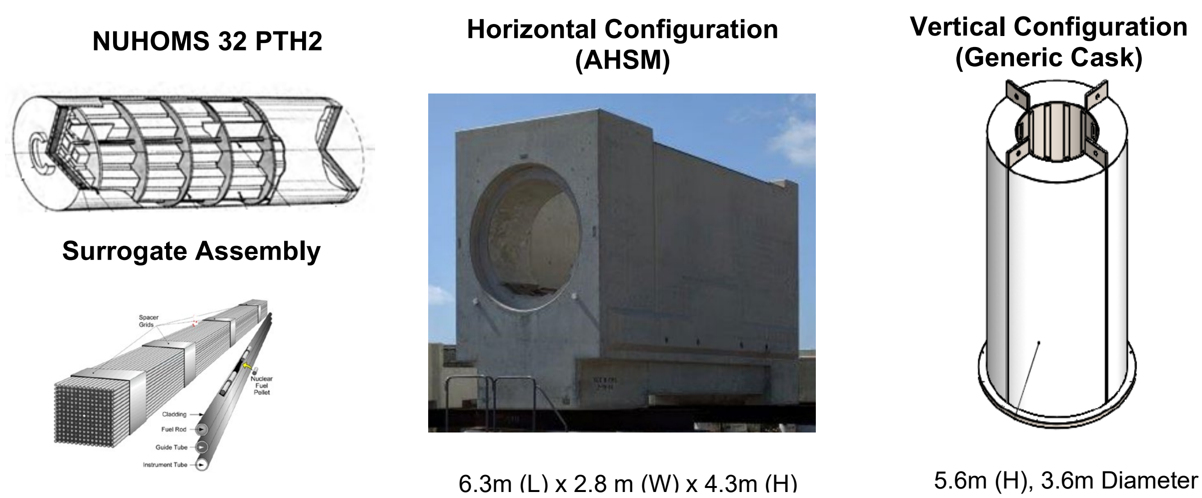


Figure 1-4. Test Units Components: NUHOMS 32 PTH2 Canister and Surrogate Assembly (left), AHSM (middle), and Generic Vertical Cask (right).

In a horizontal configuration, an actual NUHOMS AHSM will be used. In a vertical configuration, a generic vertical cask (to be manufactured) will be used. The canister will be placed inside each system for the test. The test unit will be placed on the shake table. A concrete layer will be installed on the top of the shake table before the unit placement to provide the friction expected from a dry storage pad.

A preliminary agreement to conduct the seismic test was made with the world's largest outdoor earthquake simulator, large capacity high-performance outdoor shake table (LHPOST), operated by structural engineers at the University of California in San Diego (UCSD). This is the only facility in the US that can accommodate the large size and weight of the test units. The facility is a part of the Natural Hazards Engineering Research Infrastructure (NHERI) program. The facility is currently under renovation to implement the capability to conduct 6 degrees of freedom testing and will reopen in the fall of 2021. [7] The seismic test is tentatively scheduled for the late summer of 2022. A photo of LHPOST reproduced from the NHERI website (http://nheri.ucsd.edu/) is shown in Figure 1-5. Figure 1-6 is a diagram that provides a closeup view of the shake table surface. As mentioned above, concrete will be poured on this surface before the test.

Table 1-1. Type of Dry Storage at the Different NPPs.

NPPs with Horizontal Dry Storage Systems		NPPs with Vertical Dry Storage Systems	
Horizontal System Type	**NPP Name**	**Vertical System Type**	**NPP Name**
Advanced NUHOM	SONGS 1	HI-STORM	ANO
	SONGS 2		Braidwood
NUHOM 708	Robinson		Browns Ferry
NUHOM HD	North Anna		Byron
	Seabrook		Columbia
	St.Lucie		Comanche Peak
	Surry		D.C.Cook
	Turkey Point		Diablo Canyon
NUHOM Standardized	Brunswick		Dresden
	Calvert Cliffs		Farley
	Cooper		Fitzpatrick
	Davis-Besse		GE Trojan
	Duane Arnold		Grand Gulf
	Fort Calhoun		Hatch
	Ginna		Hope Creek
	Kewaunee		Indian Point 1
	Limerick		Indian Point 2 &
	Millstone		LaSalle
	Monticello		Perry
	Nine Mile Point		Quad Cities
	Oconee		River Bend
	Oyster Creek		Salem
	Palisades		Sequoyah
	Point Beach		Vermont Yankee
	Rancho Seco		Vogtle
	Robinson		Waterford
	Susquehanna	NAC-MAGNASTOR	Catawba
			McGuire
			Zion
		NAC_MPC	Connecticut
			Lacrosse
			Yankee Rowe
		NAC-UMS	Catawba
			Maine Yankee
			McGuire
			Palo Verde
		VSC 24	ANO
			Palisades
			Point Beach

Figure 1-5. LHPOST Outdoor Earthquake Simulator (U.C. San Diego).

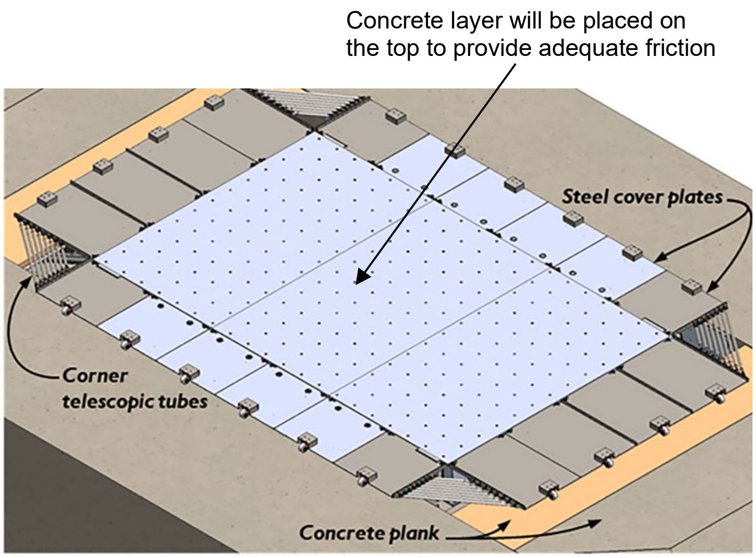


Figure 1-6. Closeup View of the LHPOST Shake Table Surface.

The seismic shake table plan is under development and is expected to be completed by the end of FY21. This report documents the development of the ground motions for the shake table test.

2. EARTHQUAKE GROUND MOTION BACKGROUND INFORMATION

2.1 Conceptual Description of the Problem

The major input into the shake table test are the seismic excitations or the earthquake ground motions – acceleration time histories in two horizontal and one vertical direction modified to represent the movements of the top of the concrete pad on which an ISFSI dry storage system is placed. The time histories must be representative of the seismotectonic conditions at the site and have to provide good fit to the target response spectra that define the seismic excitation frequency content.

Figure 2-1 shows the conceptual differences between the sites located on rocks and the sites located on soil. The free-field ground motions represent the movements of the surface without any engineering structure on the top of it in response to an earthquake. The movement of the surface has to be converted to the movement of the structure foundation (top of the ISFSI pad) to study the effects of an earthquake on the structure (dry storage system). The soil sites are more complex because they require calculations of soil amplifications and soil-structure interaction. Due to non-linearity of soil properties, the amplifications and interaction are a function of the applied seismic load. The steps to define the shake table motions for the rock and soil sites are described below.

The following steps are required to define the shake table motion for the rock sites:

- Define rock free-field ground motions
- Estimate pad amplification/attenuation
- Define shake table motions

The following steps are required to define the shake table motion for the soil sites:

- Define rock free-field ground motions
- Model soil column to estimate soil amplification
- Model soil column and structure to estimate soil-structure interaction
- Define shake table motions

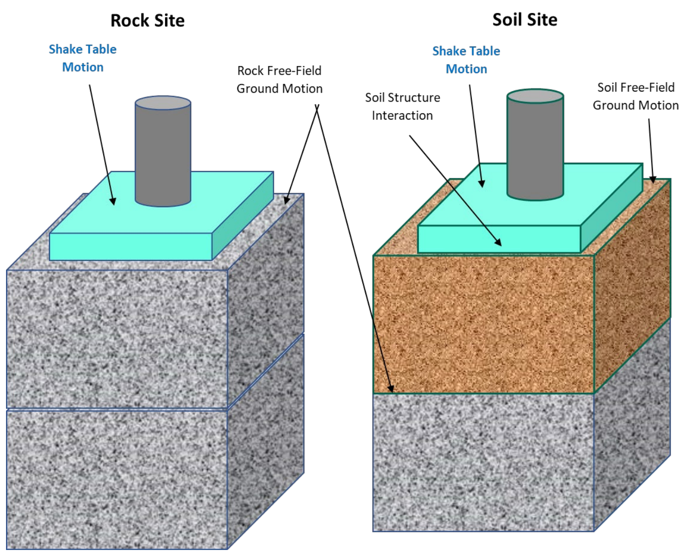


Figure 2-1. Conceptual Representation of a Dry Storage System Located on Rock and Soil for the Shake Table Test.

Figure 2-2 shows an example of soil amplifications for one of the deep soil sites in the CEUS. The soil amplifications (soil spectral acceleration divided by rock spectral acceleration) were taken from the site Final Safety Analysis Report (FSAR) [6]. Soil spectral accelerations are amplified within the frequency band from 0 to 10 Hz with the peak (4 times the rock spectral acceleration) at 0.5 Hz.

Figure 2-3 shows an example of soil-structure interaction taken from NUREG/CR-6865. The response spectra in the cases when there is a vertical dry storage cask on the pad are different from the response spectra of the free-field soil. Within the frequency band greater than 10 Hz (0.1 s) the peak difference is around 33 Hz (0.03 s). The position of the cask on the pad (Figure 2-4), in the center or on the edge of the pad, affects the response spectra as well.

Finally, the ground motions can be affected by the ISFSI pad flexibility and the existence of the neighboring casks. These effects can potentially result in rotational motions which can be simulated on a 6 degrees of freedom (6DF) shake table.

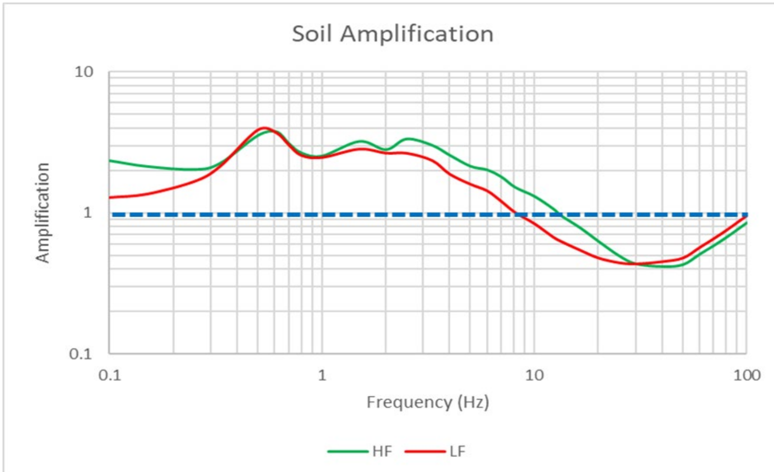


Figure 2-2. Soil Amplification Example for Low Frequency (LF) and High Frequency (HF) Earthquakes (Deep Soil Site).

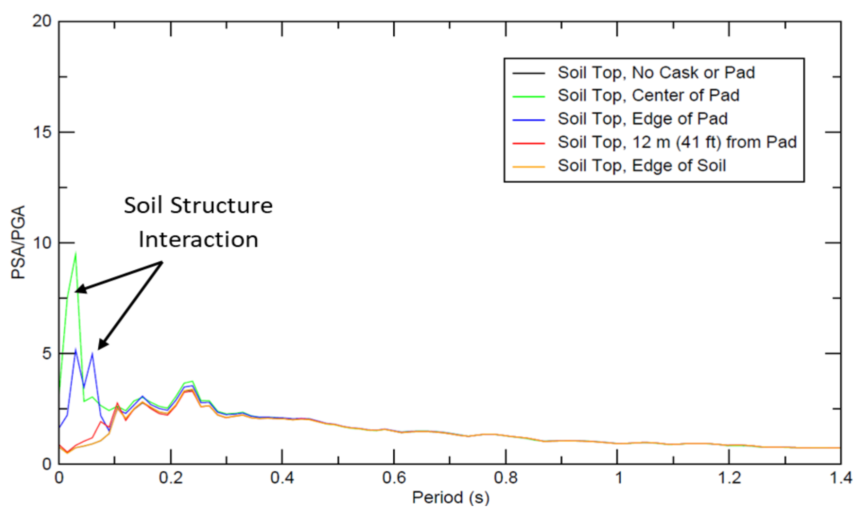


Figure 2-3. Example of Soil-Structure Interaction from NUREG/CR-6865.

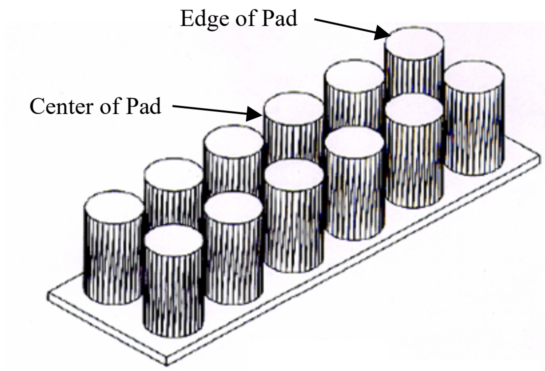


Figure 2-4. ISFSI Pad with Vertical Dry Storage Casks Diagram (left) and Personal Photo of the Diablo Canyon NPP ISFSI (right).

2.2 Site-Specific Conditions at the Different NPP Sites in the US

There are 7 NPP (ISFSIs) in the Western US (WUS) and they are all located on soft rock, except one. All the other NPPs (ISFSIs) are located in the Central and Eastern US (CEUS). Among the CEUS sites, 34 were classified as rock sites and 27 were classified as soil sites in Generic Issue 199 (GI-199), NRC (2010) [8]. Figure 2-5 shows the CEUS sites and their type as defined in NRC (2010) [8]. The soil sites were further placed in one of the five categories defined by EPRI soil classification [9] depending on the soil thickness (depth) and soil average shear velocity v_s (Table 2-1). The site category data are summarized in Table 2-2. In this table the site-specific soil type (not from one of EPRI's categories) is shown as Soil (SS). If the type was defined in the FSAR, "FSAR" is shown in parentheses next to the category.

Table 2-1. Soil Categories from EPRINP-6395-D

Category	Average Depth (m)	Depth Range (m)	Soil Average Vs (m/s)
I	6	3.0-9	343
II	15	9.0-24	404
III	37	24-55	488
IV	76	55-122	579
V	152	>122	681

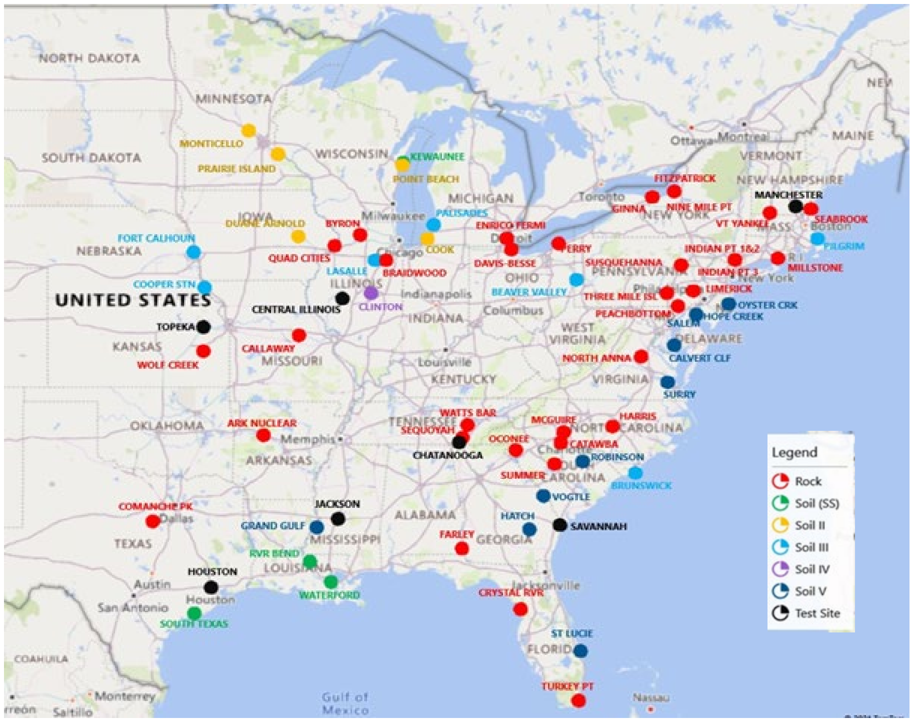


Figure 2-5. Rock and Soil NPPs (ISFSIs) Sites in CEUS (Based on the Data in [8].

Table 2-2. NPPs Site Categories Based on Data in [8].

Site Name	Site Type	Site Name	Site Type	Site Name	Site Type
Arkansas 1&2	Rock	Peach Bottom 2&3	Rock	Duane Arnold	Soil II (FSAR)
Braidwood 1&2	Rock	Perry	Rock	Beaver Valley	Soil III
Browns Ferry 1&2	Rock	Quad Cities 1&2	Rock	Brunswick 1&2	Soil III
Byron 1&2	Rock	Seabrook	Rock	LaSalle 1&2	Soil III
Callaway	Rock	Sequoyah 1&2	Rock	Pilgrim 1	Soil III
Catawba 1&2	Rock	Shearon Harris 1	Rock	Cooper	Soil III
Comanche Peak 1&2	Rock	Summer	Rock	Fort Calhoun 1	Soil III
Crystal River	Rock	Susquehanna 1&2	Rock	Palisades	Soil III
Davis Besse	Rock	Three Mile Island 1	Rock	Clinton	Soil IV
Dresden 2&3	Rock	Turkey Point 3&4	Rock	Calvert Cliffs	Soil V
Farley 1&2	Rock	Vermont Yankee	Rock	Grand Gulf	Soil V
Fermi 2	Rock	Watts Bar	Rock	Hatch 1&2	Soil V
Fitzpatrick	Rock	Wolf Creek	Rock	Hope Creek	Soil V
Ginna	Rock	Kewaunee	Soil (SS)	Oyster Creek	Soil V
Indian Point 2&3	Rock	River Bend	Soil (SS)	Robinson (HR)	Soil V
Limerick	Rock	South Texas 1&2	Soil (SS)	Saint Lucie	Soil V (FSAR)
McGuire 1&2	Rock	Waterford 3	Soil (SS)	Salem 1&2	Soil V
Millstone 2&3	Rock	Monticello	Soil II	Surry 1&2	Soil V
Nine Mile Point 1&2	Rock	Point Beach 1&2	Soil II	Vogtle 1&2	Soil V
North Anna 1&2	Rock	Prairie Island 1&2	Soil II	Vogtle 3&4	Soil V
Oconee 1,2&3	Rock	D.C. Cook 1&2	Soil II (FSAR)		

Figure 2-6 shows how many CEUS sites fall into the rock category and each of the soil categories. Ten soil sites are deep soil sites. Twelve soil sites are intermediate soil depth (categories II and III) sites. Four sites are categorized as site-specific soil sites. Only one site is a category IV site. There are no sites in category I, shallow soil.

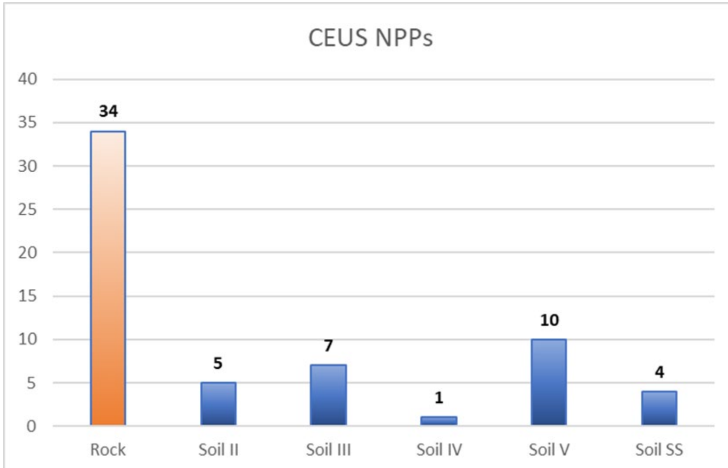


Figure 2-6. Number of Rock Sites and Sites in Different Soil Categories in (CEUS NPPS).

Finally, each NPP site has site-specific seismic hazards that are calculated for the peak ground acceleration (PGA) and other spectral accelerations based on the distance from each seismic source to the site, reoccurrence (in terms of the annual probability of exceedance) of the earthquakes of different magnitudes associated with this source, and source-to-site spectral attenuation relationships. The individual seismic hazards are combined to represent the total seismic hazard at the site. The total seismic hazards along with the site conditions (rock or soil) define the site-specific response spectrum shape and spectral amplitudes of the free-field ground motion from which the site-specific design based ground motion (prior to RG 1.208) or safe shutdown earthquake (SSE) is developed.

In summary, there are 73 NPP sites with on-site ISFSIs. The remaining 2 NPP sites are expected to have on-site ISFSIs in the near future. Two sites, one in New Mexico and one in Texas, submitted license applications to NRC and may become operational private consolidated storage facilities if licenses are approved. Finally, the US Department of Energy (DOE) is considering a consolidated storage facility. The location of this facility is yet to be determined. If approved, it may become operational sometime further in the future. Consequently, the dry storage systems might be spread over 79 different sites with different site conditions and seismic hazards. Because the site of a geologic repository for SNF has not been constructed, the SNF will remain in dry storage at these locations for a long time during which they may be subjected to earthquakes of different magnitudes.

2.3 Why Site-Specific Ground Motions from the NPP FSARs Should Not Be Directly Used

The goal of the ground motion task is to develop the ground motions that would be representative of the range of seismotectonic and other conditions that any site in the WUS or CEUS might entail.

There are multiple reasons, besides the large number of ISFSI sites, why the site-specific ground motions from the NPP FSARs should not be directly used for developing the shake table inputs. A few major reasons are described below.

First, the data and approaches have been constantly evolving and the FSARs developed prior to 1997 are very different from the later FSARs in how they define the design-basis ground motion. The design-basis ground motions at 30 NPP sites in the US were defined using the U.S. Nuclear Regulatory Commission

(NRC) Regulatory Guide (RG) 1.60 [10] response spectra anchored to a site-specific peak ground acceleration determined using deterministic hazard analyses. The NRC issued RG 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants", in 1973. To reflect new seismic data and methods developed since 1973, in 1997 the NRC issued RG 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion" [11].

RG 1.165 was withdrawn and replaced in 2010 with the improved guidance in RG 1.208, "A Performance-Based Approach to Define the Safe Shutdown Earthquake Ground Motion" [11] [12]. RG 1.208 "incorporates new developments in ground motion estimation models; updated models for earthquake sources; methods for determining site response; and new methods for defining a site-specific, performance-based ground motion response spectrum (GMRS)". Per RG 1.208, the surface 1E-04 and 1E-05 uniform hazard response spectra (UHRS) are site-specific earthquake ground motions that form the basis of the performance-based site GMRS. The design-based earthquake (DBE) ground motion is now defined using modern probabilistic techniques and is called the safe shutdown earthquake (SSE) ground motion. The licensees of the new NPPs or new NPP units are required to use RG 1.208.

One example of the potential implications is the recommendation regarding the horizontal to vertical response spectrum ratio. An old approach [13] recommends that the vertical response spectrum be equal to 2/3 of the horizontal response spectrum uniformly at all periods. The new CEUS studies [14], concluded that the conventional V/H factor of 2/3 is not appropriate at CEUS rock and soil sites and may only be appropriate for WUS sites at periods longer than about 0.3 sec and for distances beyond about 50 km.

In early 2000, the concern regarding the potentially higher seismic hazards than previously estimated at some NPPs resulted in NRC issuing Generic Issue 199 (GI-199) "Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern United States on Existing Plants". To address this concern, in 2010 the NRC RES staff performed an assessment to determine the implications of updated probabilistic seismic hazards in the CEUS on existing NPPs [8]. It was concluded that the estimated seismic hazard levels at some current CEUS operating sites might have been higher than the seismic hazard used in previous evaluations. An example in NRC (2010) [8] given for 4 early site permit (ESP) submittals (North Anna, Grand Gulf, Vogtle, and Clinton) shows that these sites have a higher seismic hazard over most of the frequency range compared to the earlier EPRI-SOG study results.

The Fukushima Dai-ichi accident in 2011 resulted in another re-evaluation of the seismic hazards at existing NPP sites. The re-evaluation process is explained below and illustrated in Figure 2-7.

On March 12, 2012 NRC issued a letter, "Request for Information related to the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident" [15]. In this letter NRC requested all power reactor licensees and holders of construction permits located in the CEUS to submit a Seismic Hazard Evaluation and Screening Report. In preparing the screening report, each NPP was asked to re-evaluate seismic hazards against present-day NRC requirements (e.g. RG 1.208).

To assist the NPP sites in these re-evaluations, EPRI issued "Seismic Evaluation Guidance, Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation" (EPRI Report 1025287) [16]. This report provides the industry guidance and detailed information to be included in the Seismic Hazard Evaluation and Screening Report. The NPP sites used this guidance and the updated EPRI ground motion attenuation model to calculate new GMRS. The new GMRS is based on modern techniques and updated models compared to the ones used for plant licensing. The new GMRS was used to characterize the amplitude of the new seismic hazard at each of the NPP sites. The new GMRS was compared to the previously determined SSE. If the new GMRS exceeded the SSE, the NPP site was required to conduct an additional evaluation per the Expedited Seismic Evaluation Process (ESEP).

The screening reports were prepared and submitted to NRC for review. It is expected that the summary of the screening reports and the NRC reviews will be documented in a NUREG. While some NPP sites screened out, the other ones did not and will be conducting further evaluations and developing ESEP reports. The consistent GMRS across all the NPP sites are expected sometime in the future. Note that some sites that were previously classified as the rock sites (Table 2-2) reconsidered the site conditions and did re-evaluation assuming some soil layer on the top of the rock.

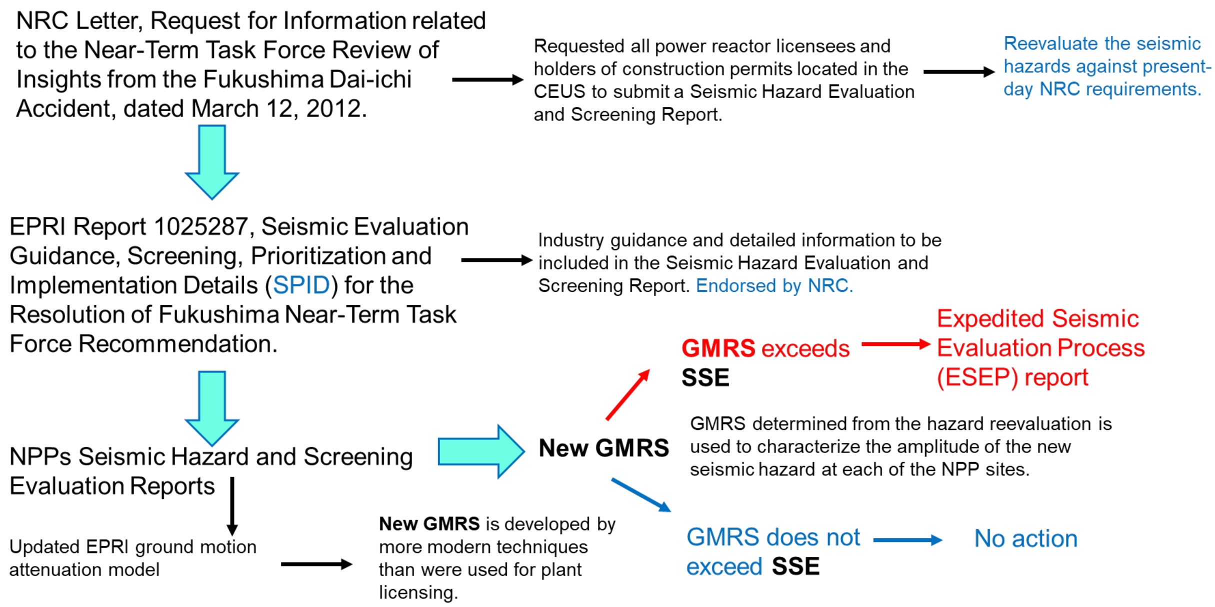


Figure 2-7. Illustration of Post Fukushima Dai-ichi Seismic Hazard Evaluation and Screening.

2.4 Test Site Approach to Developing Ground Motions

Due to the reasons explained in Section 2.3, an approach taken was to leverage recent extensive study of the CEUS "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" documented in NUREG-2115 [14]. In NUREG 2115, seven test sites were selected to illustrate the effects that the seismic sources have on calculated seismic hazard. The test sites were selected to be representative of the range of seismotectonic conditions that any site in the CEUS might entail. The site information and reasons for selection are listed in Table 2-3 reproduced from NUREG 2115 (Table 8.1-1). Figure 2-8 reproduced from NUREG 2115 (Figure 5.4.4-1) shows the seismotectonic zones in the CEUS and spatial distribution of earthquakes in the CEUS from the Seismic Source Characterization (SSC) Project catalog. This provides an illustration of how different the seismotectonic conditions are in the different parts of CEUS.

The test sites are shown as black circles in Figure 2-5. The Savannah Test Site is located close to the Vogtle NPP. The Houston Test Site is located close to the South Texas NPP. The Manchester Test Site is located close to the Seabrook NPP. The Jackson Test Site is located close to Grand Gulf NPP. The Central Illinois Test Site is located close to Clinton NPP. The Topeka Test Site is located close to Wolf Creek NPP. The Chattanooga Test Site is located close to Sequoyah and Watts Bar NPPs.

Table 2-3.Test Sites from NUREG-2115 [14].

Test Site Name	N. Latitude	W. Longitude	Reason for Selection
Central Illinois	40.000	-90.000	Hazard from New Madrid seismic zones and paleoearthquake zones in central Illinois
Chattanooga	35.064	-85.255	Hazard from Eastern Tennessee seismic zone
Houston	29.760	-95.363	Hazard in Gulf Coast region
Jackson	32.312	-90.178	Hazard from New Madrid seismic zone
Manchester	42.991	-71.463	Hazard in New England
Savannah	32.082	-81.097	Hazard from Charleston source
Topeka	39.047	-95.682	Hazard in central plains region

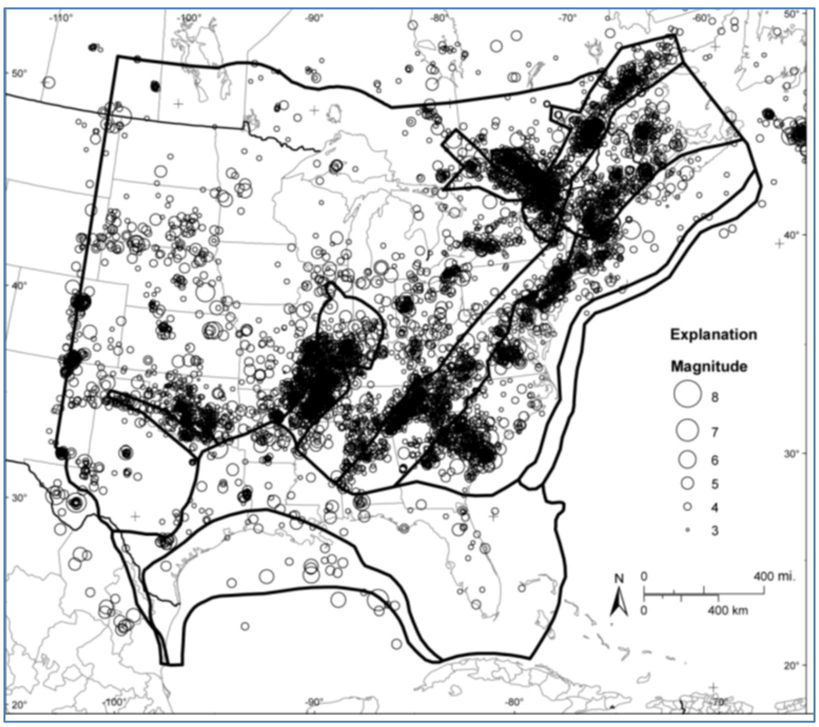


Figure 2-8. Seismotectonic Regions in CEUS and Earthquakes in the CEUS SSC Project Catalog [14].

The seismic hazards at the test sites in NUREG 2115 were calculated for hard rock conditions using the ground motion equations from EPRI (2004, 2006) [17] [18]. The hard rock is defined as rock with a shear wave velocity greater than 9,200 ft/s (2,800 m/s). Seismic hazards were also presented for two soil conditions - shallow, stiff soil and deep, soft soil. These conditions cover a range of hazard results that might be expected at the seven test sites.

Figure 2-9 shows the rock seismic hazard curves for the seven test sites for PGA plotted using the tabulated data in NUREG 2115. It illustrates the differences in hazards between the test sites which are apparent at all levels of the annual frequency of exceedance. At the 1E-04 annual frequency of exceedance the highest PGA hazard is associated with the Savannah and Chattanooga test sites. At the 1E-05 annual frequency of exceedance the highest PGA hazard is associated with the Chattanooga test site. The lowest PGA hazard at both 1E04 and 1E-05 annual frequency of exceedance is associated with the Houston test site.

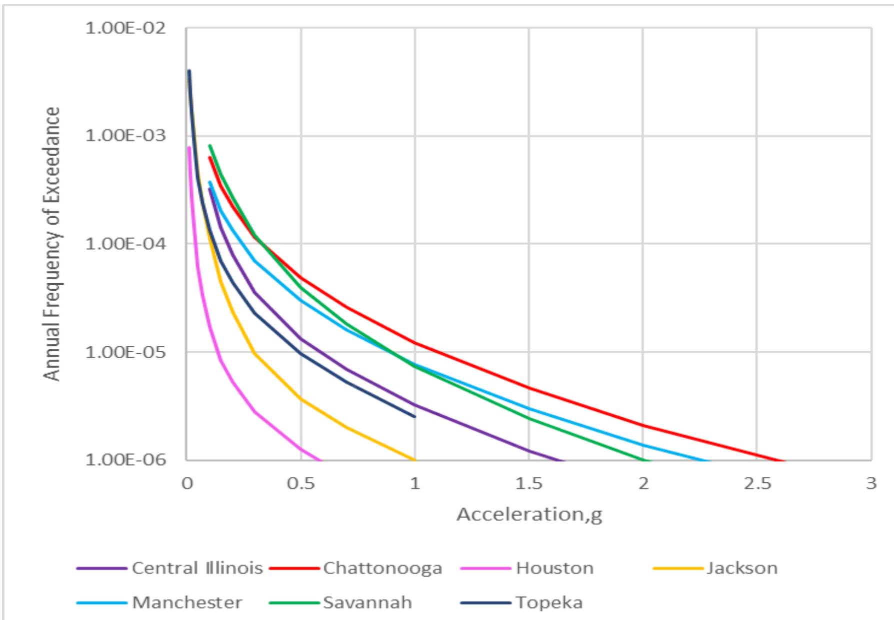


Figure 2-9. PGA Rock Seismic Hazard Curves for the Seven Test Sites.

Figure 2-10 compares the test sites rock spectral accelerations (1Hz, 10 Hz, and PGA) at the 1E-05 annual frequency of exceedance. At all sites, the 10 Hz spectral accelerations are the highest ones followed by the PGA and 1 Hz spectral accelerations. The 1 Hz, 10 Hz, and PGA seismic hazards at 1E-05 annual frequency of exceedance are highest at the Chattanooga, Savannah, and Manchester test sites. The 1 Hz, 10 Hz, and PGA seismic hazards at 1E-05 annual frequency of exceedance are lowest at the Houston site.

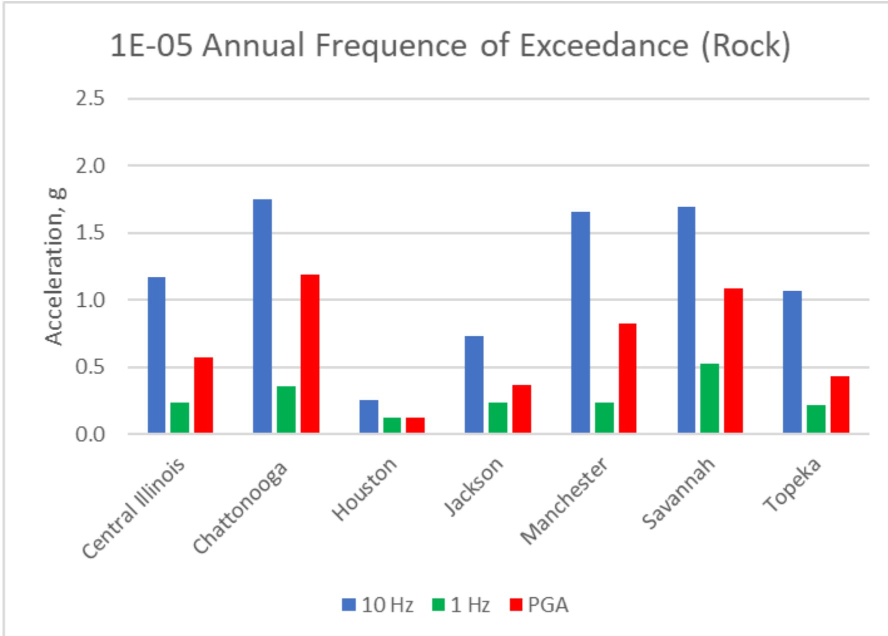
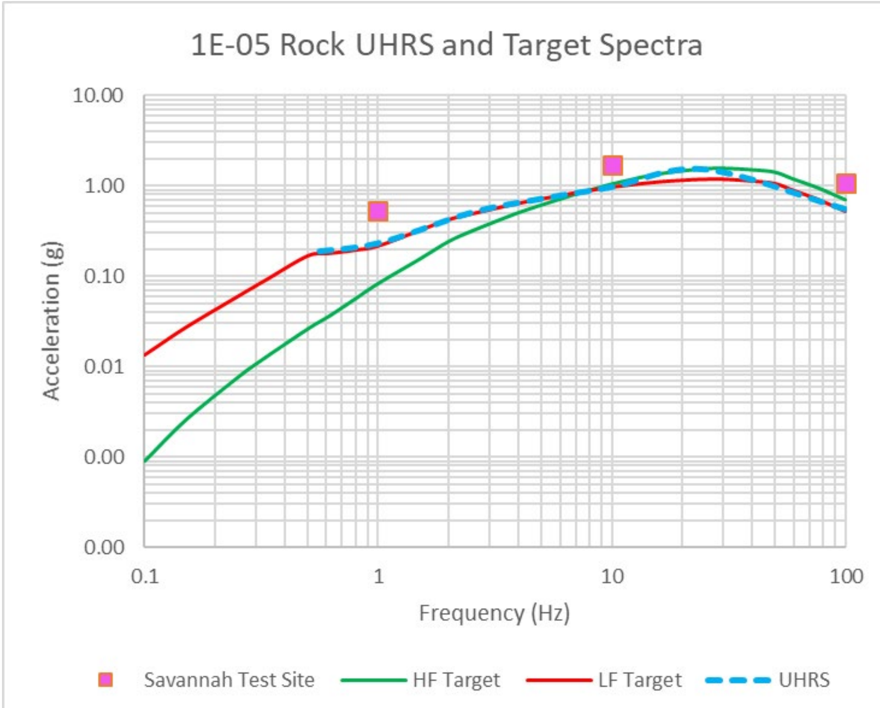


Figure 2-10. Seismic Hazards at 1E-05 Annual Frequency of Exceedance at Seven Test Sites.

Figure 2-11 was plotted using the data from the Vogtle Unit 3 and 4 FSAR [6] and NUREG -2115. The Vogtle FSAR considered two controlling (target earthquakes). The high frequency earthquake was of magnitude 5.6 with the source at 12 km from the site. The low frequency earthquake was of magnitude 7.2 with the source at 130 km from the site. The same parameters of the controlling earthquakes (magnitude and distance) were considered in 1E-04 and 1E-05 annual frequency of exceedance scenarios. Shown in the figure are the rock low and high frequency target response spectra and 1E-05 UHRS for Vogtle site and the 1 Hz, 10 Hz, and PGA rock spectral accelerations for the Savannah test site at 1E-05 annual frequency of exceedance. The Savanah test site data points envelop the Vogtle UHRS.



Note: LF is the low frequency controlling (target) earthquake and HF is the low frequency controlling (target) earthquake.

Figure 2-11. Vogtle NPP (Unit 3 and 4) 1E-05 Rock UHRS Compared to the Savannah Test Site Rock Spectral Accelerations.

Figure 2-12 was plotted using the soil amplification data in Vogtle FSAR [6] and NUREG 2115 (deep soil profile) [14]. The Vogtle is a deep soil site (category V) with the depth to bedrock of 1,300 ft. Shown in the figure are the Vogtle soil GMRS and the Savannah test site soil UHRS. Also shown in this figure is the soil GMRS used in NUREG 6865 to represent a generic CEUS soil profile. The Savanah test site soil data points envelop the Vogtle soil GMRS. The generic soil GMRS in NUREG 6865 does not envelop the Vogtle soil GMRS within the frequency band from 0 to 10 Hz. The examples on Figures 2-11 and 2-12 demonstrate that Savannah test site is representative of the seismotectonic conditions of the Vogtle NPP located in the same seismotectonic region.

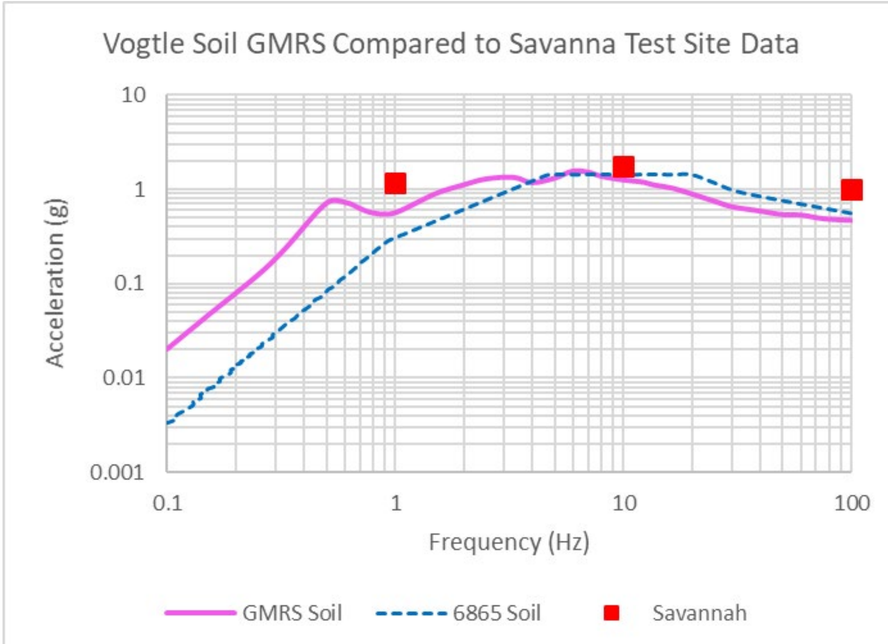


Figure 2-12. Vogtle NPP (Unit 3 and 4) Soil GMRS Compared to the Savannah Test Site Soil Spectral Accelerations.

The following example compares data from the Byron NPP FSAR and Byron post-Fukushima screening report to the Central Illinois test site. The Byron NPP and Central Illinois test site are in the same seismotectonic region. Figure 2-13 compares the PGA, 1 Hz, and 10 Hz seismic hazard curves from the Byron NPP screening report and Central Illinois test site (NUREG 2115) [14]. The PGA and 10 Hz curves are similar. The Central Illinois test site 1 Hz hazard curve envelopes the Byron 1 Hz hazard curve.

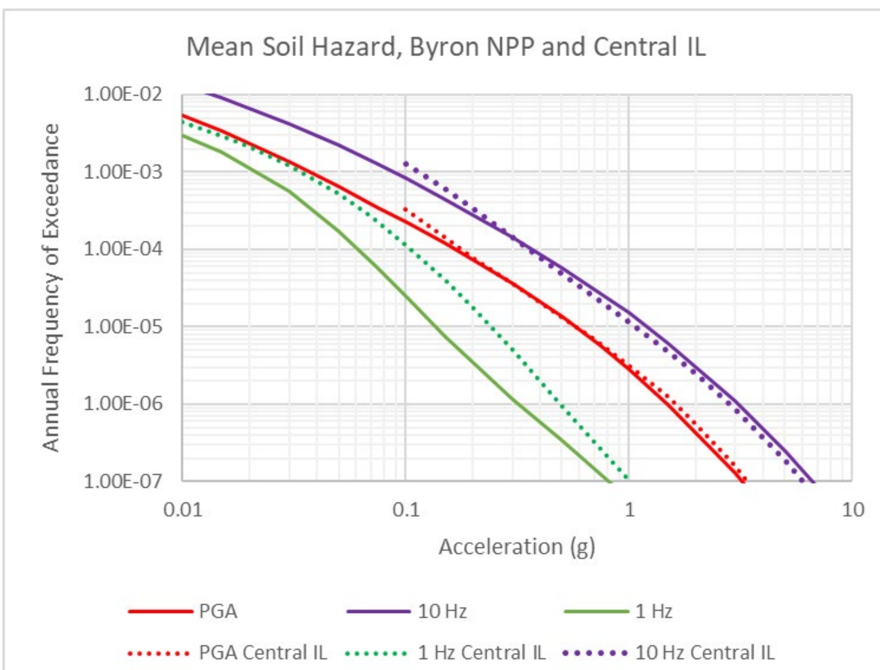


Figure 2-13. Seismic Hazard Curves for Byron NPP and Central Illinois Test Site.

Figure 2-14 shows Byron SSE from the Byron NPP FSAR, new GMRS and 1E-04 and 1E-05 UHRS from the Byron screening report [19], and 1E-05 UHRS data points from the Central Illinois test site. The new GMRS exceed the SSE within the frequencies greater than 7 Hz. The Central Illinois test site 1E-05 UHRS envelopes the Byron 1E-05 UHRS re-evaluated in the screening report.

This example demonstrates the effects of the seismic hazard re-evaluation on the GMRS. It also demonstrates that the Central Illinois test site is representative of the re-evaluated seismotectonic conditions at the Byron NPP.

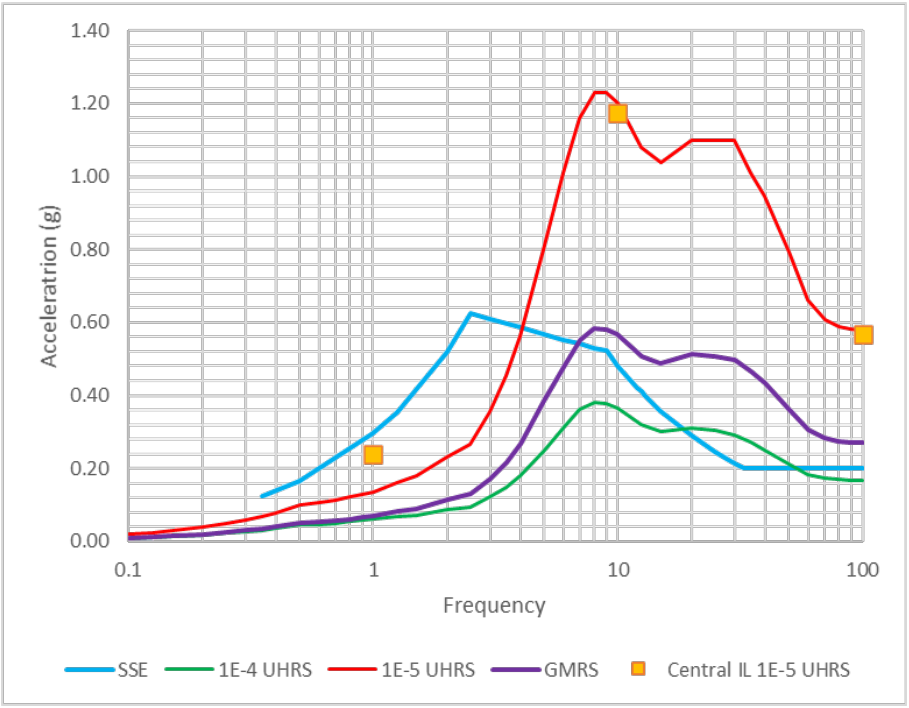


Figure 2-14. Byron SSE. UHRS, and GMRS Compared to Central Illinois 1E-05 UHRS Data.

2.5 Ground Motion Development Plan

As demonstrated in the previous sections, developing ground motions for the shake table test is a challenging task. A contract was placed with SC Solutions, a reputable and well-known company in the seismic field, to assist with this task. The ground motion development work was divided into two phases. Phase 1 focuses on the development of the free-field ground motions and an approach to the soil-structure interactions. It will be completed at the end of FY21. Phase 2 will be devoted to the soil-structure interactions and will be based on the approach developed in Phase 1. This phase will begin in FY22.

Free-Field Ground Motions: Tasks 1-3

The goal of Tasks 1-3 is to develop a suite of representative free-field ground motions (time histories) that cover the range of seismotectonic conditions that are expected at the existing and future ISFSI sites in the US.

Task 1. Developing Representative Spectral Shapes

- Evaluate the range of spectral shapes for the 1E-3 to 1E-5 UHRS at the existing and future ISFSIs in the US using 7 CEUS test sites in NUREG 2115 (Table 2-3) and four WUS sites (PVNGS, SONGS, DCPP, and PNNL). This covers a range of site conditions: hard-rock, soft-rock, and soil (shallow and deep soil conditions).

- Define spectral shapes based on the site conditions and on the Magnitude (M) and Distance (R) pairs M,R of the controlling earthquake scenarios. The controlling scenarios include three main groups:
  - Moderate magnitudes at short distances (<20 km)
  - Large magnitudes at large distances (>100 km)
  - Large magnitudes at short distance (<20 km).
- Define 9 (or more if needed) spectral shapes (3 site conditions for 3 controlling scenarios) to capture the full range. This number may be larger if significant differences in spectral shape exist between the deep and shallow soil conditions.

Task 2. Amplitudes

- Develop scale factors for the suite of spectral shapes from Task 1 to cover the hazard from 1E-3 to 1E-5 at any of the ISFSIs sites. These scale factors will be combined with the spectral shapes from Task 1.

Task 3. Time Histories

- Develop a set of 5 representative time histories for each target spectral shape from Task 1.
- Apply spectral modification if needed (spectral matching) while maintaining variability in the spectral shape about the target shape to keep a realistic variability.
- Apply linear scaling to the time histories using the scale factors from Task 2.

Approach to Modeling Soil-Structure Interactions: Tasks 4-5

One of the goals of the project is to reproduce the flexibility of soil and foundation pad (SSI effects) in the shake table tests. Concerns exist that the rigid shake table setup may interfere with reproducing flexible SSI effects during the tests. This work will focus on designing and verifying that a realistic prescribed motion (with translational and potential rotational degrees of freedom at the center of the pad, and frequency content representative of the seismologic and site conditions) can be effectively applied to the LHPOST shake table.

Task 4. Review of Previous Work and Collect Data Needed to Develop Conceptual Model of an ISFSI.

- Review past SSI analyses of ISFSI projects.
- Review past SSI institutional and regulatory reports and leverage information from “Parametric Evaluation of Seismic Behavior of Freestanding Spent Fuel Dry Cask Storage Systems” (NUREG/CR-6865).
- Collect the data in support of developing a conceptual model of an ISFSI.

Task 5. Simplified Modeling

- Perform numerical tests to verify that an input motion including SSI effects can be replicated in a rigid environment. The simulation will apply an input motion that includes representative SSI effects to a numerical model of an ISFSI built on rigid rock (to simulate the shake table stiffness).
- Extract the structural response at the concrete pad. The alignment between the structural response of the pad and the input motion will serve as an initial calibration of the experimental setup and also will support a second phase experimental calibration during the shake table test campaign.

This initial revision of the report documents Task 1 and 2 (Section 3) and Task 4 (Section 4). Tasks 3 and 5 will be documented in the FY22 revision of this report. The later report will provide the time histories that will be used in the shake table test.

3. SPECTRAL SHAPES AND AMPLITUDES

This section summarizes the major results related to the development of the spectral shapes and amplitudes (peak ground acceleration scaling factors) that cover the range of seismotectonic and site conditions at the CEUS and WUS NPPs. This work was performed by Nicholas Gregor and Linda Al Atik (SC Solutions) and reviewed by Norman Abrahamson (SC Solutions). The report documenting this work is included as Appendix A to this report. Appendix A is the SC Solution preliminary report in its entirety and without any changes to the document (as submitted). The references supporting this work are not included in this section, they can be found in Appendix A.

3.1 Spectral Shapes

This section describes horizontal (Section 3.1.1) and vertical (Section 3.1.2) spectral shapes that cover the range of seismotectonic and site conditions in CEUIS and WUS. A total of 13 spectral shapes (9 for CEUS and 4 for WUS) were developed.

3.1.1 Horizontal Spectral Shapes

The horizontal spectral shapes were developed for hard rock, soft rock, and soil conditions for CEUS and soft rock and soil conditions for WUS for the different scenarios (Magnitude-Distance pairs). The selection of the scenario events was based on the observed controlling earthquakes for sites located in the CEUS and WUS, separately.

In the CEUS, representative controlling events were selected based on the de-aggregation of the PSHA results for 7 test sites in the CEUS. The USGS web tool was queried to extract the modal de-aggregation values from the USGS 2014 PSHA results for hard rock site conditions at 1E-04 annual frequency of exceedance. Based on these de-aggregation results, three scenarios were selected as being representative for sites in the CENA:

- Local event with magnitude 5.5 at 15 km
- Moderate event with magnitude 6.5 at 40 km
- Large magnitude distant event with magnitude 7.8 at 200 km

The median horizontal ground motion spectra from these events (Figure 3-1) were computed based on the NGA-East GMM.

The median horizontal ground motion spectra for the soft rock and soil conditions were calculated from the hard rock ground motion spectra using the site amplification factor model. In this model, the selected shear velocity in the top 30 m (Vs30) values for the soft rock and soil were based on the average Vs30 values for the NPP sites. The soil sites were the sites with Vs30 less than 500 m/sec. The soft sites were the sites with Vs30 ranging from 500 to 1000 m/sec. The average Vs30 values were 698.7 and 320.7 m/sec for the soft rock and soil site, respectively. The median hard rock PGA was used in the application of the site amplification model. The horizontal ground motion spectra for the soft rock and soil conditions are shown in Figures 3-2 and 3-3.

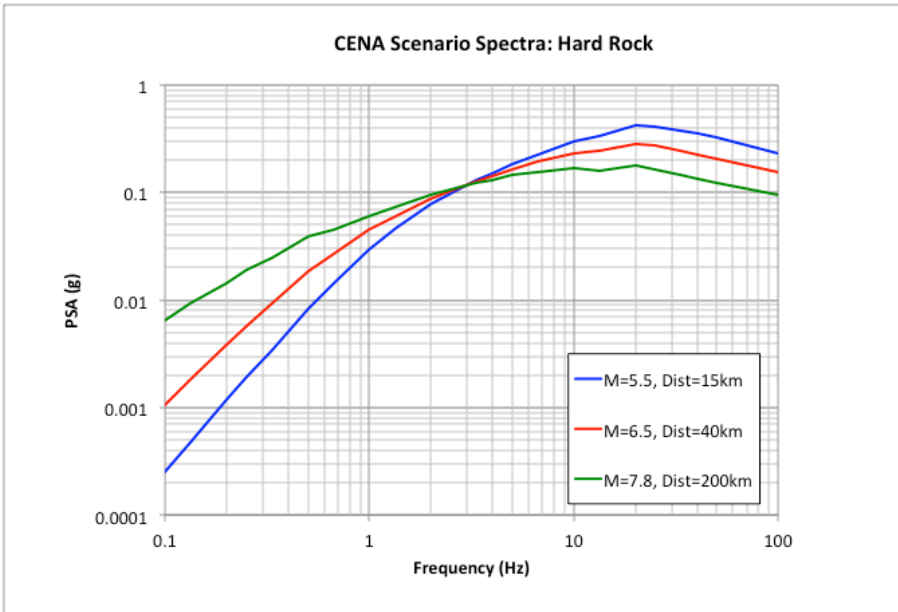


Figure 3-1. Median Ground Motion Spectra for CEUS Sites for Hard Rock Site Conditions.

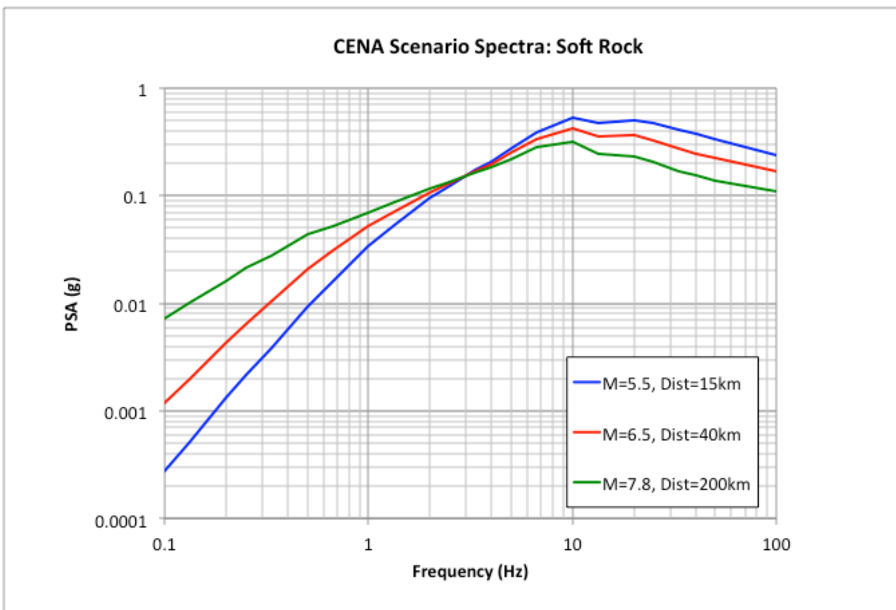


Figure 3-2. Median Ground Motion Spectra for CEUS Sites for Soft Rock Site Conditions.

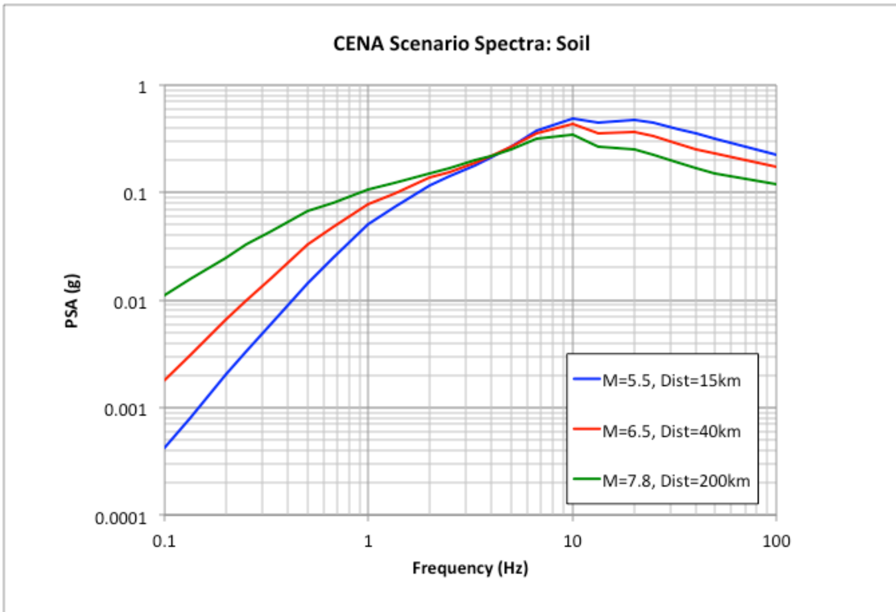


Figure 3-3. Median Ground Motion Spectra for CEUS Sites for Soil Site Conditions.

For the WUS case, the PSHA results from Diablo Canyon, Hanford, and Palo Verde NPPs were used. Based on the de-aggregation from the recently conducted PSHAs, three controlling scenario events were selected:

- Local event with magnitude 6.25 at 10 km
- Large magnitude local event with magnitude 7.5 at 5 km
- Large magnitude distant event with magnitude 7.5 at 200 km

The first two scenarios are applicable to the Diablo Canyon and Hanford NPP sites. Both sites have Vs30=760 m/sec which is representative of soft rock conditions. The first and third scenarios are applicable to Palo Verde site. This site has Vs30=344 m/sec which is representative of soil conditions.

The median horizontal ground motion spectra for these scenarios represent weighted mean calculated from four NGA-West2 GMMs. Figure 3-4 shows the median ground motion spectra for WUS sites with soft rock conditions. Figure 3-5 shows the median ground motion spectra for WUS sites with soil conditions.

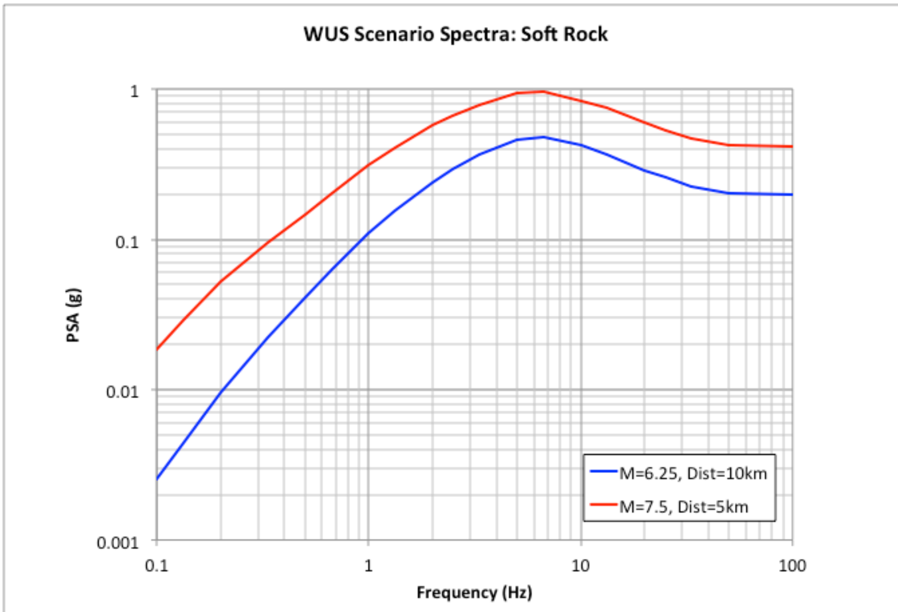


Figure 3-4. Median Ground Motion Spectra for WUS Sites with Soft Rock Conditions.

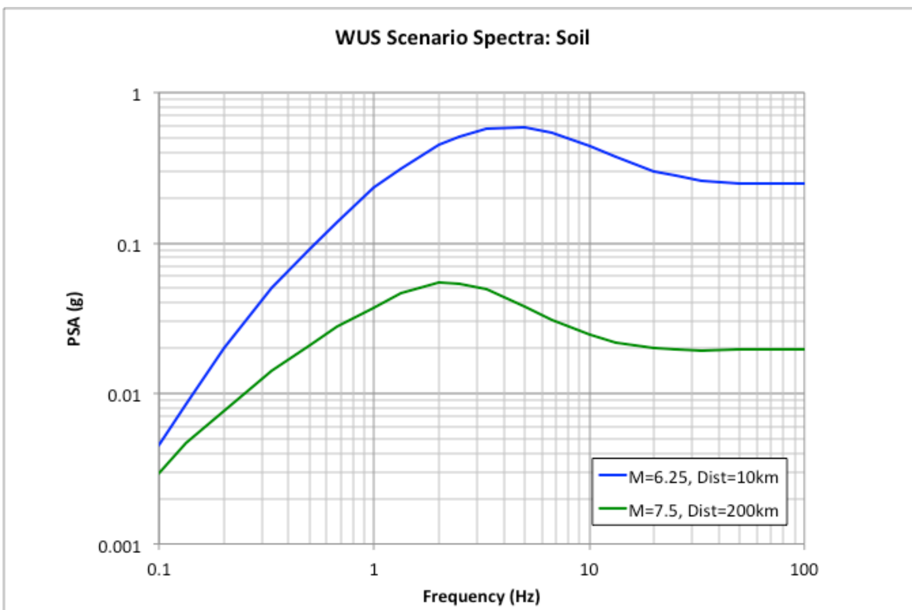


Figure 3-5. Median Ground Motion Spectra for WUS Sites with Soil Conditions.

3.1.2 Vertical Spectral Shapes

The vertical spectral shapes are based on an empirical vertical to horizontal (V/H) spectral ratio model developed by Gulerce and Abrahamson. The model was developed from empirical data recorded on sites in active tectonic regions and in general with Vs30 values less than about 1,000 m/sec and is applicable to soft-rock and soil sites. An adjustment of the model was developed to address the effects of hard-rock sites on the V/H ratio.

The calculated V/H ratios for the different scenarios and site conditions in CEUS and WUS were used to calculate the corresponding vertical spectra. These spectra are shown in Figure 3-6 to 3-10.

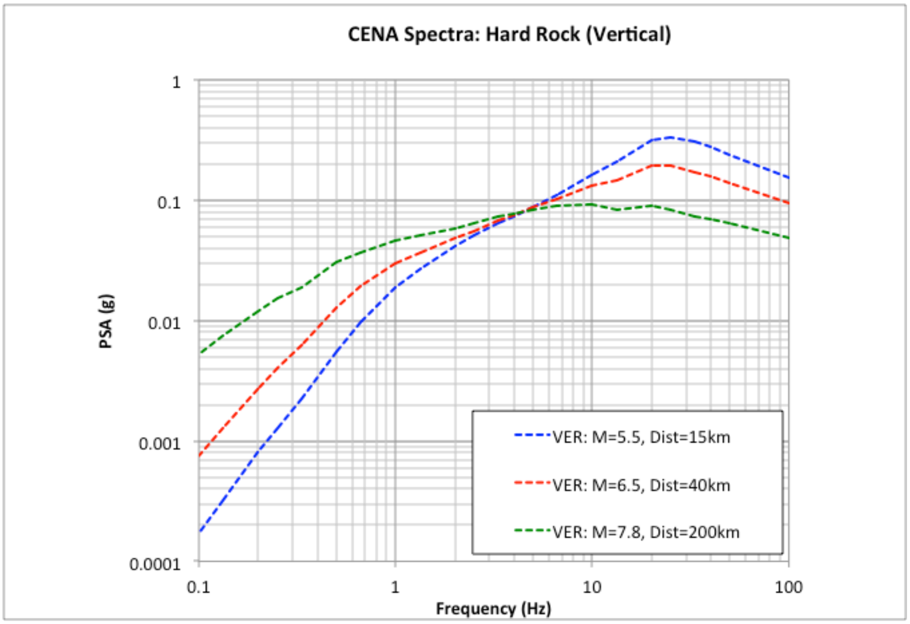


Figure 3-6. Median Vertical Ground Motion Spectra for CEUS Sites for Hard Rock Site Conditions.

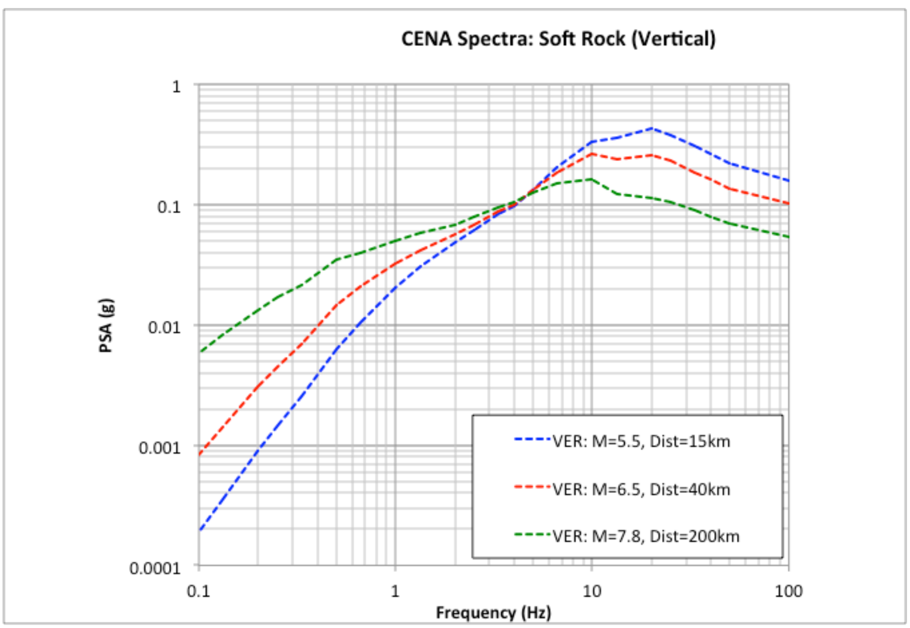


Figure 3-7. Median Vertical Ground Motion Spectra for CEUS Sites for Soft Rock Site Conditions.

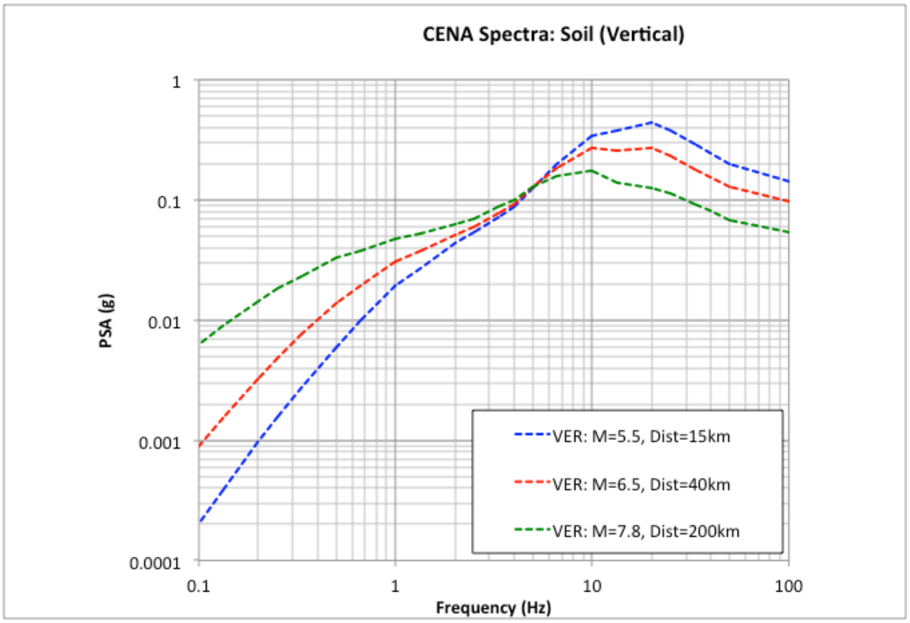


Figure 3-8. Median Vertical Ground Motion Spectra for CEUS Sites for Soil Site Conditions.

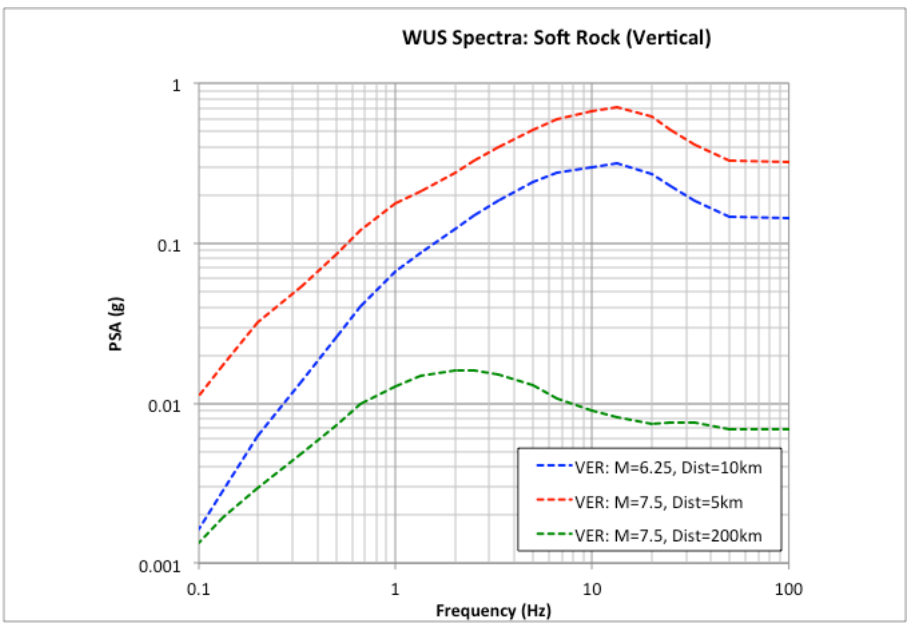


Figure 3-9. Median Vertical Ground Motion Spectra for WUS Sites for Soft Rock Site Conditions.

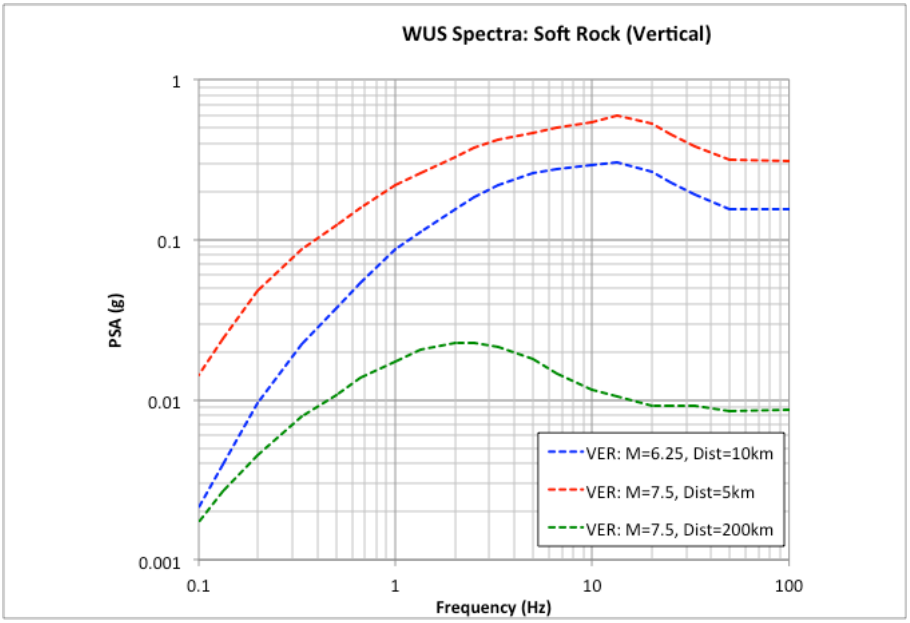


Figure 3-10. Median Vertical Ground Motion Spectra for WUS Sites for Soil Site Conditions.

3.2 Amplitudes

To define the amplitudes, the spectral shapes described in Section 3.1 have to be scaled to cover the seismic hazard from 1E-3 to 1E-5 annual frequency of exceedance at any of the ISFSI sites. The following procedure was developed to calculate the scaling factors.

In the first step, the 1E-04 UHRS were extracted for the 3 sites in WUS, the 7 test sites in CEUS, and for the 51 NPP sites in the CEUS. The latter were extracted from the NPP screening reports (Section 2.3).

For the CEUS NPP sites, either hard rock or soft rock, or soil horizontal spectra for each Magnitude-Distance scenario were anchored to the corresponding site-specific (hard rock, soft rock or soil) PGA. For the WUS sites, either soft rock or soil horizontal spectra for each Magnitude-Distance scenario were anchored to the corresponding site-specific (soft rock or soil) PGA.

At each site, the 1E-04 UHRS was compared to the applicable (hard rock, soft rock, or soil) scaled Magnitude-Distance scenario spectra. The curve enveloping these scenarios was calculated next. Additional scaling was performed to reduce the difference between the enveloping curve and the UHRS over the frequency range of 0.5 – 40 Hz. The scaling factors were calculated next using the adjusted scenario spectra for each Magnitude-Distance scenario. For the CEUS sites, the scaling factors were calculated for hard rock sites, soft rock sites, and soil sites. The cumulative distributions of scaling factors for these three site conditions are shown in Figures 3-11 – 3-13. The scaling factors for the 3 WUS sites are provided in Table 3.1. These factors represent the seismic hazards at 1E-4 annual frequency of exceedance.

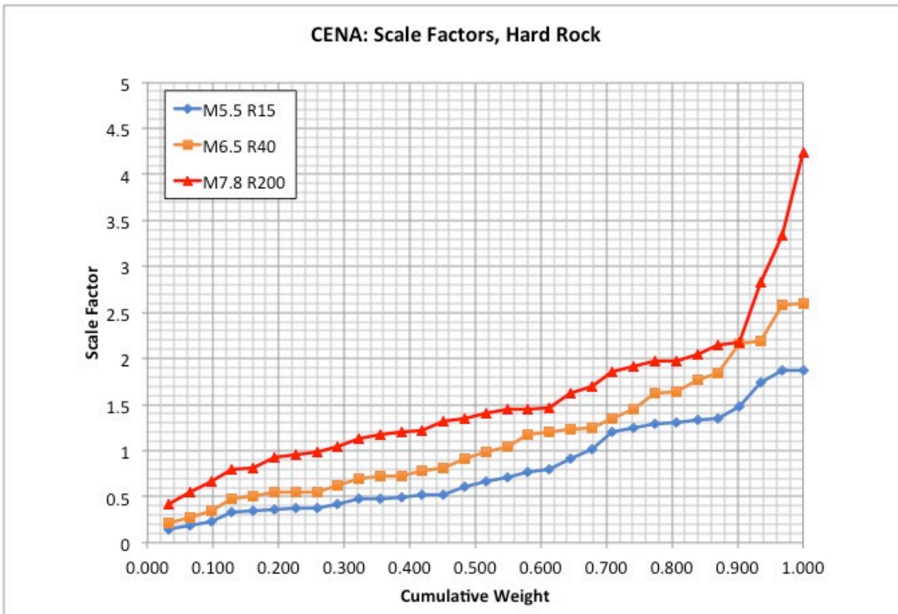


Figure 3-11. Ranked PGA Scaling Factors for CEUS Hard Rock Site Conditions.

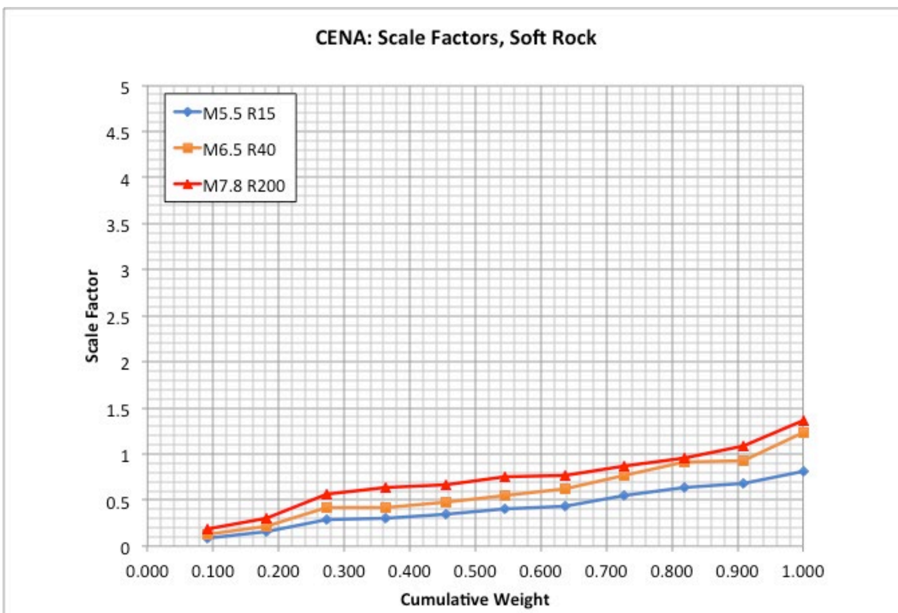


Figure 3-12. Ranked PGA Scaling Factors for CEUS Soft Rock Site Conditions.

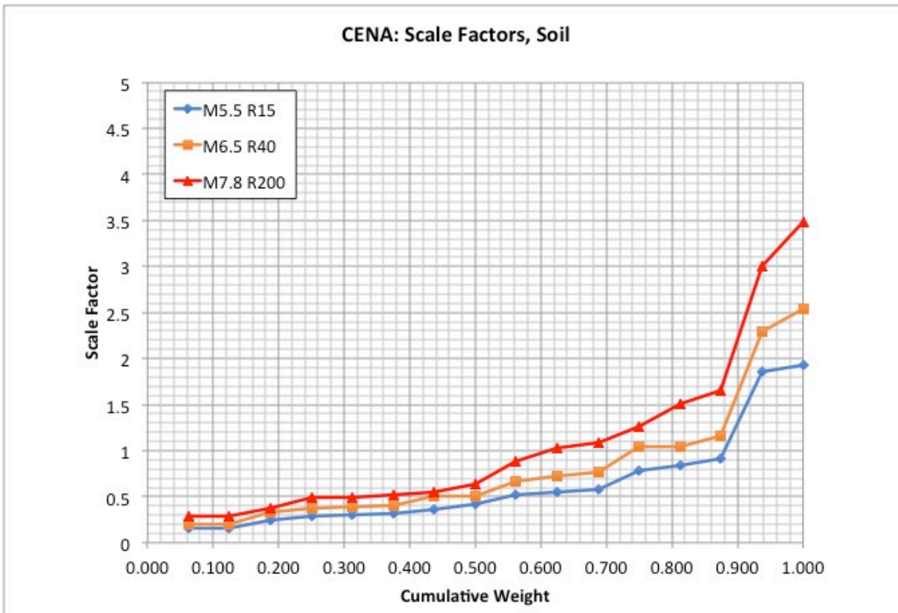


Figure 3-13. Ranked PGA Scaling Factors for CEUS Soil Site Conditions.

Table 3-1. Scaling Factors for WUS Sites.

Case	6.25 Magnitude at 10 km	7.5 Magnitude at 5 km	7.5 Magnitude at 200 km
Soft Rock	1.887	0.969	---
Soft Rock	4.022	2.206	---
Soil	0.670	---	5.151

To develop the scaling factors representing the seismic hazards at 1E-3 and 1E-5 annual frequency of exceedance the spectral ratios of 1E-03/1E-04 UHRS and 1E-05/1E-04 UHRS were calculated for the CEUS (hard rock, soft rock, and soil) and WUS (soft rock and soil) site conditions. The average PGA ratios were very similar for the different site conditions (Table 3-2). It was recommended that the values estimated from the average across all of the data are applicable to scale the spectra and time histories for the two additional hazard levels of 1E-3 and 1E-5. Scale factors for other hazard levels can be estimated based on a linear interpolation of the log of the hazard level and log of the scale factors given the values provided in Table 3-2 and the desired interpolation hazard level.

Table 3-2. Average Scaling Factors for 1E-3 and 1E-5 Hazard Levels.

Case	Average, All Site Conditions	Hard Rock	Soft Rock	Soil
CEUS Sites				
1E-3/1E-4	0.32	0.29	0.33	0.37
1E-5/1E-4	3.04	3.21	3.03	2.74
WUS Sites				
1E-3/1E-4	0.37	-	0.36	0.40
1E-5/1E-4	2.38	-	2.32	2.52

4. ISFSI SURVEY

To determine appropriate inputs for the shake table test, modeling of the vibration response of the ISFSIs with the casks resting on them will be performed. The goal of the modeling will be to define typical response spectra at the top of the ISFSI pad generic to CEUS seismotectonic and site conditions. The software SC Sassi will be used to model the soil structure interaction of several of these generic ISFSIs. A survey of ISFSIs and casks used in the US was conducted to determine the characteristics of typical ISFSI pads, their accompanying casks, and site soil properties. These characteristics will be used to develop generic conceptual models and determine appropriate inputs for modeling.

The ISFSI site survey focused on ISFSIs at soil sites (with a couple of exceptions) around the CEUS. There are ISFSIs located on the site of the 27 NPPs that satisfy this requirement (Table 2-2). The Pacific Earthquake Engineering Research Center (PEER) project Next Generation Attenuation for Central and Eastern North America (NGA-East) recently released a report detailing a new ground motion characterization model [20]. To showcase this model, they chose seven test sites to demonstrate hazard calculations (Table 2-3). These sites are shown in Fig. 4-1 (reproduced from [20]) along with the location of the twelve surveyed power plants. The basis of selection of ISFSI survey sites from the 27 CEUS soil sites was a focus on proximity to the test sites. Table 4-1 lists the NPPs for which ISFSI data was surveyed, as well as their location and the closest CEUS demonstration site.

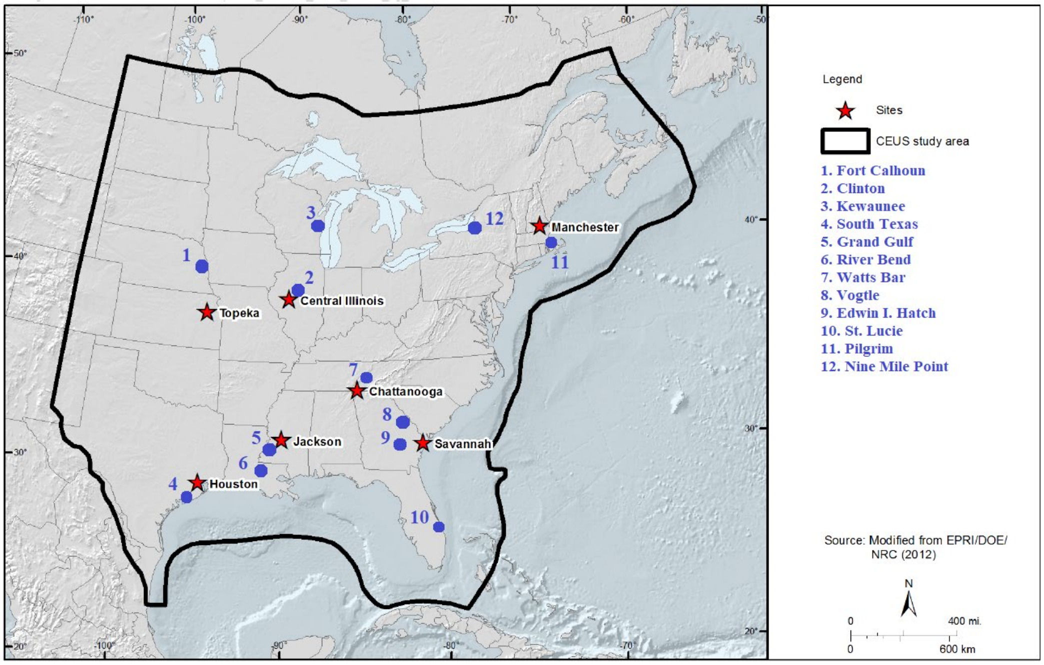


Figure 4-1. CEUS Test Sites and Surveyed NPP Locations (modified from [20]).

Table 4-1. NPP ISFSI's surveyed, their location, and the closest CEUS demonstration site.

Name	Location	Closest CEUS Demo Site
Fort Calhoun Nuclear Generating Station	Blair, NE	Topeka, KS
Clinton Power Station	Clinton, IL	Central Illinois
Kewaunee Power Station	Kewaunee, WI	Central Illinois
South Texas Generating Station	Bay City, TX	Houston, TX
Grand Gulf Nuclear Station	Port Gibson, MS	Jackson, MS
River Bend Nuclear Generating Station	St. Francisville, LA	Jackson, MS
Watts Bar Nuclear Plant	Spring City, TN	Chattanooga, TN
Vogtle Electric Generating Plant	Waynesboro, GA	Savannah, GA
Edwin I. Hatch Nuclear Power Plant	Baxley, GA	Savannah, GA
St. Lucie Nuclear Power Plant	Jensen Beach, FL	Savannah, GA
Pilgrim Nuclear Power Station	Plymouth, MA	Manchester, NH
Nine Mile Point Nuclear Generating Station	Oswego, NY	Manchester, NH

At each of the ISFSI sites surveyed, an attempt was made to find information on the structural parameters of the ISFSI, the cask dimensions and configurations on the pads, the site soil parameters, and the site ground motion response spectra. These data, along with the ground motions at the test sites, will be used to determine the generic ISFSI and cask cases for developing conceptual models to be analyzed and tested.

The data for this survey came from a variety of sources. A handful of ISFSIs have a specific license, but most use a general license for the NPP they are associated with. This means that the site information published in an NPP FSAR also applies to the NPP's corresponding ISFSI. However, it does not provide ISFSI specific data. The NPP FSARs were the primary source of data for this survey, as none of the ISFSI's examined were on a specific license. However, many of the FSARs available came from power plants built in the 1970s and 1980s and contained limited data on the soil and ground motion response spectra.

FSARs from new power plant applications at the same sites, dated around 2007 – 2008, provided much more detailed and up-to-date data on the soil and GMRS. The best example of this is Vogtle units 3 & 4, which are the only units from these applications to be fully constructed. For power plants without new FSARs, much of the up-to-date data was found from the seismic hazard and screening reports (Section 2.3). Information on the casks used at a given ISFSI was found in the cask FSAR. In addition to structural parameters, the cask FSARs usually provide recommended generic configurations of casks on the pad. The generic configurations were compared to satellite images of the ISFSIs found using Google maps to determine site specific cask configurations. Additional information was obtained from cask registration documents and a few miscellaneous conference papers on various ISFSIs.

4.1 Structural Parameters

Dry storage systems are designed and fabricated by several different manufacturers and are either designed with a horizontal or vertical orientation. In the vertical designs, the dry storage canister (metal containers containing an array of spent fuel assemblies), are placed vertically in a concrete cask (overpack). In the horizontal designs, the metal canister is placed in a horizontal storage module. The dry storage casks and storage modules are then placed on a concrete pad at an ISFSI. Horizontal storage modules are placed directly adjacent to each other for added stability. Structural parameters for the dry storage systems were found primarily in FSARs and are shown in Table 4-2.

Of the sites surveyed, three utilized horizontal storage modules for the dry storage canisters, whereas all other sites used concrete overpacks and vertical canister storage. The vertical cask varied in height from 18.75 to 20 feet and in diameter from 11.04 to 11.6 feet. Vertical overpack concrete compressive strength varied from 3,300 psi to 4,000 psi. Vertical cask center of gravity height varied from 9.6 feet to 10 feet. In some cases, information relating to the centers of gravity of the storage units was unavailable. In these cases, for vertical casks the center of gravity can be assumed to be half the height of the cask. The weight of a fully loaded vertical cask varied from 335,000 lbs. to 425,700 lbs.

The horizontal storage module (HSM) is utilized for the NUHOMS 32PT dry storage cask at the ISFSI site of Fort Calhoun. Its length is 20.7 feet, width is 9.7 feet, and its height is 18.5 feet. The compressive strength of the concrete used in the HSM is 5,000 psi. Fully loaded, the storage unit weighs 415,400 lbs. Information regarding the center of gravity height of the NUHOMS 32PT storage unit was unavailable. The St. Lucie and Nine Mile Point sites uses NUHOMS 32PTH and 61BT canisters respectfully that are stored in similar HSMs.

Table 4-2. Parameters of the Dry Storage Canisters Used at Surveyed NPP ISFSI Sites.

Site	Canister	Diameter or WxL (ft)	Height (ft)	Concrete Strength (psi)	CG Height (ft)	Loaded Weight (lbs)
Fort Calhoun **[21]**	NUHOMS Standard	9.7x20.7	18.5	5,000	NA	415,400
Clinton **[22]**	HI-STORM FW	11.60	20	3,300	10	425,700
Kewaunee **[23]**	Magnastor	11.33	18.75	4,000	9.42	335,000
South Texas **[22]**	HI-STORM FW	11.60	20	3,300	10	425,700
Grand Gulf **[24]**	HI-STORM 100S B	11.04	19.125	3000-4200	9.67	360,000
River Bend **[24]**	HI-STORM 100S	11.04	19.96	3,300	9.5	360,000
Watts Bar **[22]**	HI-STORM FW	11.60	20	3,300	10	425,700
Vogtle **[24]**	HI-STORM 100S B	11.04	19.13	3000-4200	9.67	360,000
Hatch **[24]**	HI-STORM 100S, 100S B	11.04	19.13	3000-4200	9.67	360,000
St. Lucie **[25]**	NUHOMS HD	9.7x20.7	18.5	5,000	NA	415,400
Pilgrim **[24]**	HI-STORM 100	11.04	19.96	3,300	9.89	360,000
Nine Mile Point **[24]**	NUHOMS Standard	9.7x20.7	18.5	5,000	NA	415,400

Parameters for generic ISFSI pads were found in the cask FSARs. The specific pad length and width data was augmented using satellite imagery from Google maps. The ISFSI pad dimensions are provided in Table 4-3. Suggested ISFSI pad thicknesses varied from 2 to 3 feet. The length and width of the pads varied considerably, some being square shaped, some rectangular. Most cask FSARs provided guidelines for cask layouts on the ISFSI pads. Most vertical cask FSARs recommended either NxN (square) or 2xN (rectangular) cask layouts but in some cases non-standard cask layouts and pad sizes were used. The River Bend site is an example of this. Its FSAR provides guidelines for NxN or 2xN arrays, whereas satellite imagery appears to show a 4x10 pad layout. Horizontal cask FSARs generally recommended the horizontal storage modules be placed in rows back to back. The Clinton Power Station ISFSI is shown in Figure 4-2 as an example of a vertical cask layout. The Nine Mile Point Nuclear Generating Station ISFSI is shown in Figure 4-3 as an example of a typical layout for a horizontal cask array.

Table 4-3. Estimated Dimensions of Surveyed ISFSI's.

Site	Cask	Pad thickness (ft)	Length (ft)	Width (ft)
Fort Calhoun	NUHOMS-32PT	NA	210	142
Clinton **[22]**	HI-STORM FW	2 – 2.33	120	120
Kewaunee **[23]**	Magnastor	3	168	40
South Texas **[22]**	HI-STORM FW	2 – 2.33	173	156
Grand Gulf **[26]**	HI-STORM 100S B	3	196	61
River Bend **[24]**	HI-STORM 100S	3	210	60
Watts Bar **[22]**	HI-STORM FW	2 – 2.33	182	142
Vogtle **[27]**	HI-STORM 100S B	2.5	417	48
Hatch **[28]**	HI-STORM 100S B	2	96.5	31
St. Lucie	NUHOMS HD 32 PTH	NA	369	123
Pilgrim **[24]**	HI-STORM 100	3	238	52
Nine Mile Point	NUHOMS 61BT	NA	218	196

Figure 4-2. Clinton Power Station ISFSI, Satellite Image from Google Maps (accessed 6/17/2021).

Figure 4-3. Nine Mile Point Nuclear Generating Station ISFSI, Satellite Image from Google Maps, (accessed 6/17/2021).

Friction values between the pad and the cask were difficult to find. The only place this value was found was in the HI-STORM 100 FSAR [24]. The value to be used was 0.53. Higher values needed to be verified by testing. Only one document, a construction report for the Grand Gulf ISFSI, performed experiments to verify a higher value, and found the coefficient of friction to be 0.54 [26].

4.2 Soil Parameters

Soil profiles for the NPPs were found in either the NPP FSARs or the seismic hazard screening reports. Competent soil depth, defined as the soil depth when the shear wave speed reaches 1,000 ft/s, and hard rock depth, defined as the depth when the shear wave speed reaches 9,200 ft/s, are shown for each site in Table 4-4. As can be seen from Table 4-4, because of the depth of the soil, most of the NPPs surveyed are considered soil sites, with two exceptions. Pilgrim Nuclear Power Station is built on a rocky island and is a known rock site. However, this NPP was included because of its very close proximity to the Manchester, NH test site. Kewaunee Power Station also has shallow soil with a hard rock depth of 150 feet. There was no new FSAR available for this site and it was shut down in 2013, so there is no seismic hazard screening report available either. As a result, the Kewaunee data is incomplete.

The soil sites varied in depth, with the Midwest sites such as Calhoun and Clinton having similar soil depth orders of magnitudes, around 2,000 to 6,000 ft. NPPs on the Gulf of Mexico, close to the Mississippi River, including South Texas, Grand Gulf, and River Bend, had very deep soil depths, greater than 10,000 ft. Vogtle, Hatch, Watts Bar, and St. Lucie, in the southeast all fell into the range of 2,000 – 9,000 ft. Nine Mile Point, in the northeast, had a hard rock depth of 1,800 ft. Detailed soil stratigraphy profiles are available for each of these sites. Generally speaking, the soil site stratigraphy included alternating layers of sand, silt, and clay, with the occasional layer of sandstone or limestone. Figure 4-4 shows the shear velocity profile at the Vogtle site (Southern Nuclear Operating Company, 2017) and the deep soil shear velocity profile from NUREG 2115.

Table 4-4. Competent Soil and Hard Rock Depths for the Surveyed NPPs.

Name	Competent Soil Depth (ft)	Hard Rock Depth (ft)
Fort Calhoun Nuclear Generating Station **[29]**	50	2,200
Clinton Power Station **[30]**	0	6,000
Kewaunee Power Station **[31]**	NA	150
South Texas Generating Station **[32]**	50	> 20,000 ($V_s \approx$ 5,000 ft/s)
Grand Gulf Nuclear Station **[33]**	100	>10,000
River Bend Nuclear Generating Station **[34]**	30	>18,000 ($V_s \approx$ 7600 ft/s)
Watts Bar Nuclear Plant **[35]**	0	9,300
Vogtle Electric Generating Plant **[36]**	40	2,300
Edwin I. Hatch Nuclear Power Plant **[37]**	100	4,050
St. Lucie Nuclear Power Plant **[38]**	50	5,100
Pilgrim Nuclear Power Station **[39]**	0	48
Nine Mile Point Nuclear Generating Station **[40]**	0	1800

NOTE: NA indicates that data was not available.

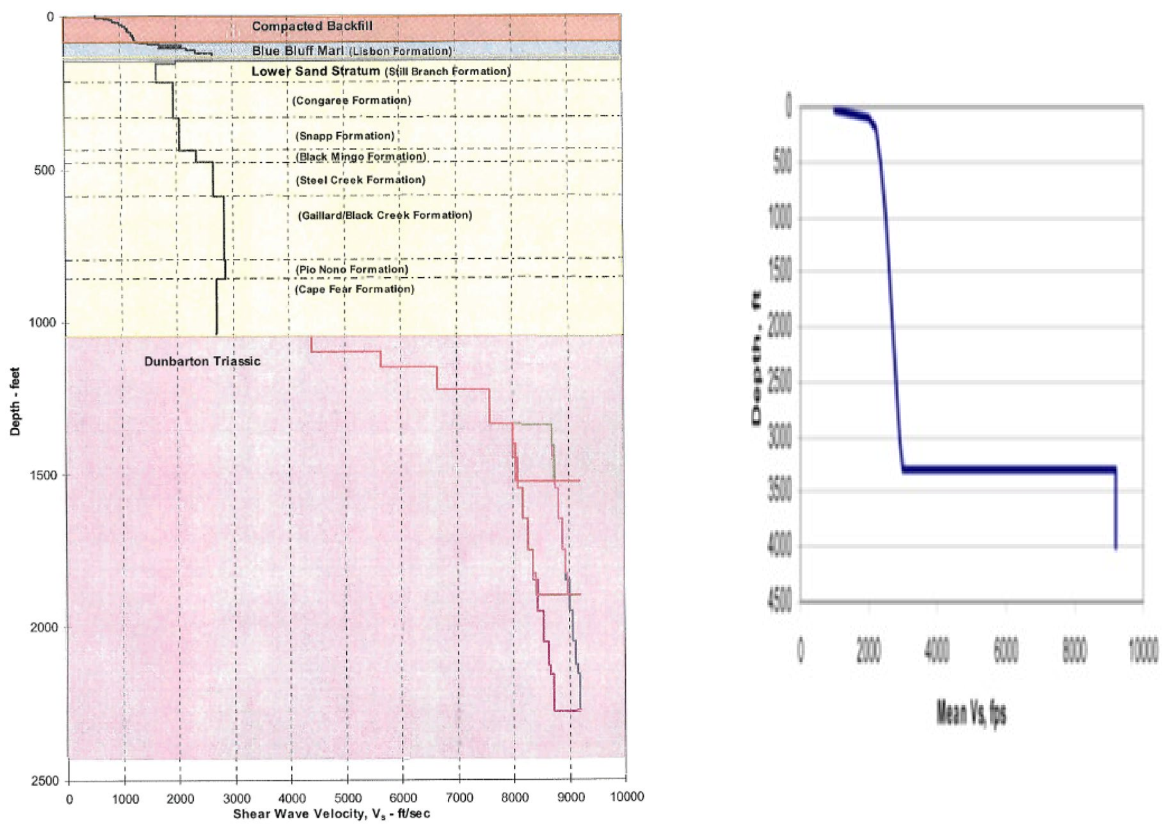


Figure 4-4. Shear Velocity Profile at Vogtle Site (left) and Deep Soil Profile from NUREG 2115.

Soil ground motion response spectra data was not available, however soil amplification factors from the frequency range of 0.1 − 100 Hz was provided in the screening reports. These data show that typical soil amplification has a maximum between 1 and 10 Hz, with shallower hard rock depths peaking closer to 10 Hz and deeper hard rock depths having a maximum shifted closer to 1Hz.

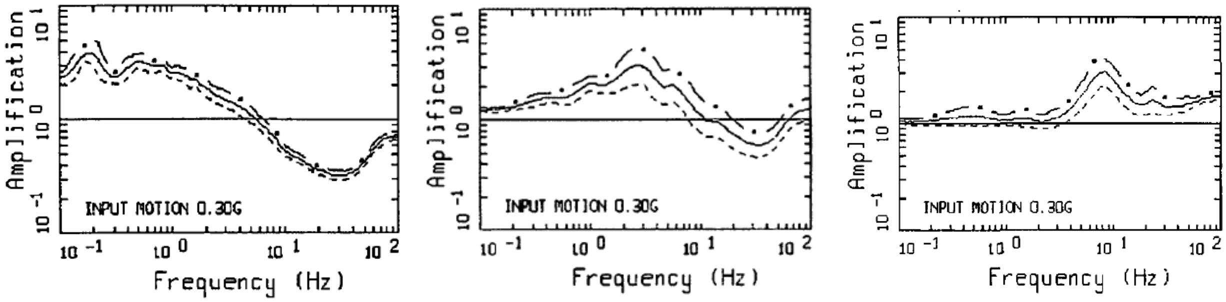


Figure 4-5. Soil Amplification Factors for River Bend [41] , Fort Calhoun [29], and Pilgrim [39] NPPs (from left to right).

4.3 Ground Motion Response Spectra

Data on the frequency response spectra of the sites was difficult to find. Frequency response spectra at the pad were entirely unavailable. The seismic hazard screening reports supplied the GMRS in the horizontal direction, and most FSARs for the combined license applications of new NPPs provided both horizontal and vertical GMRS data. Table 4-5 provides a summary of the key values of these spectra, including the PGA, the maximum amplitude, and the frequency at which the maximum amplitude occurs, for both the horizontal and vertical directions, when available.

Table 4-5. Ground Motion Response Spectra Summary.

Site Name	Horizontal GMRS			Vertical GMRS		
	PGA (g)	Max amp. (g)	Freq. of max amp. (Hz)	PGA (g)	Max amp. (g)	Freq. of max amp. (Hz)
Fort Calhoun Nuclear Generating Station **[29]**	0.2	0.43	5	NA	NA	NA
Clinton Power Station **[30]**	0.27	0.59	8	NA	NA	NA
Kewaunee Power Station	NA	NA	NA	NA	NA	NA
South Texas Generating Station **[42]**	0.085	0.19	0.5	0.085	0.16	4.5
Grand Gulf Nuclear Station **[33]**	0.11	0.35	1	0.068	0.15	6
River Bend Nuclear Generating Station **[34]**	0.095	0.21	1	0.054	0.11	10
Watts Bar Nuclear Plant **[35]**	0.375	0.76	15	NA	NA	NA
Vogtle Electric Generating Plant **[36]**	0.29	0.8	10	NA	NA	NA
Edwin I. Hatch Nuclear Power Plant **[37]**	0.14	0.32	6	NA	NA	NA
St. Lucie Nuclear Power Plant **[38]**	0.055	0.105	7	NA	NA	NA
Pilgrim Nuclear Power Station **[39]**	0.5	1.2	10	NA	NA	NA
Nine Mile Point Nuclear Generating Station **[40]**	0.07	0.19	25	0.055	0.15	35

Generally speaking, sites with deeper soils had a lower maximum amplitude frequency. They also tended to have lower maximum amplitudes. The obvious exception to this trend was the Nine Mile Point NPP. It has a hard rock depth of 1,800 ft, which has a 25 Hz peak, much higher than hard rock sites evaluated. However, it also had amplitudes similar to those with very deep soil. In general, the vertical PGA and maximum amplitude were always lower than their horizontal counterparts.

5. Summary

Currently, spent nuclear fuel (SNF) is stored in on-site independent spent-fuel storage installations (ISFSIs) at seventy-three (73) nuclear power plants (NPPs) in the US. Because a site for geologic repository for permanent disposal of SNF has not been constructed, the SNF will remain in dry storage significantly longer than planned. During this time, the ISFSIs, and potentially consolidated storage facilities, will experience earthquakes of different magnitudes. The dry storage systems are designed and licensed to withstand large seismic loads. When dry storage systems experience seismic loads, there are little data on the response of SNF assemblies contained within them. The Spent Fuel Waste Disposition (SFWD) program is planning to conduct a full-scale seismic shake table test to close the gap related to the seismic loads on the fuel assemblies in dry storage systems. This test will allow for quantifying the strains and accelerations on surrogate fuel assembly hardware and cladding during earthquakes of different magnitudes and frequency content.

The main component of the test unit will be the full-scale NUHOMS 32 PTH2 dry storage canister. The canister will be loaded with three surrogate fuel assemblies and twenty-nine dummy assemblies. Two dry storage configurations will be tested – horizontal and vertical above-ground concrete overpacks. These configurations cover 91% of the current dry storage configurations.

The major input into the shake table test are the seismic excitations or the earthquake ground motions – acceleration time histories in two horizontal and one vertical direction that will be applied to the shake table surface during the tests. The shake table surface represents the top of the concrete pad on which a dry storage system is placed. The goal of the ground motion task is to develop the ground motions that would be representative of the range of seismotectonic and other conditions that any site in the Western US (WUS) or Central Eastern US (CEUS) might entail. This task is challenging because of the large number of the ISFSI sites, variety of seismotectonic and site conditions, and effects that soil amplification, soil-structure interaction, and pad flexibility may have on the ground motions.

The ground motion development work was divided into two phases. This report describes the results of Phase 1. This phase focused on the development of the free-field ground motions and an approach to the soil-structure interactions.

Sections 1 and 2 of this report provides brief information on the shake table test, background information describing the dry storage systems used at the different ISFSI sites, site-conditions, and site-specific ground motion data. It also discusses an approach to developing ground motions. This approach leverages a recent extensive study of the CEUS "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities" documented in NUREG-2115 [14]. In NUREG-2115, seven test sites were selected to represent the seismic hazards in 7 different seismotectonic regions in the CEUS. In addition to the sites from NUREG-2115, four representative sites were selected in WUS.

Section 3 summarizes the major results related to the development of the spectral shapes and amplitudes (peak ground acceleration scaling factors) that cover the range of seismotectonic and site conditions at the CEUS and WUS NPP (ISFSI) sites. The work was performed by Nicholas Gregor and Linda Al Atik (Consultants to SC Solutions) and reviewed by Norman Abrahamson (SC Solutions). The report documenting this work is included as Appendix A to this report.

Section 4 provides the summary of the ISFSI survey. The structural parameters, soil parameters, and ground motion response spectra are discussed.

Phase 2 will be devoted to the soil-structure interactions and will be based on the approach developed in Phase 1. The results of Phase II will be documented in an update to this report.

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Appendix A

SC Solutions Preliminary Report

"Ground Motions for Shake-Table Testing of Dry Casks"

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Ground Motions for Shake-Table Testing of Dry Casks

Intermediate Report

Prepared by

SC SOLUTIONS

For

Sandia National Laboratories

Sandia National Laboratories

June 28, 2021

Ground Motions for Shake-Table Testing of Dry Casks

Intermediate Report

Revision 0b

June 28, 2021

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Revision History

Revision	Date	Description
0	6/18/2021	Initial Issue Document
0a	6/23/2021	Minor editorial changes, Revised Table 2-9
0b	6/25/2021	Revised Table 2-14
0c	6/28/2021	Revised Figure 2-6

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1 Introduction

Currently, spent nuclear fuel (SNF) is stored in onsite independent spent fuel storage facilities (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. To address these concerns, SNL/NTESS under the Spent Fuel Waste Disposition (SFWD) program is planning to conduct an earthquake shaker table test. The goal of this test 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.

It is widely known that soil-structure interactions (SSI) effects will alter the ground motions as they interact with the ISFSI concrete pad and dry storage system. This SSI is needed 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 the Large High-Performance Outdoor Shake Table (LHPOST) at the University of California San Diego (UCSD).

The major input into the shaker table test is the earthquake ground motions. The ground motions must capture the range of seismic environments for dry-cask storage in the United States for seismic hazard levels from 1E-3 to 1E-5 mean annual frequency of exceedance. This report presents the development of applicable spectral shapes and amplitudes representative of the different seismic, tectonic and site conditions in United States. Time histories compatible with these spectral shapes will be provided at a later date, These time histories are expected to be used in the analyses of the dry storage systems.

The development of the spectral shapes presented in this report is guided by the examination of the PSHA results from a suite of nuclear power plant (NPP) sites in both the Central and Eastern North America (CENA) and the Western United States (WUS). However, the recommended spectra are not meant to represent any site-specific ground motion characterization from the suite of NPP examined.

2 Spectral Shapes Development

For this study, spectral shapes based on selected scenario events are developed. The selection of the scenario events are based on the observed controlling earthquakes for sites located in the CENA and WUS, separately. For the CENA cases, three controlling scenario events are selected. For the WUS, three different scenario events are also selected but only two are applied for the different site classifications.

For the CENA cases, the recently developed NGA-East ground motion model (GMMs) (Goulet et al., 2018) are implemented given the scenario event magnitude and distance values. The weighted mean of the suite of NGA-East models is used in this study. For the WUS cases, four NGA-West2 GMMs (Abrahamson et al., (2014); Boore et al. (2014), Campbell and Bozorgnia (2014); Chiou and Youngs (2014)) are employed. Each of these four models is assigned equal weights. Median response spectra from the NGA-East and NGA-West2 GMMs are defined for the horizontal component of motion. Vertical component spectra are developed based on the application of a vertical to horizontal spectral ratio model (Gulerce and Abrahamson, 2011) as presented later in this report.

2.1 Controlling Scenario Events and Horizontal Spectral Shapes

Representative controlling events are selected based on the deaggregation of the PSHA results for selected sites in the CENA. As part of the NGA-East GMM study, seven selected representative sites in the CENA were chosen to perform PSHA calculations. Note that none of these seven sites corresponds to a specific NPP site location. These seven sites are shown in Figure 2-1. Also indicated is the regional boundary for the Central and Eastern United States (CEUS) seismic source characterization model used in the PSHA.

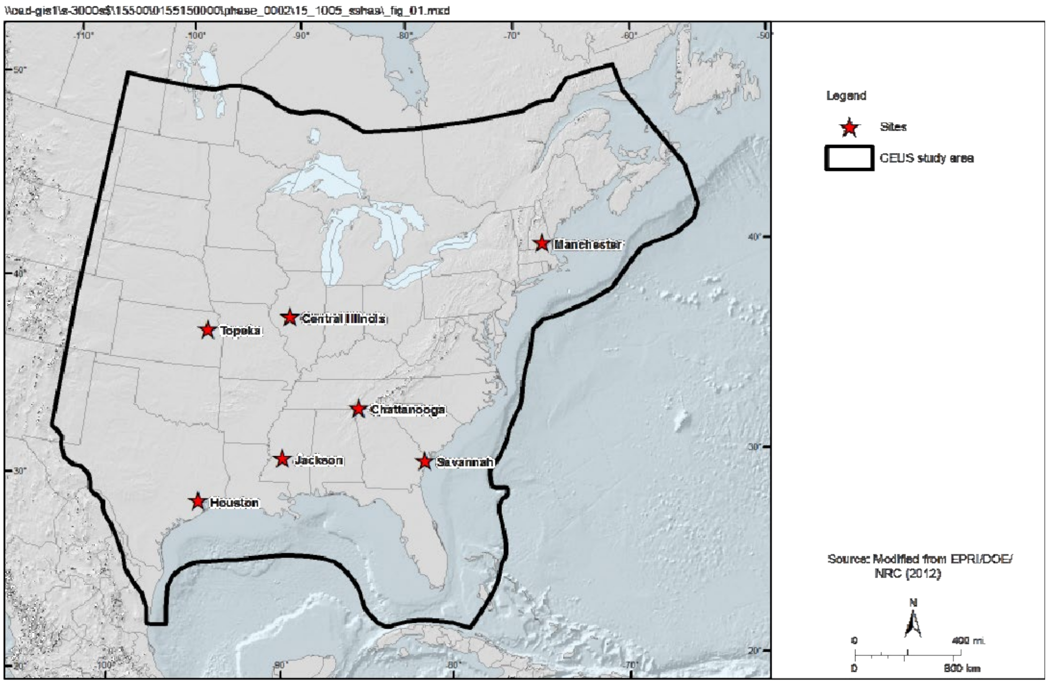


Figure 2-1 Seven demonstration sites from the NGA-East study (Goulet et al., 2018)

Given these seven demonstration sites locations, the USGS web tool was queried to extract the modal deaggregation values from the USGS 2014 PSHA results for hard rock site conditions. This extraction was performed at the 1E-4 annual exceedance level. It is not expected that these general deaggregation results would change significantly given the use of more current GMMs or revised seismic source characterization (SSC) model.

Based on these deaggregation results, three selected scenario events are selected as being representative for sites in the CENA. These events are listed in Table 2-1.

Table 2-1 Selected scenario events for site in the CENA.

Scenario Event	**Magnitude**	**Distance (km)**
Local event	5.5	15
Moderate event	6.5	40
Large magnitude distant event	7.8	200

Given the three scenario events listed in Table 2-1, the median ground motion spectra from these events are computed based on the NGA-East GMM. The horizontal spectral values are listed in Table 2-2 and plotted in Figure 2-2.

Table 2-2 Median ground motion spectra (g) from the NGA-East GMM for the three selected scenario events for CENA sites for hard rock site conditions.

Period (sec)	Frequency (Hz)	M=5.5, Dist=15km	M=6.5, Dist=40km	M=7.8, Dist=200km
0.010	100.000	0.22958	0.15521	0.09655
0.020	50.000	0.32293	0.20618	0.12199
0.025	40.000	0.35442	0.22671	0.13444
0.030	33.333	0.38034	0.2442	0.14532
0.040	25.000	0.41336	0.2741	0.16598
0.050	20.000	0.41663	0.2866	0.17667
0.075	13.333	0.33878	0.24429	0.16131
0.100	10.000	0.29943	0.23386	0.169
0.150	6.667	0.22456	0.19266	0.15689
0.200	5.000	0.18259	0.16612	0.14509
0.250	4.000	0.15046	0.14162	0.13109
0.300	3.333	0.13027	0.1282	0.1242
0.400	2.500	0.09753	0.10296	0.10642
0.500	2.000	0.07718	0.08712	0.094
0.750	1.333	0.04591	0.06079	0.07351
1.000	1.000	0.02934	0.04492	0.06075
1.499	0.667	0.01426	0.02716	0.04542
2.000	0.500	0.00823	0.01858	0.03869

3.003	0.333	0.00345	0.00924	0.02477
4.000	0.250	0.00191	0.00574	0.019
5.000	0.200	0.00118	0.00382	0.01457
7.519	0.133	0.00047	0.00181	0.00924
10.000	0.100	0.00025	0.00106	0.00648

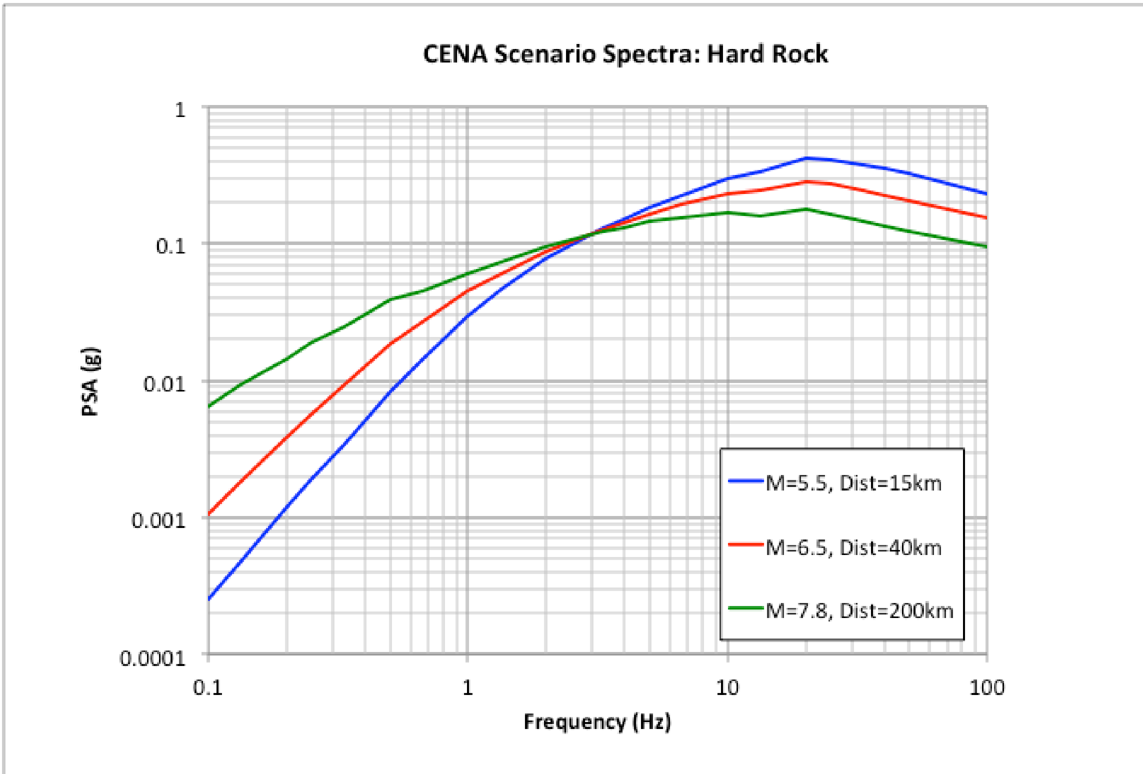


Figure 2-2 Median ground motion spectra for the three scenario events for CENA sites for hard rock site conditions

In addition to the hard rock site conditions, two additional site classifications are considered: soft rock and soil. For the NGA-East GMM the site amplification factor model (Stewart et al., 2018) is applied given a Vs30 value. The selected Vs30 values for the soft rock and soil site classifications are based on the average Vs30 values for the NPP sites examined within the Vs30 bins of 500 – 1000 m/sec (soft rock) and less than 500 m/sec (soil). These average Vs30 values are 698.7 and 320.7 m/sec for the soft rock and soil site condition, respectively. Given the application of the Stewart et al., (2018) site amplification factors, the resulting median scenario spectra are listed in Table 2-3 and plotted in Figure 3 for soft rock and Table 2-4 and Figure 2-5 for soil conditions. For the nonlinear component of the soil amplification motion, the median hard rock PGA is used in the application of the site amplification model.

Table 2-3 Median ground motion spectra (g) from the NGA-East GMM for the three selected scenario events for CENA sites for soft rock site conditions (Vs30=698.7 m/sec).

Period (sec)	**Frequency (Hz)**	**M=5.5, Dist=15km**	**M=6.5, Dist=40km**	**M=7.8, Dist=200km**
0.010	100.000	0.23859	0.16825	0.10904
0.020	50.000	0.33560	0.22351	0.13777
0.025	40.000	0.37203	0.24823	0.15335
0.030	33.333	0.40937	0.27417	0.16997
0.040	25.000	0.47381	0.32773	0.20675
0.050	20.000	0.50406	0.36169	0.23227
0.075	13.333	0.46857	0.35244	0.24245
0.100	10.000	0.52955	0.42670	0.31792
0.150	6.667	0.38717	0.33872	0.28121
0.200	5.000	0.27114	0.25006	0.22138
0.250	4.000	0.20833	0.19777	0.18463
0.300	3.333	0.17266	0.17090	0.16651
0.400	2.500	0.12382	0.13092	0.13554
0.500	2.000	0.09513	0.10745	0.11601
0.750	1.333	0.05444	0.07209	0.08718
1.000	1.000	0.03380	0.05175	0.06999
1.499	0.667	0.01616	0.03078	0.05147

2.000	0.500	0.00935	0.02111	0.04396
3.003	0.333	0.00390	0.01044	0.02800
4.000	0.250	0.00215	0.00645	0.02134
5.000	0.200	0.00132	0.00428	0.01631
7.519	0.133	0.00052	0.00201	0.01026
10.000	0.100	0.00028	0.00117	0.00717

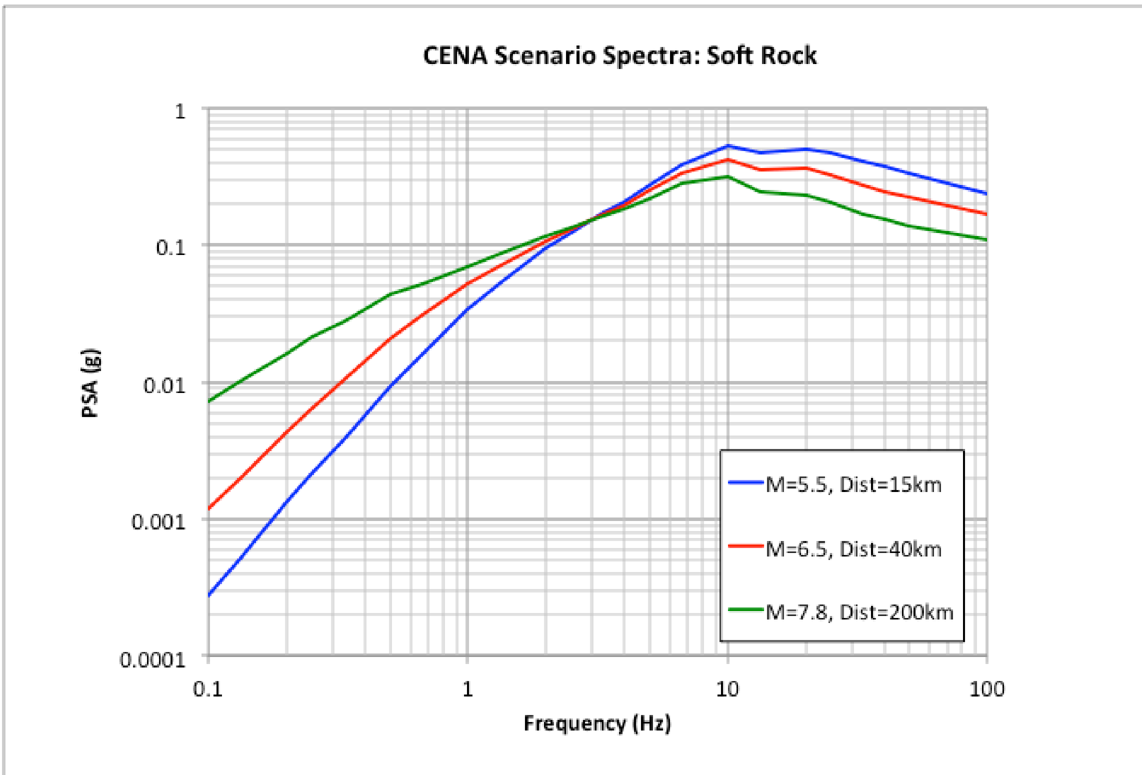


Figure 2-3 Median ground motion spectra for the three scenario events for CENA sites for soft rock site conditions (Vs30=698.7 m/sec).

Table 2-4 Median ground motion spectra (g) from the NGA-East GMM for the three selected scenario events for CENA sites for soil site conditions (Vs30=320.7 m/sec).

Period (sec)	Frequency (Hz)	M=5.5, Dist=15km	M=6.5, Dist=40km	M=7.8, Dist=200km
0.010	100.000	0.22610	0.17210	0.12011
0.020	50.000	0.31804	0.22862	0.15176
0.025	40.000	0.35256	0.25391	0.16893
0.030	33.333	0.38795	0.28044	0.18723
0.040	25.000	0.44901	0.33522	0.22774
0.050	20.000	0.47768	0.36996	0.25586
0.075	13.333	0.44405	0.36050	0.26707
0.100	10.000	0.49347	0.43057	0.34677
0.150	6.667	0.37198	0.35174	0.31532
0.200	5.000	0.27076	0.26847	0.25545
0.250	4.000	0.21303	0.21647	0.21621
0.300	3.333	0.18147	0.19120	0.19823
0.400	2.500	0.14120	0.15555	0.16797
0.500	2.000	0.11737	0.13651	0.15187
0.750	1.333	0.07367	0.09935	0.12249
1.000	1.000	0.05111	0.07850	0.10652
1.499	0.667	0.02478	0.04730	0.07930
2.000	0.500	0.01441	0.03258	0.06796
3.003	0.333	0.00604	0.01621	0.04354
4.000	0.250	0.00333	0.01002	0.03325

5.000	0.200	0.00202	0.00656	0.02506
7.519	0.133	0.00080	0.00308	0.01577
10.000	0.100	0.00042	0.00180	0.01102

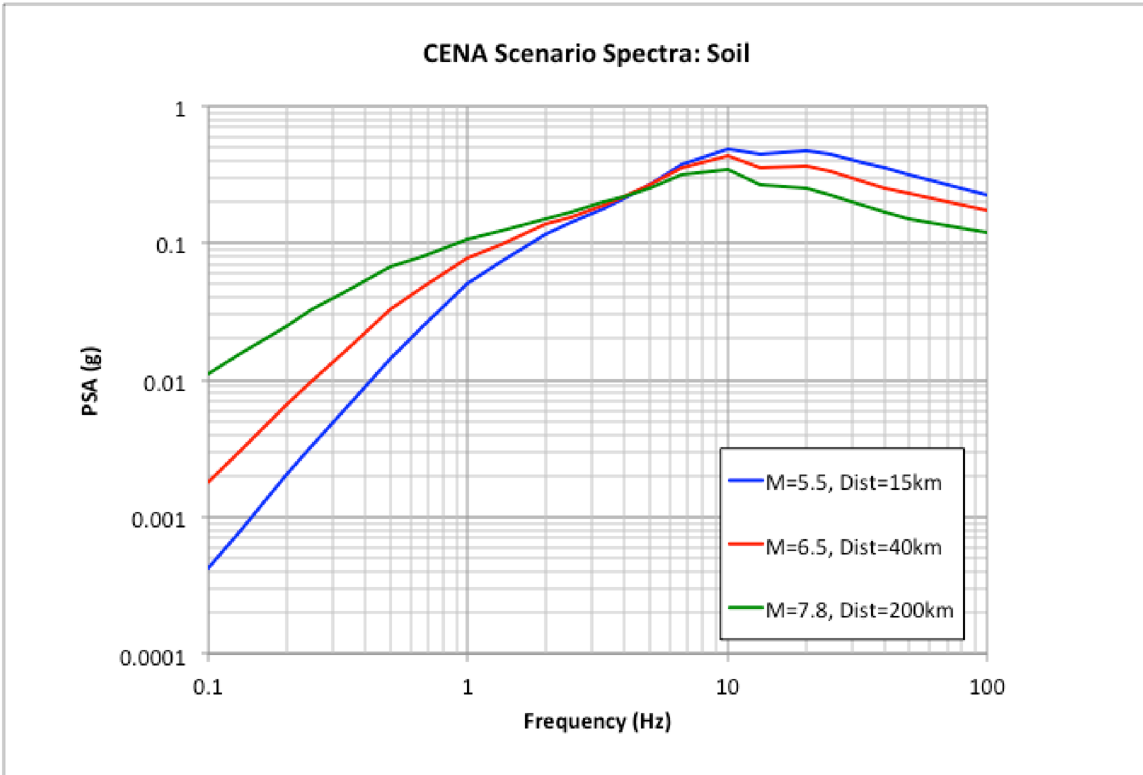


Figure 2-4 Median ground motion spectra for the three scenario events for CENA sites for soil site conditions (Vs30=320.7 m/sec).

For the WUS case, the PSHA results from three NPP sites are reviewed: Diablo Canyon, Hanford, and Palo Verde. Based on the deaggregation from the supporting documentation for the PSHA conducted recently for these three NPP sites, three controlling scenario events were selected and are listed in Table 2-5. As noted in Table 2-5, the first two scenario events are applicable for the Diablo Canyon and Hanford NPP sites while for Palo Verde the first and third scenario events are applicable.

Table 2-5 Selected scenario events for site in the WUS.

Scenario Event	Magnitude	Distance (km)	Applicable NPP
Local event	6.25	10	Diablo Canyon, Hanford, Palo Verde
Large magnitude local event	7.5	5	Diablo Canyon, Hanford
Large magnitude distant event	7.5	200	Diablo Canyon, Hanford, Palo Verde

For the three NPP sites considered in WUS, both Diablo Canyon and Hanford developed ground motions for Vs30=760 m/sec. For Palo Verde the site condition had a Vs30=344 m/sec. Following the site classification structure applied to the CENA sites, the Diablo Canyon and Hanford sites are assigned soft rock site classification and the Palo Verde is assigned soil. Taking scenario events listed in Table 2-5 with the four NGA-West2 GMMs, weighted median ground motion spectra are computed and listed in Table 2-6 and Figure 2-5 for soft rock and Table 2-7 and Figure 2-6 for soil site condition. These ground motions are based on a vertical strike-slip fault with the default parameters (e.g., depth to top of rupture, Z1, Z25) given the input values listed in Table 2-5.

Table 2-6 Median ground motion spectra (g) from the NGA-West2 GMMs for the two selected scenario events for WUS sites for soft rock site conditions (Vs30=760 m/sec).

Period (sec)	Frequency (Hz)	M=6.25, Dist=10km	M=7.5, Dist=5km
0.010	100.000	0.1998	0.4168
0.020	50.000	0.2043	0.4274
0.030	33.333	0.2261	0.4726
0.040	25.000	0.2575	0.5332
0.050	20.000	0.2887	0.5937
0.075	13.333	0.3697	0.7439
0.100	10.000	0.4223	0.8389

0.150	6.667	0.4747	0.9516
0.200	5.000	0.4582	0.9336
0.300	3.333	0.3656	0.7879
0.400	2.500	0.2928	0.6681
0.500	2.000	0.2392	0.5720
0.750	1.333	0.1559	0.4091
1.000	1.000	0.1102	0.3116
1.500	0.667	0.0626	0.2010
2.000	0.500	0.0415	0.1452
3.000	0.333	0.0223	0.0948
5.000	0.200	0.0096	0.0527
7.500	0.133	0.0044	0.0287
10.000	0.100	0.0025	0.0184

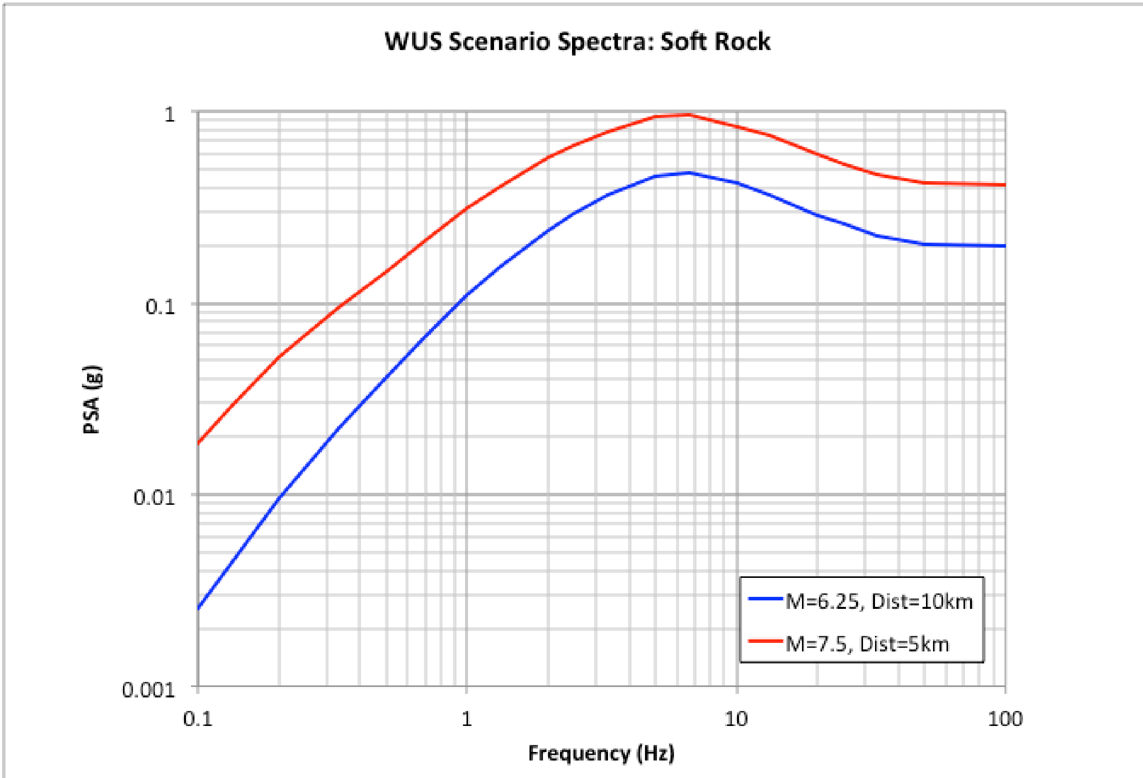


Figure 2-5 Median ground motion spectra for the two scenario events for WUS sites for soft rock site conditions (Vs30=760 m/sec).

Table 2-7 Median ground motion spectra (g) from the NGA-West2 GMMs for the two selected scenario events for WUS sites for soil site conditions (Vs30=344 m/sec).

Period (sec)	**Frequency (Hz)**	**M=6.25, Dist=10km**	**M=7.5, Dist=200km**
0.010	100.000	0.2465	0.0198
0.020	50.000	0.2482	0.0195
0.030	33.333	0.2591	0.0194
0.040	25.000	0.2796	0.0196
0.050	20.000	0.3000	0.0199
0.075	13.333	0.3711	0.0218
0.100	10.000	0.4401	0.0248
0.150	6.667	0.5455	0.0309
0.200	5.000	0.5931	0.0378
0.300	3.333	0.5805	0.0494
0.400	2.500	0.5137	0.0535
0.500	2.000	0.4484	0.0542
0.750	1.333	0.3132	0.0465
1.000	1.000	0.2326	0.0374
1.500	0.667	0.1380	0.0281
2.000	0.500	0.0915	0.0211
3.000	0.333	0.0499	0.0143
5.000	0.200	0.0203	0.0077
7.500	0.133	0.0085	0.0046
10.000	0.100	0.0045	0.0029

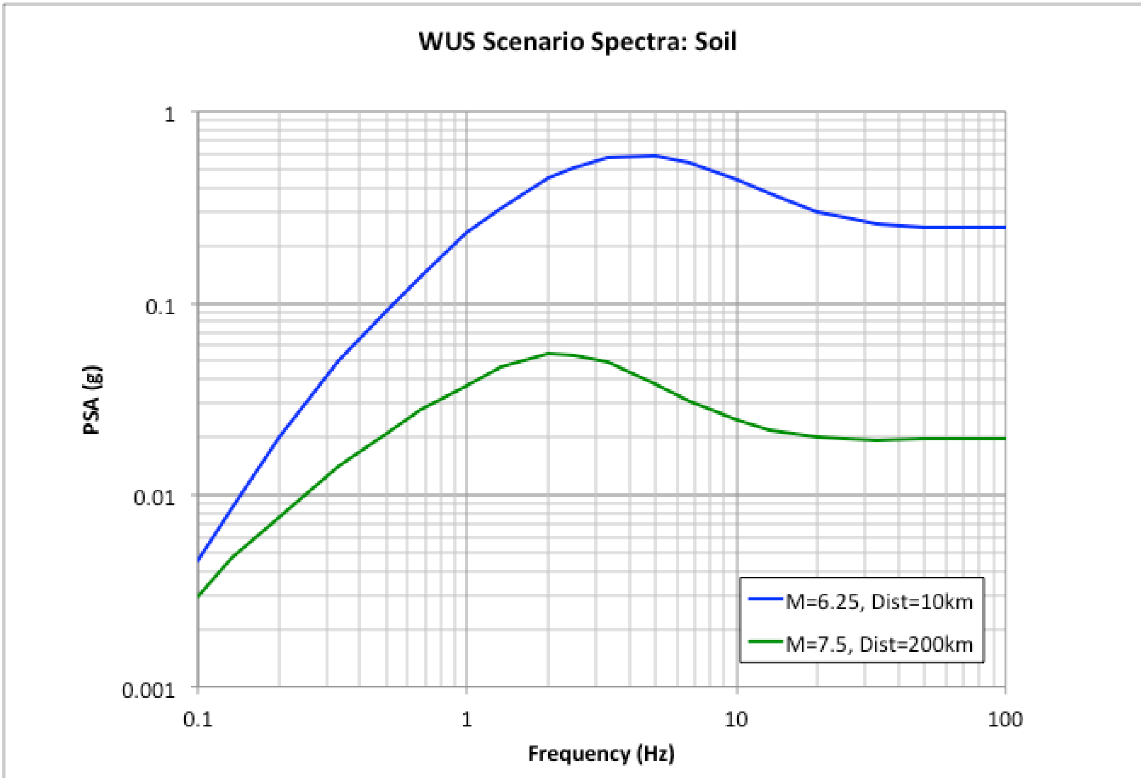


Figure 2-6 Median ground motion spectra for the two scenario events for WUS sites for soil site conditions (Vs30=344 m/sec).

2.2 CENA Uniform Hazard Spectrum

The Uniform Hazard Spectrum (UHS) for 1E-4 annual exceedance level for the seven demonstration sites is provided in the NGA-East report (Goulet et al., 2018). For the other NPP sites in CENA, the UHS were extracted from the series of NRC screening reports. Within each of these reports, the UHS and the shear wave profiles are provided. For the Vs30 values computed and used in this study, the highest weighted profile (i.e., base case profile) was used. The computed Vs30 values and site classification for all 51 of the CENA NPP sites are listed in Table 2-7. As noted earlier, the grouping of these sites into three site classifications was performed based on Vs30 values. A summary of these results is provided in Table 2-8. The suite of 1E-4 UHS are plotted for the three site classifications in Figure 2-7 (hard rock), Figure 2-8 (soft rock) and Figure 2-9 (soil).

Table 2-8 Listing of CENA NPP sites, screening report NRC accession number and computed Vs30 based on the base case profile.

NPP Site Name	**Vs30 (m/sec)**	**Site Classification**
Beaver Valley	538.4	Soft Rock
Brunswick	870.7	Soft Rock
Calvert Cliffs	397.5	Soil
Gina	2499.2	Hard Rock
Nine Mile	2214.0	Hard Rock
Clinton	436.2	Soil
Duane Arnold	2621.2	Hard Rock
Fort Calhoun	389.1	Soil
Grand Gulf	504.2	Soft Rock
Hatch	343.0	Soil
Hope Creek	607.7	Soft Rock
LaSalle	254.8	Soil
South Texas	244.8	Soil
Monticello	461.8	Soil
Oyster Creek	197.9	Soil
Palisades	305.9	Soil
Pilgrim	1018.4	Hard Rock
Point Beach	344.4	Soil
Prairie Island	748.2	Soft Rock
River Bend	334.7	Soil
Robinson	394.2	Soil
Salem	710.0	Soft Rock

St. Lucie	280.0	Soil
Surry	710.0	Soft Rock
Vogtle	322.7	Soil
Waterford	283.3	Soil
Arkansas Nuclear One	1622.8	Hard Rock
Bellefonte	2828.4	Hard Rock
Braidwood	975.3	Soft Rock
Byron	981.7	Soft Rock
Comanche Peak	1652.4	Hard Rock
Davis Besse	1386.1	Hard Rock
Dresden	1128.3	Hard Rock
Farley	267.0	Soil
Fermi	1497.0	Hard Rock
Fitzpatrick	2285.9	Hard Rock
Harris	1713.1	Hard Rock
Indian Pt.	2828.4	Hard Rock
Limerick	1059.0	Hard Rock
McGuire	2566.6	Hard Rock
North Anna	1260.7	Hard Rock
Oconee	2613.8	Hard Rock
Peach Bottom	2182.9	Hard Rock
Perry	1519.4	Hard Rock
Quad City	1353.9	Hard Rock
Seabrook	2828.4	Hard Rock
Summer	2828.4	Hard Rock

Susquehanna	2285.0	Hard Rock
Three Mile Island	1531.8	Hard Rock
Turkey Point	613.5	Soft Rock
Wolf Creek	609.3	Soft Rock

Table 2-9 Summary results from the classification of the 51 CENA NPP sites.

Site Classification	Average Vs30 (m/sec)	Number of Sites
Soil	320.7	16
Soft Rock	698.7	11
Hard Rock	1868.3	24

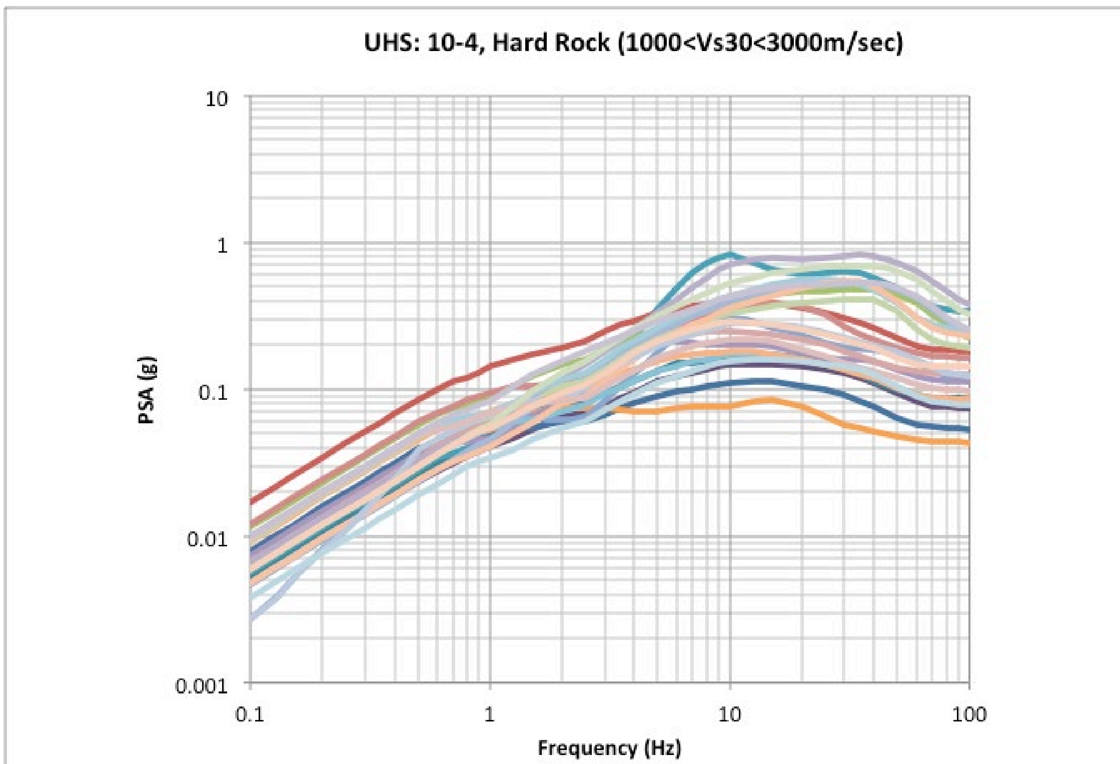


Figure 2-7 1E-4 UHS for the suite of NPP CENA sites with hard rock site conditions.

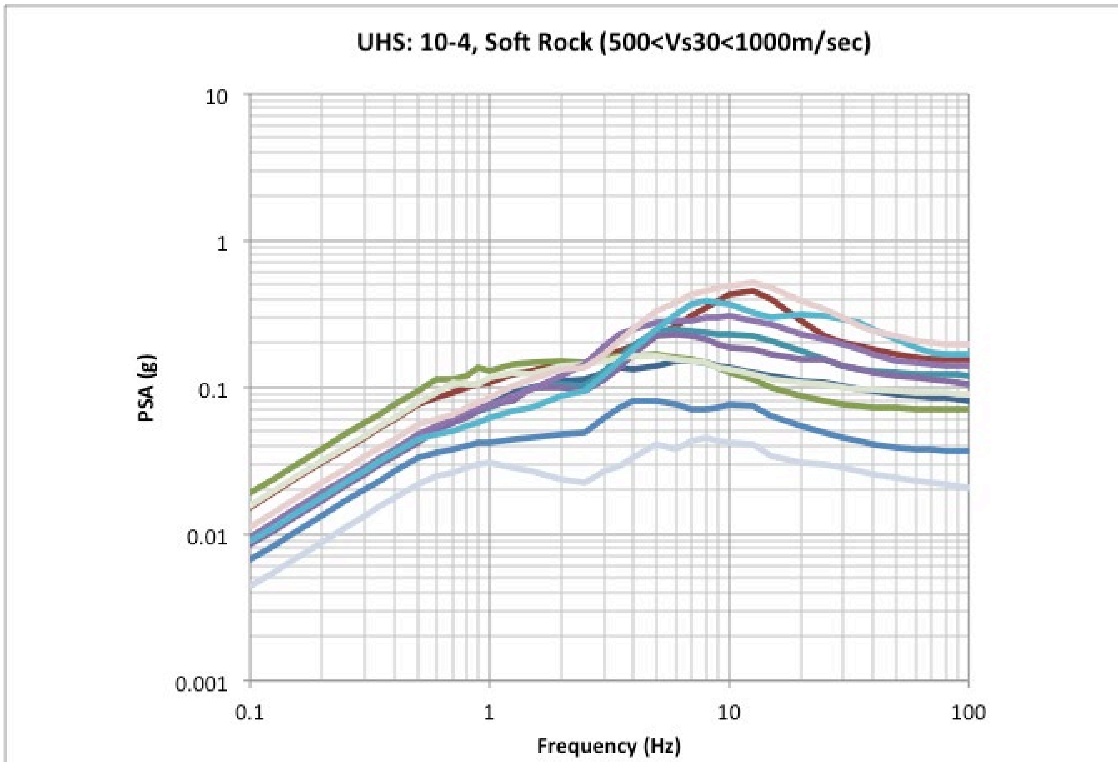


Figure 2-8 1E-4 UHS for the suite of NPP CENA sites with soft rock site conditions.

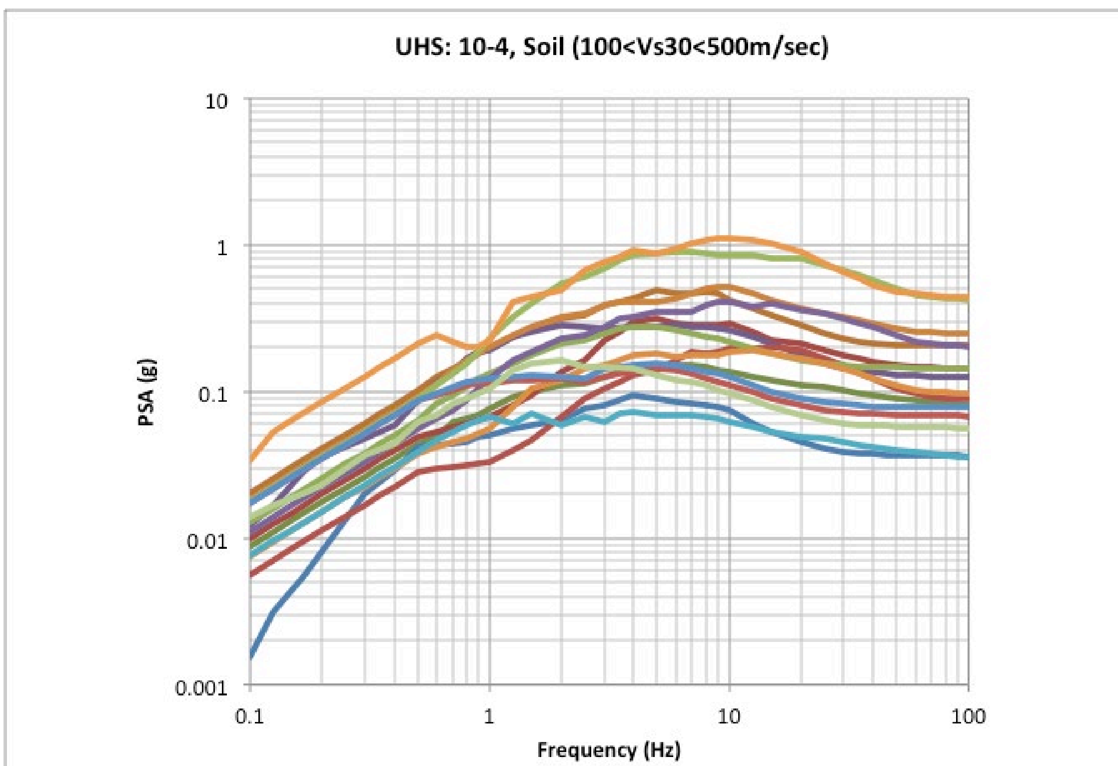


Figure 2-9 1E-4 UHS for the suite of NPP CENA sites with soil site conditions.

2.3 WUS Uniform Hazard Spectrum

For the three WUS sites the same process was performed where the UHS and Vs30 values were extracted from the relevant PSHA reports. The summary of these results is listed in Table 2-9. The 1E-04 UHS from these three sites separated by site classification are plotted in Figure 2-10 (soft rock) and Figure 2-11 (soil).

Table 2-10 Summary of WUS sites.

NPP Site Name	Vs30 (m/sec)	Site Classification
Diablo Canyon	760.0	Soft Rock
Hanford	760.0	Soft Rock
Palo Verde	344.0	Soil

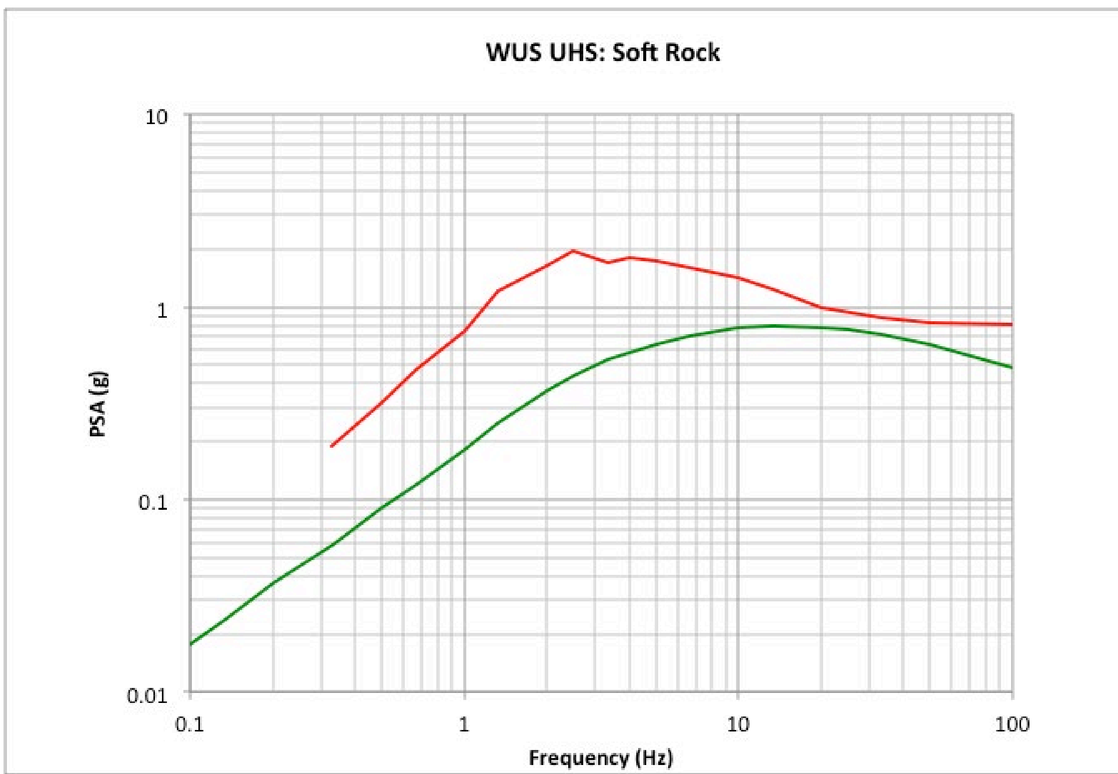


Figure 2-10 1E-4 UHS for the suite of WUS sites with soft rock site conditions.

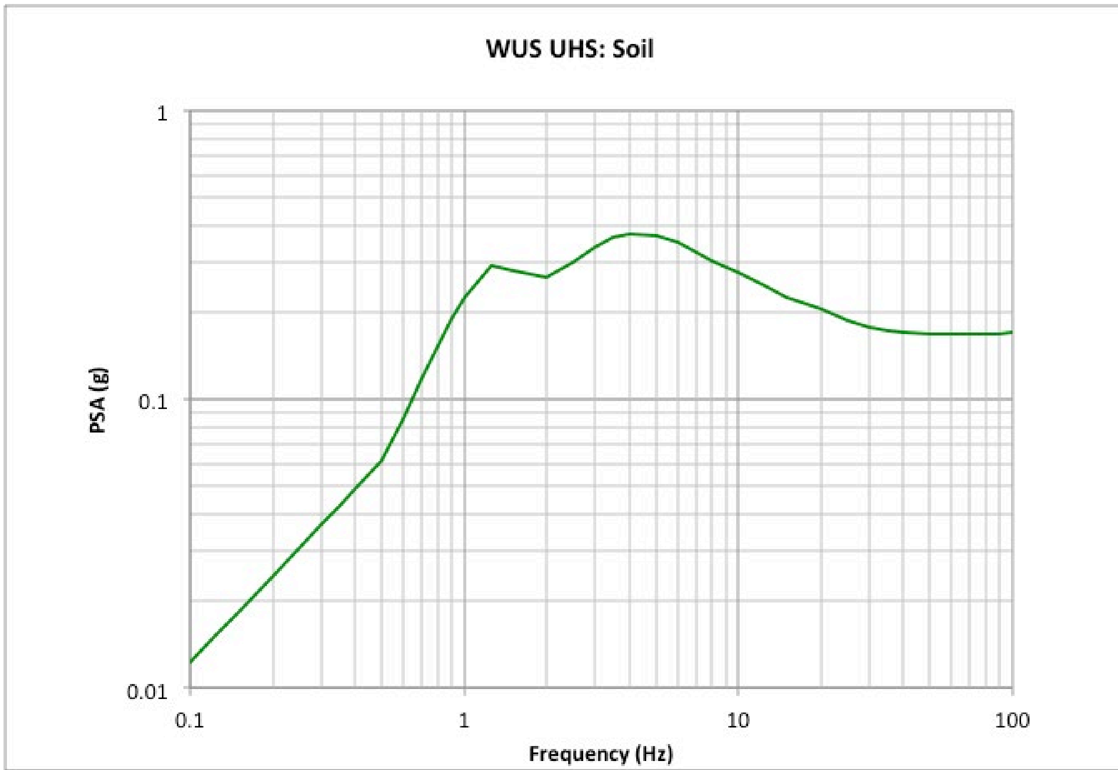


Figure 2-11 1E-4 UHS for the suite of WUS sites with soil site conditions.

2.4 Vertical Spectral Shapes

The development of the vertical spectral shapes is based on the application of the scenario events and an empirical vertical to horizontal (V/H) spectral ratio model (Gulerce and Abrahamson (2011). V/H models defined in nuclear guidelines were considered, however, the empirically based model is more consistent with empirical ground motions than the regulatory V/H factors and is used in this study.

2.4.1 CENA Vertical Spectral Shapes

For the CENA sites there are three scenario events and three site classifications. The V/H ratio has a characteristic s-shape at short periods (i.e., high frequencies) which is due to the limited high frequency content of the horizontal ground motions. The V/H ratio becomes larger at short periods because the vertical component peaks at a shorter period than the horizontal. For typical soft-rock sites, the horizontal spectrum peaks at about 0.2 sec. However, for hard-rock sites, the horizontal spectrum peaks at about 0.1 sec. Therefore, the increase in the V/H ratio will occur at a shorter period for hard-rock sites than for soft-rock sites.

The empirical V/H model of Gülerce and Abrahamson (2011) is applicable to soft-rock and soil sites, but the Vs30 scaling in the model is not well constrained for hard-rock sites. Note that this model was developed from empirical data recorded on sites in active tectonic regions and in general with Vs30 values less than about 1,000 m/sec. To address the effects of hard-rock sites on the V/H ratio, we need some measure of the period of the peak in the horizontal spectrum. Using the period of the largest value works in most cases, but there can be some cases with very broad peaks so that the peak does not represent the short period shape. Therefore, the shape of the ground motion is parameterized by the Tp95 which is the shortest period at which the spectrum reaches 95% of the peak value in the spectrum or the shortest period at which the spectral shape reaches 2, whichever is less. The V/H model is modified for periods less than 0.3 sec. The V/H ratio of hard-rock sites is given by

$$V/H_{HR}\left(M,R,T,T_{p95}\right)=\begin{cases}V/H_{GA}\left(M,R,T'',V_{S30}=760\right) & for T<0.3\sec\\ V/H_{GA}\left(M,R,T,V_{S30}=760\right) & for T\geq 0.3\sec\end{cases} \quad (1)$$

where:

$$T''=T\frac{T_{p95}}{0.2} \quad (2)$$

For this application of the adjustments, the Tp95 value was taken as 0.14 based on average expected values. Given this modification the V/H ratio adjusted for hard rock site conditions is listed in Table 2-10 for the three CENA scenario events. A comparison of the non-adjusted (solid lines) and adjust V/H ratios (dotted lines) is plotted in Figure 2-12. It is observed that the impact of the adjustment is to shift the V/H ratio peak to higher spectral frequencies (i.e., shorter spectral periods). For these calculations, the events were assumed to be strike-slip and as noted in equation (1) a Vs30 value of 760 m/sec is used.

Table 2-11 Adjusted hard rock CENA V/H factors for the three scenario events.

Period (sec)	**Frequency (Hz)**	**M=5.5, Dist=15km**	**M=6.5, Dist=40km**	**M=7.8, Dist=200km**
0.010	100.000	0.66722	0.61715	0.50668
0.020	50.000	0.74533	0.67615	0.53579
0.025	40.000	0.78480	0.69552	0.52437
0.030	33.333	0.81530	0.70708	0.50861
0.040	25.000	0.81261	0.70499	0.49954
0.050	20.000	0.76575	0.68535	0.50609

0.075	13.333	0.61373	0.60404	0.52274
0.100	10.000	0.54006	0.56210	0.54278
0.150	6.667	0.48726	0.53246	0.58128
0.200	5.000	0.48353	0.52536	0.58114
0.250	4.000	0.48873	0.52752	0.58349
0.300	3.333	0.49301	0.52929	0.58542
0.400	2.500	0.51985	0.54379	0.60433
0.500	2.000	0.53897	0.55256	0.61646
0.750	1.333	0.58470	0.60694	0.69337
1.000	1.000	0.63990	0.66423	0.75882
1.499	0.667	0.68513	0.71118	0.81246
2.000	0.500	0.66347	0.68870	0.78678
3.003	0.333	0.64844	0.67310	0.76894
4.000	0.250	0.67490	0.70057	0.80033
5.000	0.200	0.68441	0.71044	0.81161
7.519	0.133	0.68441	0.71044	0.81161
10.000	0.100	0.68441	0.71044	0.81161

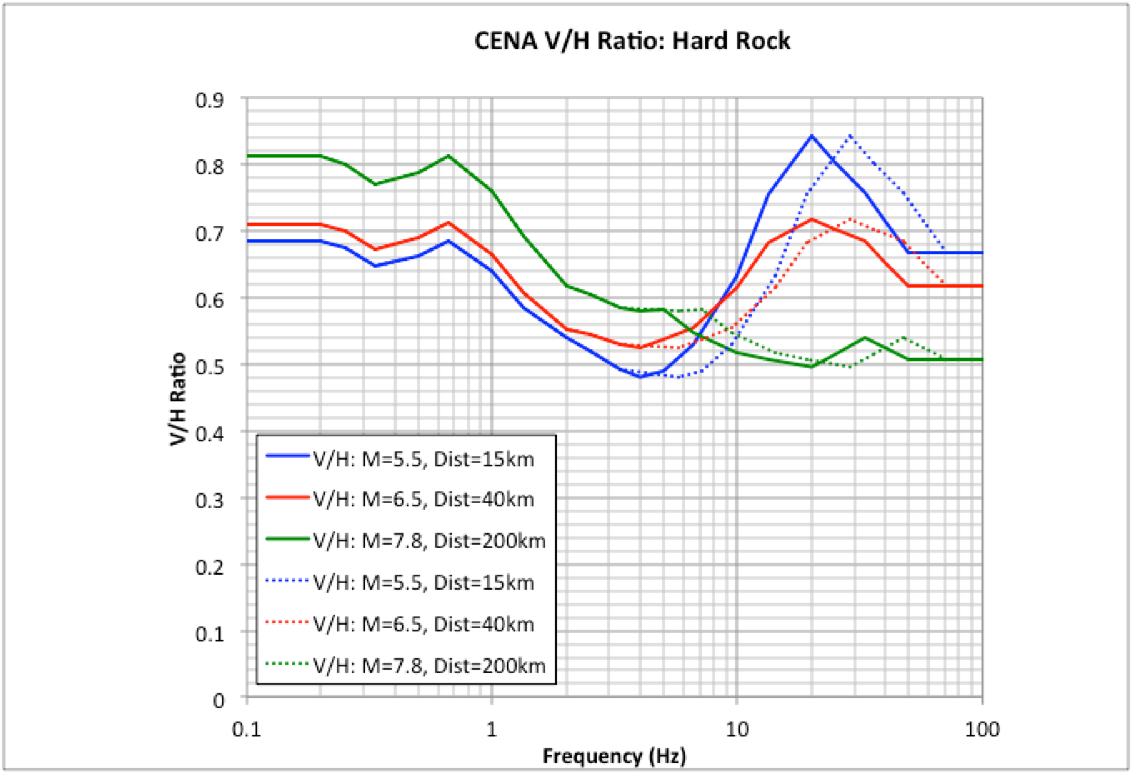


Figure 2-12 Comparison of non-adjusted V/H ratios (solid line) for the three CENA scenario events and adjusted ratios (dotted lines) for hard rock site conditions.

For the soft rock and soil site classification, the assigned Vs30 value is used along with the magnitude and distance of each scenario to develop the V/H factors. For the Gülerce and Abrahamson (2011) model, the events are assumed to be strike-slip events. The resulting V/H factors for these two site classes are listed in Table 2-11 and Table 2-12 and plotted in Figure 2-13 and Figure 2-14.

Table 2-12 Adjusted soft rock CENA V/H factors for the three scenario events.

Period (sec)	Frequency (Hz)	M=5.5, Dist=15km	M=6.5, Dist=40km	M=7.8, Dist=200km
0.010	100.000	0.66154	0.61039	0.50043
0.020	50.000	0.66166	0.61040	0.50039
0.025	40.000	0.71057	0.64755	0.51917
0.030	33.333	0.75321	0.67957	0.53504
0.040	25.000	0.80357	0.70039	0.51189
0.050	20.000	0.84495	0.71697	0.49463
0.075	13.333	0.76094	0.68296	0.50775
0.100	10.000	0.63439	0.61348	0.51591
0.150	6.667	0.52619	0.55058	0.54036
0.200	5.000	0.48493	0.52862	0.57264
0.250	4.000	0.46773	0.51019	0.56439
0.300	3.333	0.47778	0.51293	0.56733
0.400	2.500	0.50053	0.52359	0.58187
0.500	2.000	0.51710	0.53015	0.59145
0.750	1.333	0.55742	0.57862	0.66102
1.000	1.000	0.60729	0.63039	0.72015
1.499	0.667	0.64925	0.67395	0.76992
2.000	0.500	0.66273	0.68793	0.78589
3.003	0.333	0.64788	0.67252	0.76829
4.000	0.250	0.67432	0.69997	0.79964
5.000	0.200	0.68383	0.70984	0.81091

7.519	0.133	0.68383	0.70984	0.81091
10.000	0.100	0.68383	0.70984	0.81091

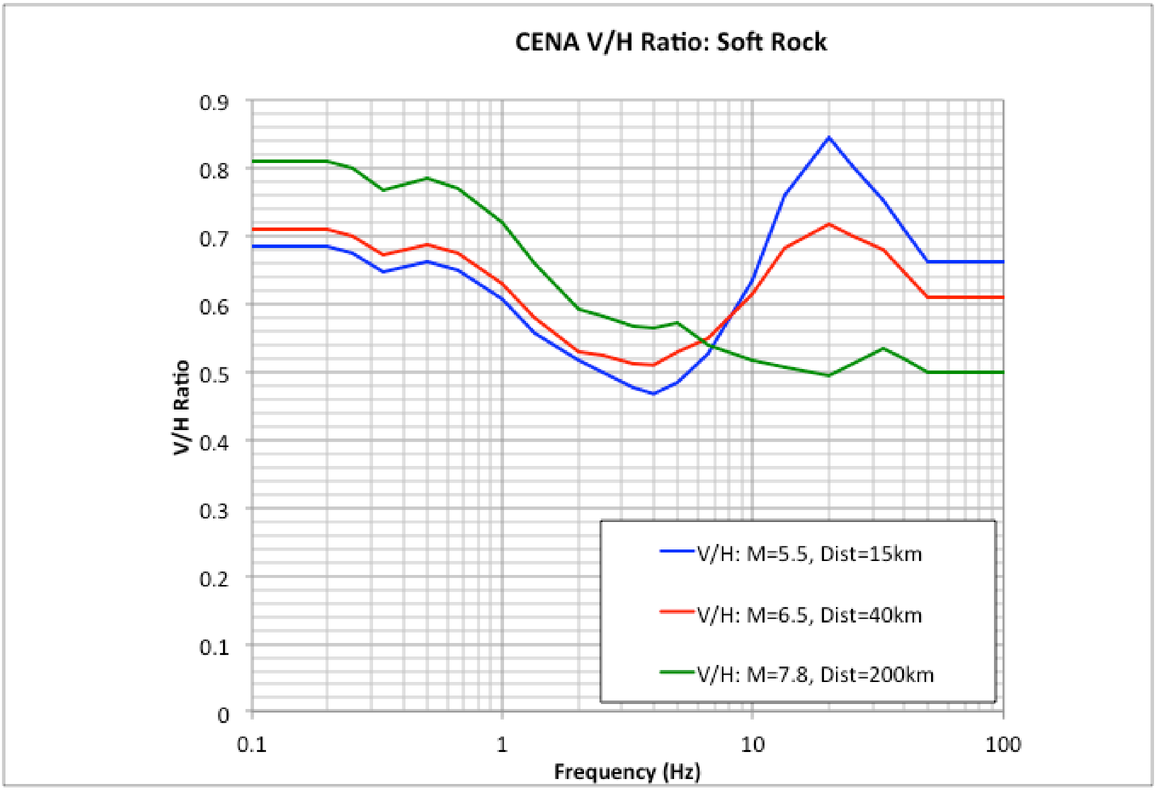


Figure 2-13 Comparison of V/H ratios for the three CENA scenario events for soft rock site conditions.

Table 2-13 Adjusted soil CENA V/H factors for the three scenario events.

Period (sec)	Frequency (Hz)	M=5.5, Dist=15km	M=6.5, Dist=40km	M=7.8, Dist=200km
0.010	100.000	0.63320	0.56255	0.45124
0.020	50.000	0.63440	0.56294	0.45123
0.025	40.000	0.69571	0.60876	0.47673
0.030	33.333	0.75017	0.64895	0.49863
0.040	25.000	0.83934	0.69740	0.49567
0.050	20.000	0.91575	0.73745	0.49338
0.075	13.333	0.85466	0.72322	0.51937
0.100	10.000	0.68684	0.62436	0.50637
0.150	6.667	0.53557	0.52645	0.49833
0.200	5.000	0.46954	0.48202	0.50450
0.250	4.000	0.41091	0.42561	0.45717
0.300	3.333	0.39621	0.40662	0.43838
0.400	2.500	0.37956	0.38440	0.41946
0.500	2.000	0.37235	0.37264	0.41012
0.750	1.333	0.36995	0.37858	0.42903
1.000	1.000	0.38300	0.39352	0.44697
1.499	0.667	0.39944	0.41241	0.46972
2.000	0.500	0.41593	0.43107	0.49202
3.003	0.333	0.45282	0.47004	0.53698
4.000	0.250	0.47130	0.48923	0.55889
5.000	0.200	0.47795	0.49612	0.56677

7.519	0.133	0.47795	0.49612	0.56677
10.000	0.100	0.47795	0.49612	0.56677

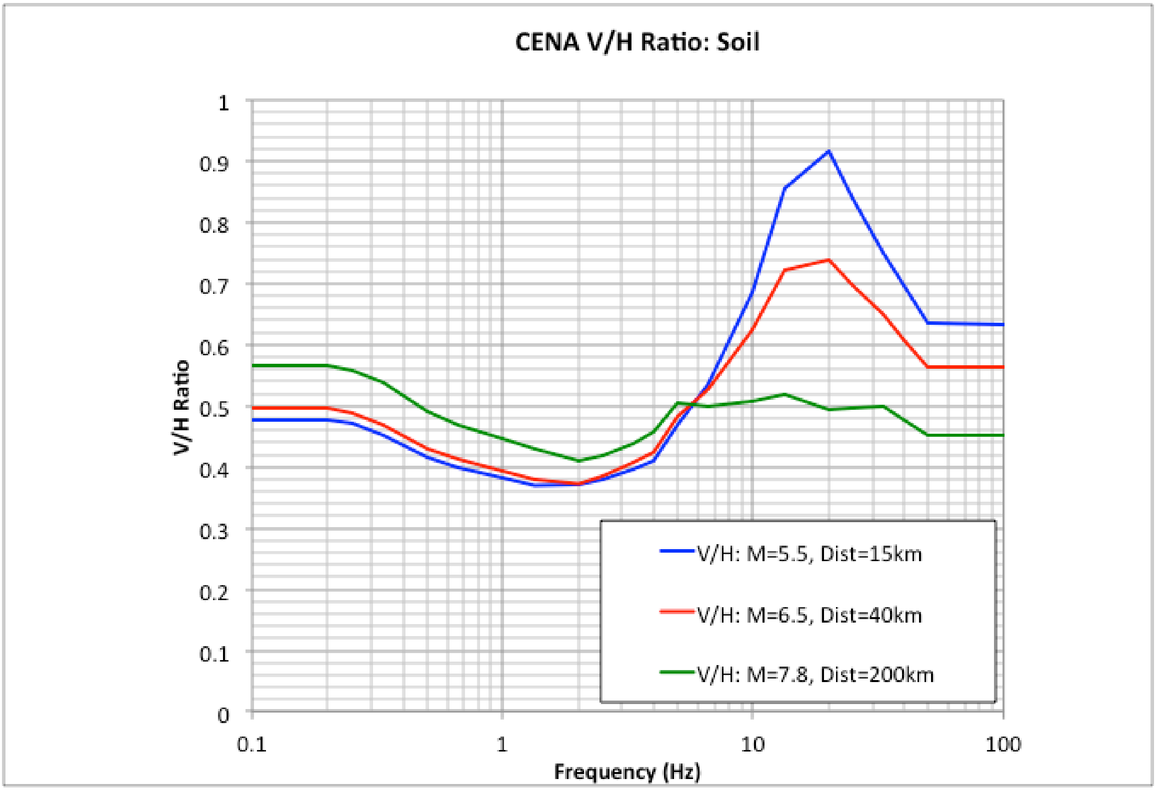


Figure 2-14 Comparison of V/H ratios for the three CENA scenario events for soil site conditions.

Given the suite of V/H ratios, the resulting vertical spectra for the CENA scenarios are listed in Table 2-13 (hard rock), Table 2-14 (soft rock) and Table 2-15 (soil). These spectra are plotted in Figure 2-15, Figure 2-15, and Figure 2-16.

Table 2-14 Median vertical ground motion spectra (g) for the three selected scenario events for CENA sites for hard rock site conditions

Period (sec)	**Frequency (Hz)**	**M=5.5, Dist=15km**	**M=6.5, Dist=40km**	**M=7.8, Dist=200km**
0.010	100.000	0.15318	0.09579	0.04892
0.020	50.000	0.24069	0.13941	0.06536
0.025	40.000	0.27815	0.15768	0.07050
0.030	33.333	0.31009	0.17267	0.07391
0.040	25.000	0.33590	0.19324	0.08291
0.050	20.000	0.31903	0.19642	0.08941
0.075	13.333	0.20792	0.14756	0.08432
0.100	10.000	0.16171	0.13145	0.09173
0.150	6.667	0.10942	0.10258	0.09120
0.200	5.000	0.08829	0.08727	0.08432
0.250	4.000	0.07353	0.07471	0.07649
0.300	3.333	0.06422	0.06785	0.07271
0.400	2.500	0.05070	0.05599	0.06431
0.500	2.000	0.04160	0.04814	0.05795
0.750	1.333	0.02684	0.03690	0.05097
1.000	1.000	0.01877	0.02984	0.04610
1.499	0.667	0.00977	0.01932	0.03690
2.000	0.500	0.00546	0.01280	0.03044
3.003	0.333	0.00224	0.00622	0.01905
4.000	0.250	0.00129	0.00402	0.01521
5.000	0.200	0.00081	0.00271	0.01183

7.519	0.133	0.00032	0.00129	0.00750
10.000	0.100	0.00017	0.00075	0.00526

Table 2-15 Median vertical ground motion spectra (g) for the three selected scenario events for CENA sites for soft rock site conditions (Vs30=698.7 m/sec).

Period (sec)	**Frequency (Hz)**	**M=5.5, Dist=15km**	**M=6.5, Dist=40km**	**M=7.8, Dist=200km**
0.010	100.000	0.15784	0.10270	0.05457
0.020	50.000	0.22205	0.13643	0.06894
0.025	40.000	0.26435	0.16074	0.07962
0.030	33.333	0.30834	0.18632	0.09094
0.040	25.000	0.38074	0.22953	0.10583
0.050	20.000	0.42590	0.25932	0.11489
0.075	13.333	0.35655	0.24070	0.12310
0.100	10.000	0.33594	0.26177	0.16402
0.150	6.667	0.20372	0.18650	0.15196
0.200	5.000	0.13148	0.13219	0.12677
0.250	4.000	0.09744	0.10090	0.10420
0.300	3.333	0.08249	0.08766	0.09447
0.400	2.500	0.06198	0.06855	0.07887
0.500	2.000	0.04919	0.05696	0.06861
0.750	1.333	0.03034	0.04171	0.05762
1.000	1.000	0.02053	0.03262	0.05040
1.499	0.667	0.01049	0.02074	0.03963

2.000	0.500	0.00620	0.01452	0.03455
3.003	0.333	0.00253	0.00702	0.02151
4.000	0.250	0.00145	0.00451	0.01707
5.000	0.200	0.00090	0.00304	0.01323
7.519	0.133	0.00036	0.00143	0.00832
10.000	0.100	0.00019	0.00083	0.00582

Table 2-16 Median vertical ground motion spectra (g) for the three selected scenario events for CENA sites for soil site conditions (Vs30=320.7 m/sec).

Period (sec)	**Frequency (Hz)**	**M=5.5, Dist=15km**	**M=6.5, Dist=40km**	**M=7.8, Dist=200km**
0.010	100.000	0.14317	0.09682	0.05420
0.020	50.000	0.20176	0.12870	0.06848
0.025	40.000	0.24528	0.15457	0.08053
0.030	33.333	0.29103	0.18199	0.09336
0.040	25.000	0.37688	0.23378	0.11289
0.050	20.000	0.43743	0.27282	0.12624
0.075	13.333	0.37951	0.26072	0.13871
0.100	10.000	0.33893	0.26883	0.17560
0.150	6.667	0.19922	0.18517	0.15713
0.200	5.000	0.12713	0.12941	0.12887
0.250	4.000	0.08754	0.09213	0.09885
0.300	3.333	0.07190	0.07775	0.08690
0.400	2.500	0.05359	0.05979	0.07046

0.500	2.000	0.04370	0.05087	0.06229
0.750	1.333	0.02725	0.03761	0.05255
1.000	1.000	0.01958	0.03089	0.04761
1.499	0.667	0.00990	0.01951	0.03725
2.000	0.500	0.00599	0.01404	0.03344
3.003	0.333	0.00273	0.00762	0.02338
4.000	0.250	0.00157	0.00490	0.01858
5.000	0.200	0.00097	0.00325	0.01420
7.519	0.133	0.00038	0.00153	0.00894
10.000	0.100	0.00020	0.00089	0.00625

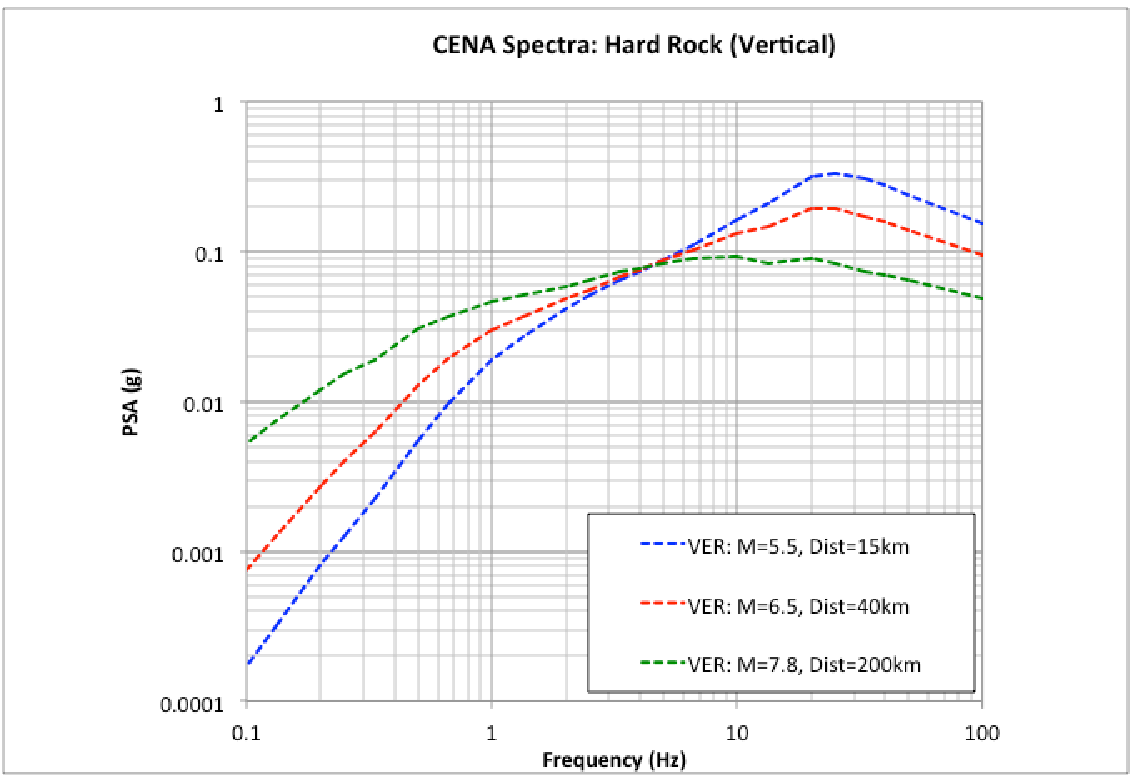


Figure 2-15 Median vertical ground motion spectra for the three scenario events for CENA sites for hard rock site conditions.

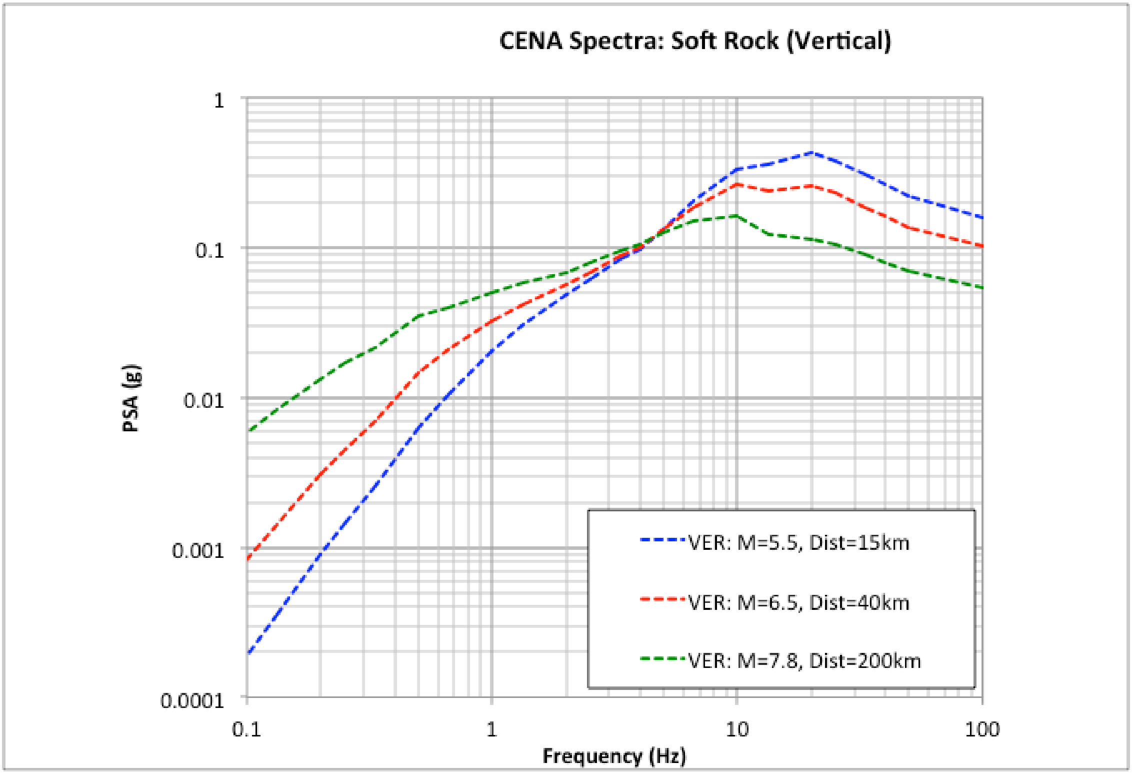


Figure 2-16 Median vertical ground motion spectra for the three scenario events for CENA sites for soft rock site conditions (Vs30=698.7 m/sec).

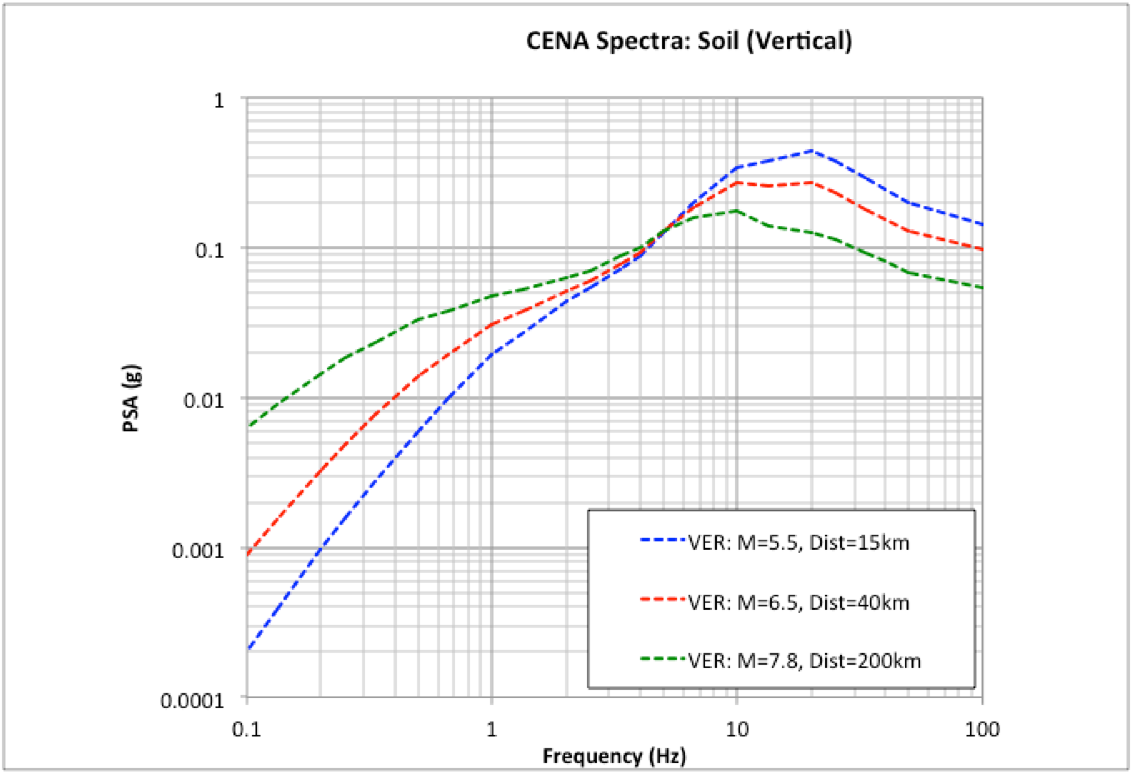


Figure 2-17 Median vertical ground motion spectra for the three scenario events for CENA sites for soil site conditions (Vs30=320.7 m/sec).

2.4.2 WUS Vertical Spectral Shapes

For the WUS cases the same methodology is applied. Unlike the CENA cases there is no hard rock site classification for the WUS and the direct application of the Gulerce and Abrahamson (2011) model is followed. The resulting V/H factors for the two scenarios for each of the two site classifications are listed in Table 2-16 and Table 2-17 and plotted in Figure 2-17 and Figure 2-18.

Table 2-17 Soft rock WUS V/H factors for the two scenario events.

Period (sec)	Frequency (Hz)	M=6.25, Dist=10km	M=7.5, Dist=5km
0.010	100.000	0.72123	0.76790
0.020	50.000	0.72114	0.76780
0.030	33.333	0.82029	0.87852
0.040	25.000	0.88275	0.96553
0.050	20.000	0.93444	1.03891
0.075	13.333	0.84702	0.95705
0.100	10.000	0.70705	0.79531
0.150	6.667	0.57976	0.63183
0.200	5.000	0.52591	0.55233
0.300	3.333	0.50642	0.50892
0.400	2.500	0.51253	0.49389
0.500	2.000	0.51468	0.48002
0.750	1.333	0.55632	0.51704
1.000	1.000	0.60884	0.56584
1.500	0.667	0.65187	0.60584
2.000	0.500	0.63127	0.58669
3.000	0.333	0.61696	0.57339
5.000	0.200	0.65119	0.60521
7.500	0.133	0.65119	0.60521
10.000	0.100	0.65119	0.60521

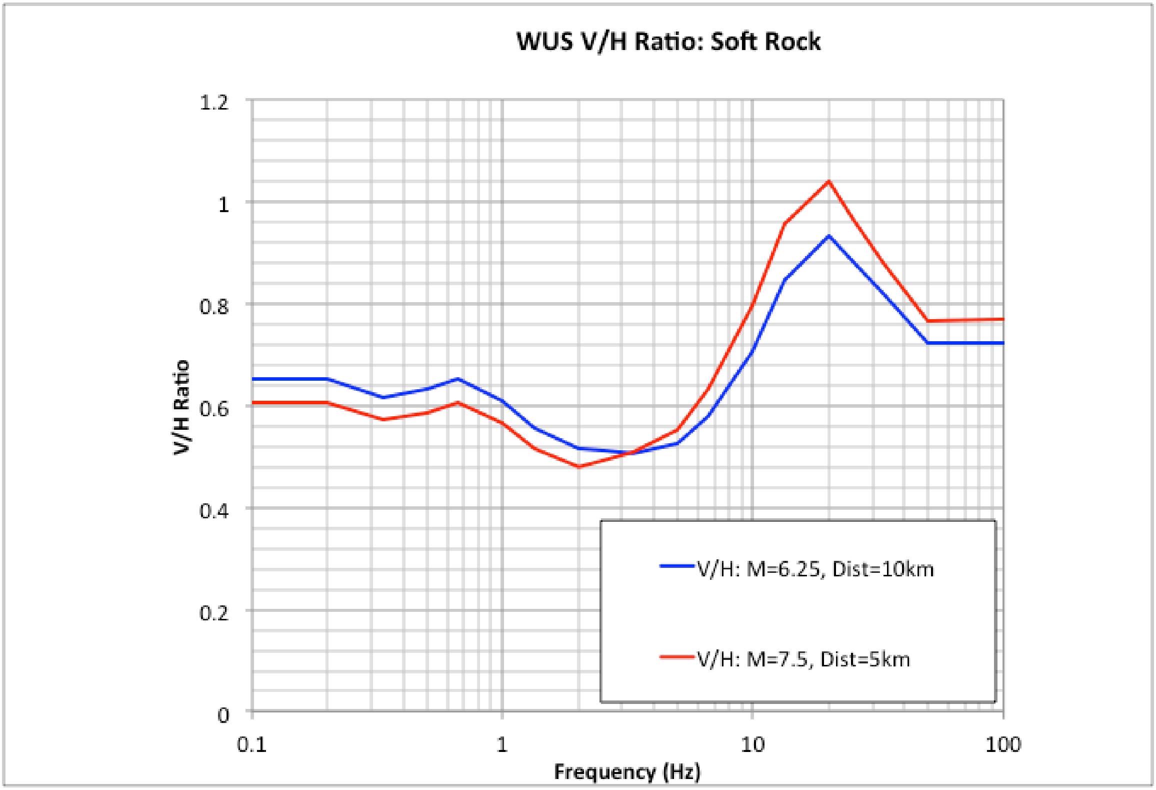


Figure 2-18 Comparison of V/H ratios for the two WUS scenario events for soft rock site conditions.

Table 2-18 Soil WUS V/H factors for the two scenario events.

Period (sec)	Frequency (Hz)	M=6.25, Dist=10km	M=7.5, Dist=200km
0.010	100.000	0.63056	0.43679
0.020	50.000	0.63002	0.43641
0.030	33.333	0.73914	0.47918
0.040	25.000	0.82292	0.47072
0.050	20.000	0.89438	0.46425
0.075	13.333	0.82726	0.48278
0.100	10.000	0.66082	0.47120
0.150	6.667	0.50885	0.46913
0.200	5.000	0.44181	0.48177
0.300	3.333	0.37672	0.43110
0.400	2.500	0.35869	0.42060
0.500	2.000	0.34835	0.41643
0.750	1.333	0.35459	0.44108
1.000	1.000	0.37189	0.46259
1.500	0.667	0.39266	0.48843
2.000	0.500	0.41136	0.51169
3.000	0.333	0.44497	0.55350
5.000	0.200	0.46966	0.58421
7.500	0.133	0.46966	0.58421
10.000	0.100	0.46966	0.58421

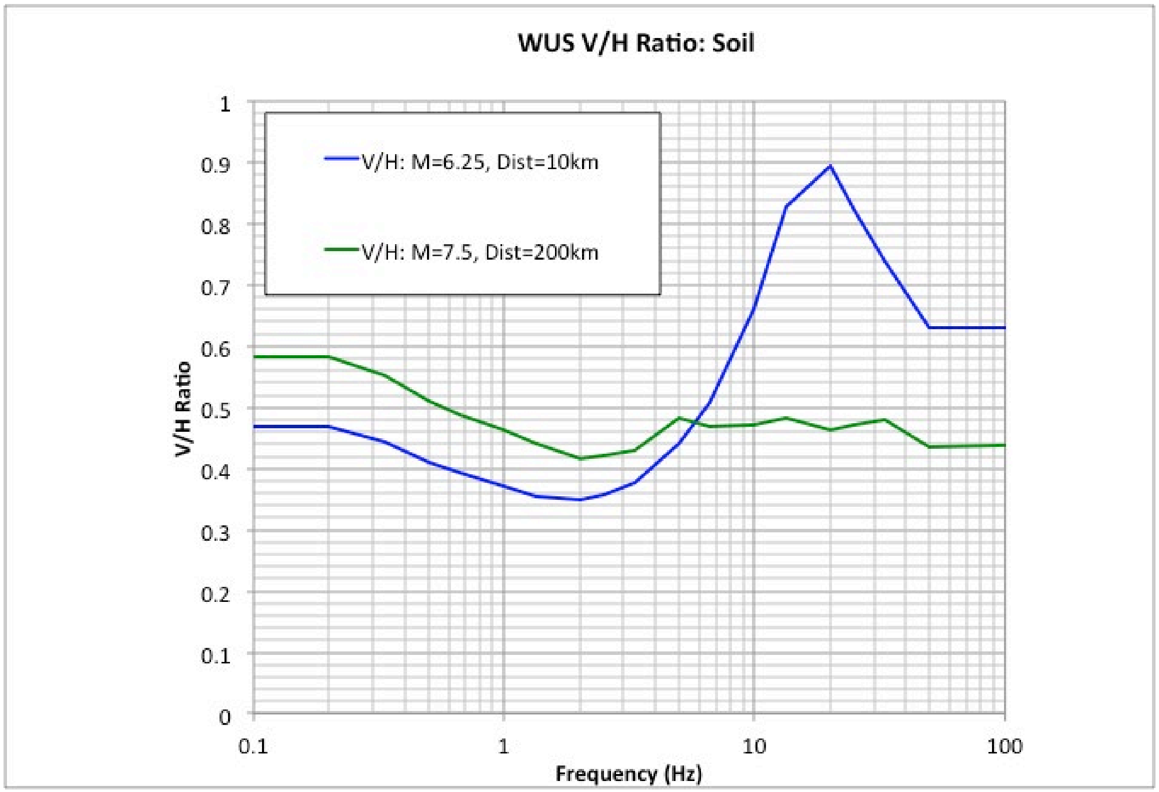


Figure 2-19 Comparison of V/H ratios for the two WUS scenario events for soil site conditions.

The resulting vertical spectra for the WUS scenarios are listed in Table 2-18 (soft rock) and Table 2-19 (soil) and plotted in Figure 2-19 (soft rock) and Figure 2-20 (soil).

Table 2-19 Median vertical ground motion spectra (g) for the two selected scenario events for WUS sites for soft rock site conditions (Vs30=760 m/sec).

Period (sec)	**Frequency (Hz)**	**M=6.25, Dist=10km**	**M=7.5, Dist=5km**
0.010	100.000	0.14413	0.32003
0.020	50.000	0.14733	0.32820
0.030	33.333	0.18543	0.41515
0.040	25.000	0.22730	0.51481
0.050	20.000	0.26976	0.61682
0.075	13.333	0.31318	0.71195
0.100	10.000	0.29857	0.66720
0.150	6.667	0.27521	0.60126
0.200	5.000	0.24098	0.51565
0.300	3.333	0.18513	0.40095
0.400	2.500	0.15005	0.32995
0.500	2.000	0.12311	0.27457
0.750	1.333	0.08674	0.21151
1.000	1.000	0.06710	0.17631
1.500	0.667	0.04079	0.12179
2.000	0.500	0.02619	0.08516
3.000	0.333	0.01377	0.05434
5.000	0.200	0.00628	0.03192
7.500	0.133	0.00284	0.01740
10.000	0.100	0.00164	0.01113

Table 2-20 Median vertical ground motion spectra (g) for the two selected scenario events for WUS sites for soil site conditions (Vs30=344 m/sec).

Period (sec)	**Frequency (Hz)**	**M=6.25, Dist=10km**	**M=7.5, Dist=200km**
0.010	100.000	0.15543	0.00865
0.020	50.000	0.15635	0.00852
0.030	33.333	0.19151	0.00928
0.040	25.000	0.23009	0.00923
0.050	20.000	0.26835	0.00922
0.075	13.333	0.30701	0.01053
0.100	10.000	0.29085	0.01166
0.150	6.667	0.27756	0.01451
0.200	5.000	0.26201	0.01820
0.300	3.333	0.21868	0.02129
0.400	2.500	0.18425	0.02252
0.500	2.000	0.15619	0.02258
0.750	1.333	0.11106	0.02053
1.000	1.000	0.08651	0.01732
1.500	0.667	0.05419	0.01371
2.000	0.500	0.03765	0.01080
3.000	0.333	0.02221	0.00792
5.000	0.200	0.00951	0.00452
7.500	0.133	0.00398	0.00271
10.000	0.100	0.00213	0.00172

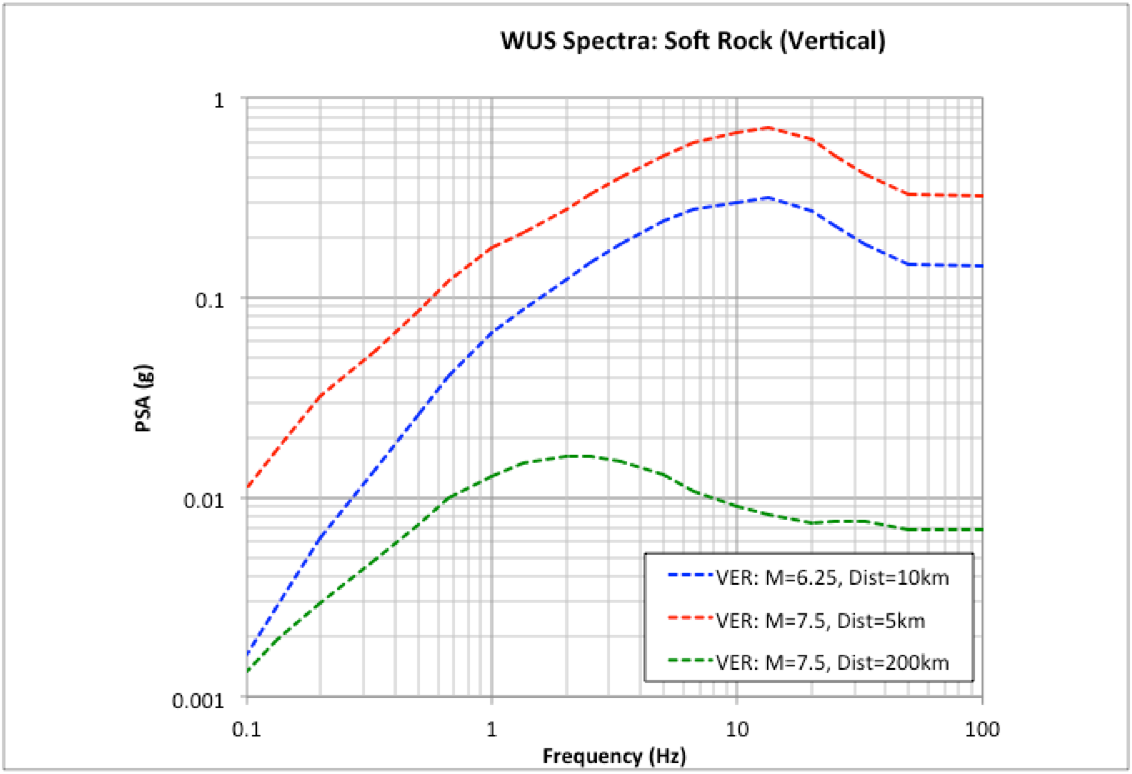


Figure 2-20 Median vertical ground motion spectra for the two scenario events for WUS sites for soft rock site conditions (Vs30=760 m/sec).

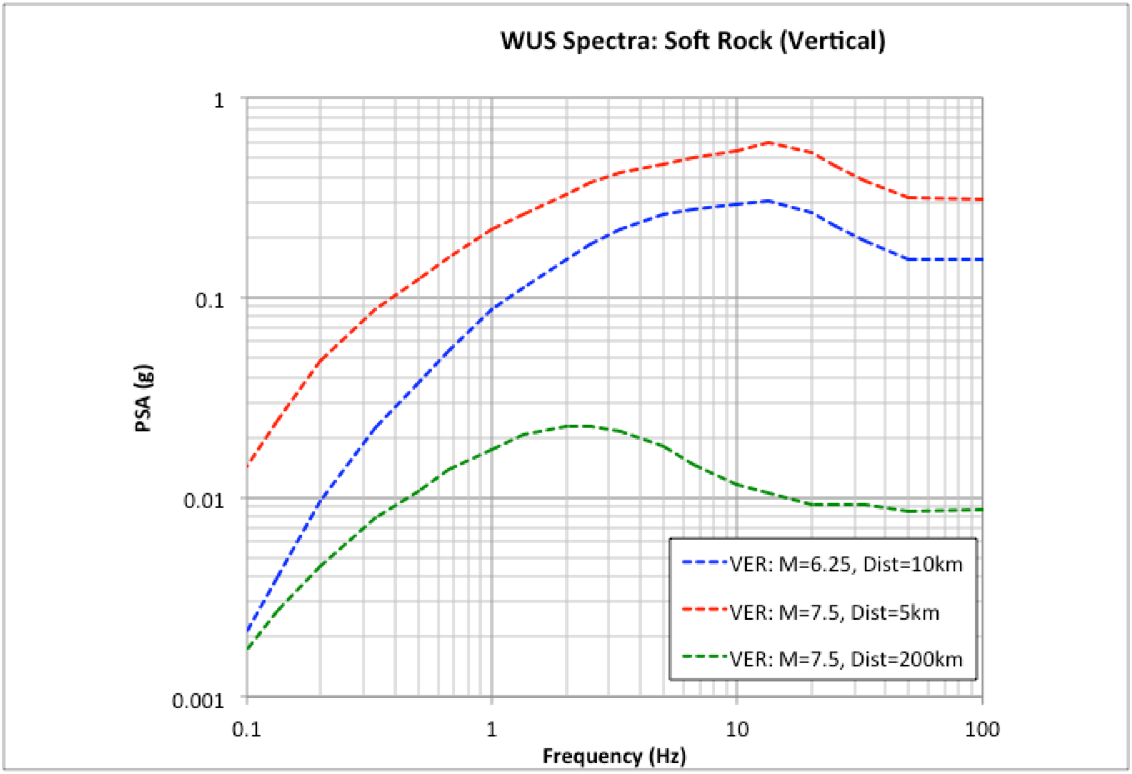
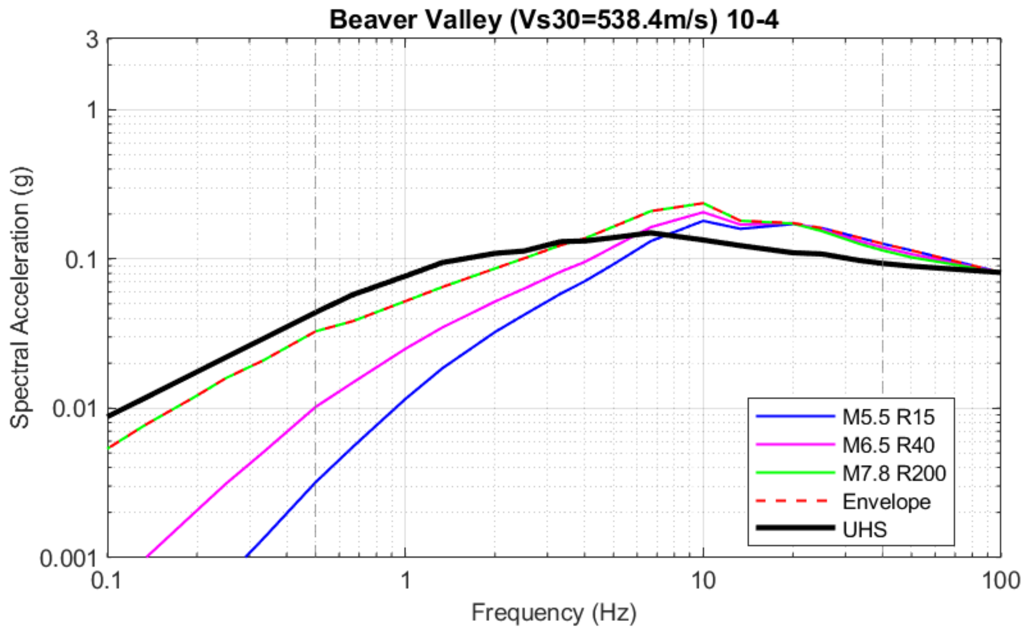


Figure 2-21 Median vertical ground motion spectra for the two scenario events for WUS sites for soil site conditions (Vs30=344 m/sec).

3 Scaling PGA Amplitude Factors

Given the horizontal scenario spectra and the 1E-4 UHS, a scaling methodology was developed to optimize (i.e., minimize) the match between the envelop of the scaled scenario spectra and the UHS. The process initially scales each scenario spectrum to the PGA of a given UHS at the 1E-4 hazard level. Then additional scaling factors are optimized to reduce the misfit between the envelope of the scaled spectra and the UHS over the frequency range of 0.5 – 40 Hz. A lower limit on the optimized scaling factors of 0.5 was applied during this process. This process is performed for each of the 51 NPP sites in the CENA, the seven demonstration sites and the three WUS sites. As an example, the initial scaled scenario spectra for Beaver Valley NPP site are plotted in the top part of Figure 3-1. In the lower figure, the additional scaling based on the optimization is plotted. For this case, the optimization resulted in an amplitude reduction in the scenario spectra between 0.76 – 0.9. The individual plots for each of the sites are provided in the Appendix.



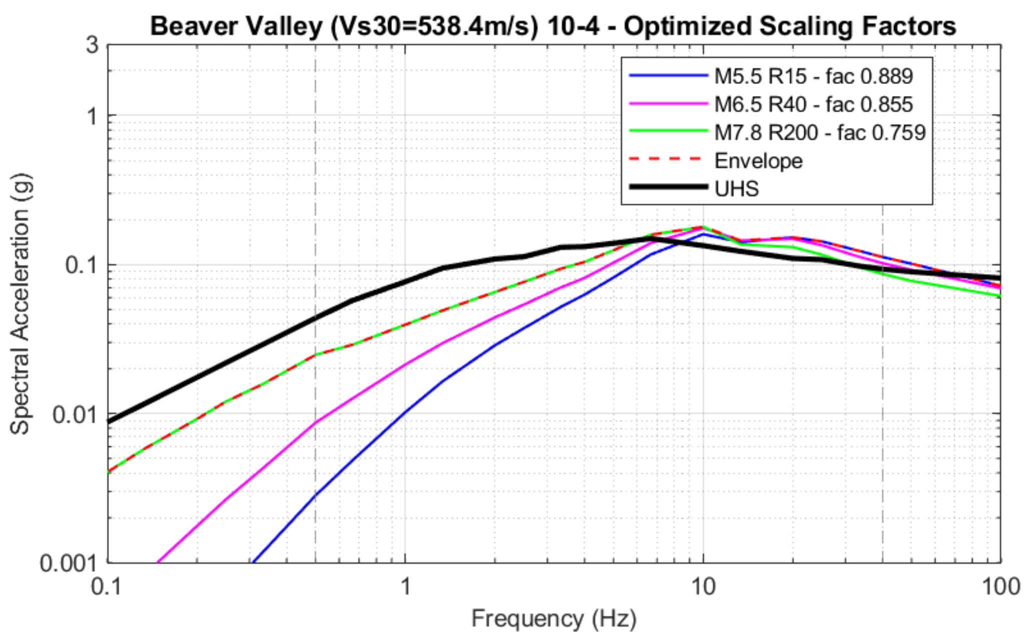


Figure 3-1 Comparison of the scaled scenario spectra to the Beaver Valley 1E-4 UHS PGA (top plot) and the optimized scaled spectra (lower plot).

3.1 CENA Scaling Factors for 1E-4 UHS

Based on this analysis, the resulting scaling factors for the 1E-4 hazard level are compiled for the three site classifications. Within each site classification, the ranking and cumulative distribution of the scaling factors are computed for each of the three scenario events. These results are provided in Table 3-1, Table 3-2, and Table 3-3 and plotted in Figure 3-2, Figure 3-3, and Figure 3-4.

Table 3-1 Ranked cumulative distribution of scaling factors for CENA site with hard rock site conditions.

Cumulative Weight	**M=5.5, Dist=15km**	**M=6.25, Dist=40km**	**M=7.8, Dist=200km**
0.032	0.1479	0.2126	0.4194
0.065	0.1886	0.2790	0.5462
0.097	0.2313	0.3421	0.6619
0.129	0.3249	0.4806	0.8028
0.161	0.3428	0.5071	0.8146
0.194	0.3681	0.5444	0.9302
0.226	0.3718	0.5528	0.9517
0.258	0.3738	0.5534	0.9834
0.290	0.4229	0.6256	1.0371
0.323	0.4741	0.6971	1.1347
0.355	0.4830	0.7248	1.1684
0.387	0.4900	0.7280	1.2090
0.419	0.5195	0.7802	1.2118
0.452	0.5275	0.8118	1.3166
0.484	0.6142	0.9084	1.3423
0.516	0.6647	0.9832	1.4034

0.548	0.7100	1.0502	1.4447
0.581	0.7607	1.1784	1.4461
0.613	0.7967	1.1986	1.4588
0.645	0.9144	1.2370	1.6313
0.677	1.0207	1.2499	1.6995
0.710	1.2036	1.3449	1.8566
0.742	1.2433	1.4432	1.9116
0.774	1.2951	1.6236	1.9710
0.806	1.3112	1.6442	1.9804
0.839	1.3348	1.7742	2.0470
0.871	1.3475	1.8446	2.1463
0.903	1.4810	2.1672	2.1779
0.935	1.7405	2.1906	2.8341
0.968	1.8715	2.5887	3.3362
1.000	1.8781	2.6021	4.2333

Table 3-2 Ranked cumulative distribution of scaling factors for CENA site with soft rock site conditions.

Cumulative Weight	**M=5.5, Dist=15km**	**M=6.25, Dist=40km**	**M=7.8, Dist=200km**
0.091	0.087	0.123	0.185
0.182	0.152	0.215	0.310
0.273	0.292	0.412	0.564
0.364	0.302	0.414	0.634

0.455	0.349	0.471	0.667
0.545	0.408	0.550	0.758
0.636	0.432	0.624	0.766
0.727	0.547	0.763	0.873
0.818	0.641	0.909	0.951
0.909	0.675	0.928	1.094
1.000	0.817	1.229	1.367

Table 3-3 Ranked cumulative distribution of scaling factors for CENA site with soil site conditions.

Cumulative Weight	M=5.5, Dist=15km	M=6.25, Dist=40km	M=7.8, Dist=200km
0.063	0.156	0.198	0.285
0.125	0.157	0.207	0.292
0.188	0.249	0.327	0.369
0.250	0.292	0.373	0.487
0.313	0.299	0.387	0.494
0.375	0.318	0.405	0.522
0.438	0.365	0.499	0.545
0.500	0.421	0.510	0.636
0.563	0.521	0.661	0.877
0.625	0.550	0.723	1.030
0.688	0.582	0.768	1.081
0.750	0.789	1.041	1.267

0.813	0.836	1.047	1.503
0.875	0.907	1.166	1.652
0.938	1.858	2.289	3.005
1.000	1.928	2.533	3.483

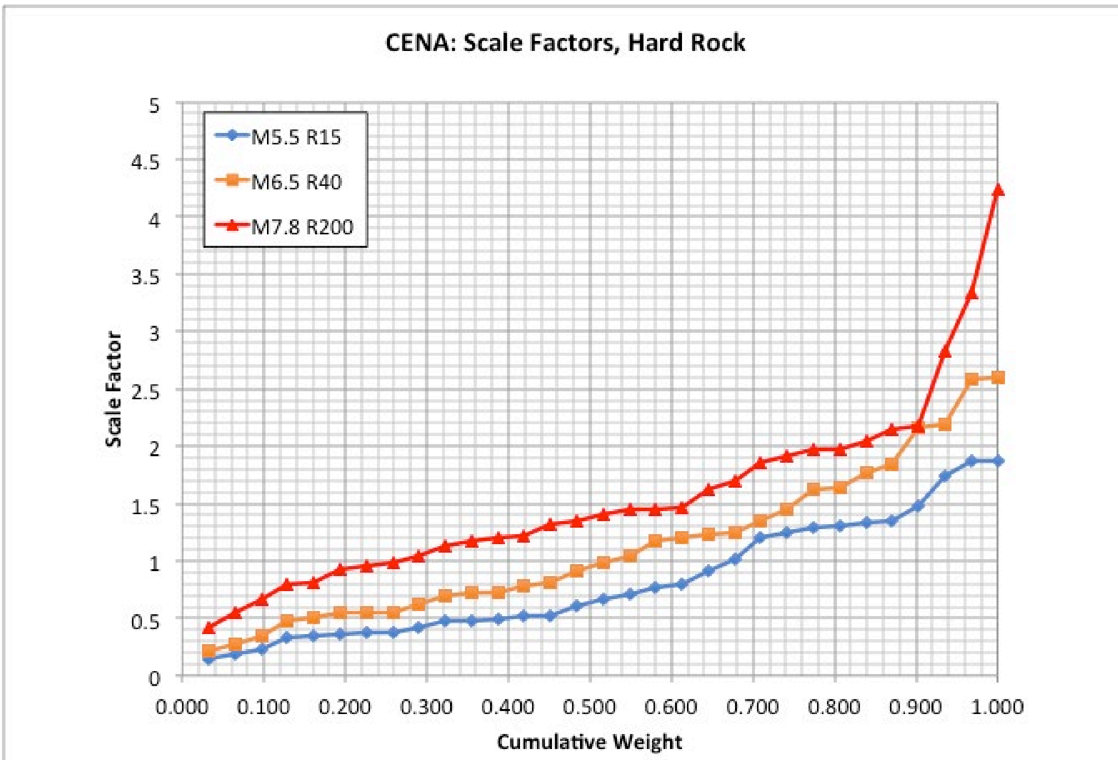


Figure 3-2 Ranked PGA scaling factors for CENA hard rock site conditions and the three scenario events.

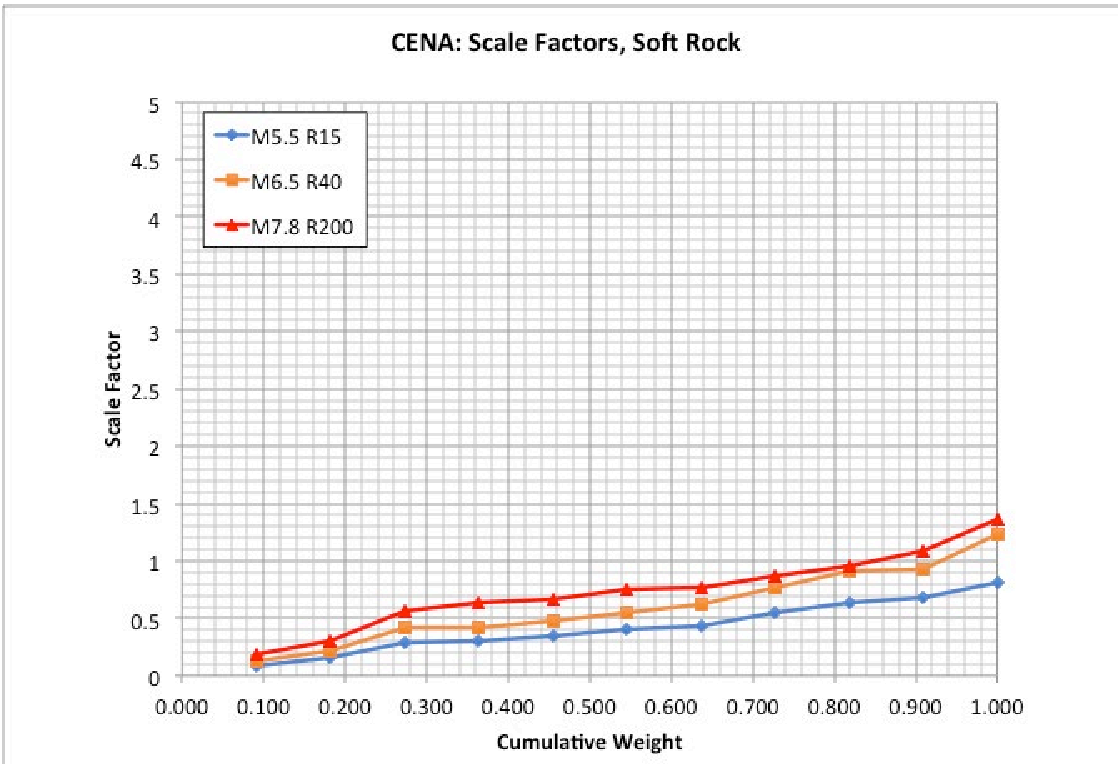


Figure 3-3 Ranked PGA scaling factors for CENA soft rock site conditions and the three scenario events.

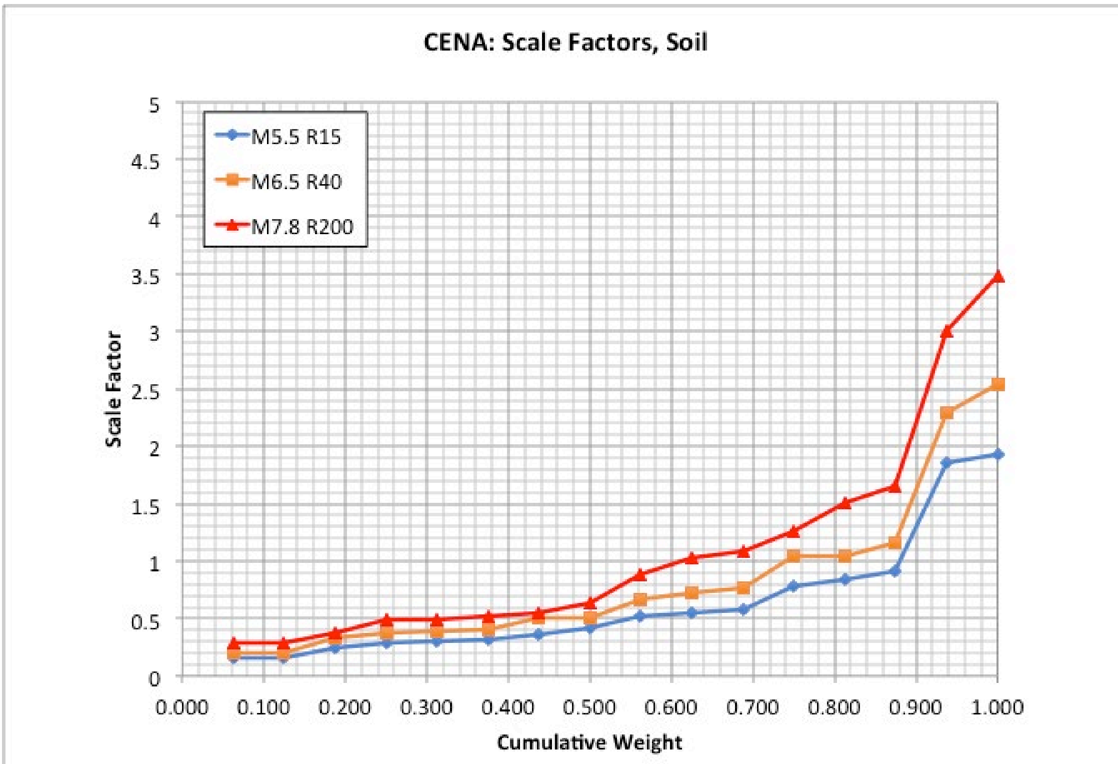


Figure 3-4 Ranked PGA scaling factors for CENA soil site conditions and the three scenario events.

3.2 WUS Scaling Factors for 1E-4 UHS

For the three WUS sites the same analysis was performed, and the results are summarized in Table 3-4.

Table 3-4 Scaling factors for WUS sites for soft rock and soil site conditions.

Case	M=6.25, Dist=10km	M=7.5, Dist=5km	M=7.5, Dist=200km
Soft Rock	1.887	0.969	---
Soft Rock	4.022	2.206	---
Soil	0.670	---	5.151

3.3 CENA Scaling Factors for 1E-3 and 1E-5 UHS

Given the scaling factors for the 1E-4 hazard level, additional scaling factors are estimated for hazard levels of 1E-3 and 1E-5 annual exceedance. These factors are based on the spectral ratios of the UHS for these two hazard levels relative to the 1E-4 UHS. For the CENA sites these spectral ratios are plotted in Figure 3-5, Figure 3-6, Figure 3-7, Figure 3-8, Figure 3-9, and Figure 3-10 for the three site classifications. Also shown on these plots as a dashed black line is the average scaling factor at PGA (i.e., 100 Hz). A summary of these values is given in Table 3-5. Based on the similar results for the different site classifications, it is recommended that the values estimated from the average across all of the data is applicable to scale the spectra and time histories for the two additional hazard levels of 1E-3 and 1E-5. Scale factors for other hazard levels can be estimated based on a linear interpolation of the log of the hazard level and log of the scale factors given the values provided in Table 3-5 and the desired interpolation hazard level.

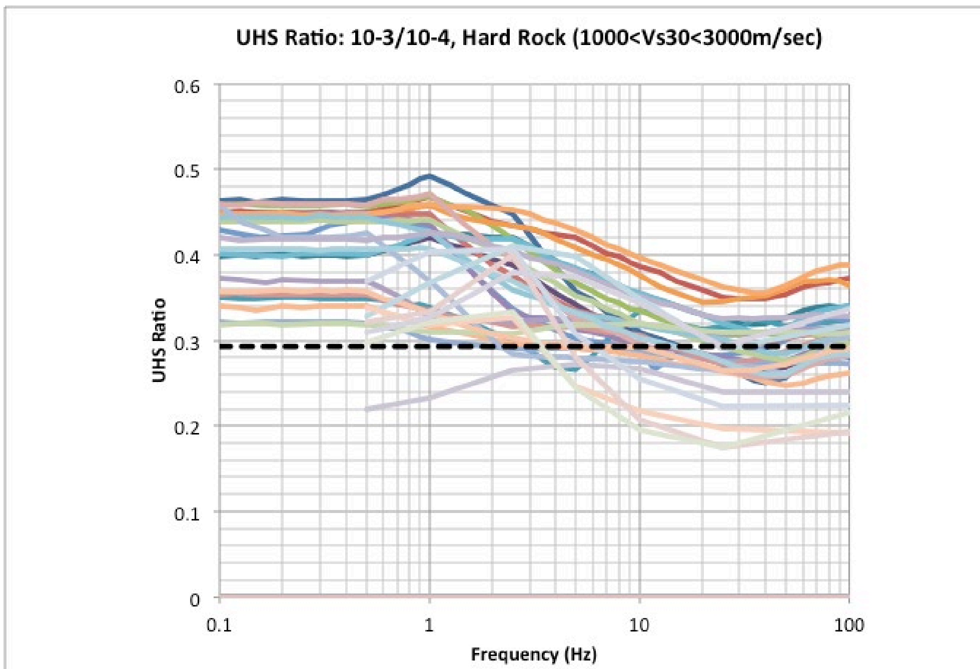


Figure 3-5 UHS spectral ratios between 1E-3 and 1E-4 from CENA hard rock site. Dashed black line is the average PGA (i.e., 100 Hz) value.

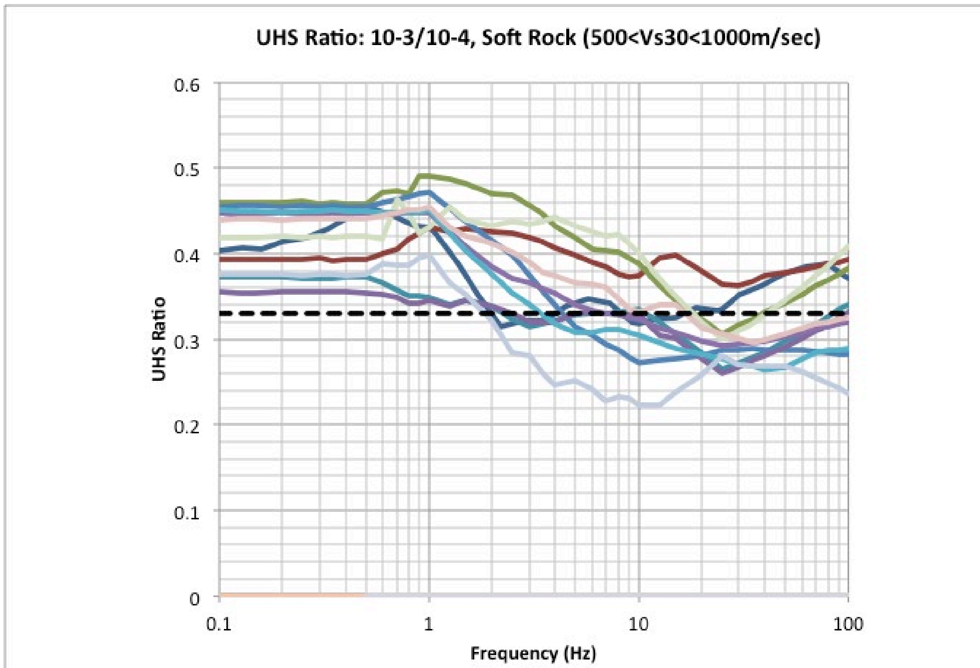


Figure 3-6 UHS spectral ratios between 1E-3 and 1E-4 from CENA soft rock site. Dashed black line is the average PGA (i.e., 100 Hz) value.

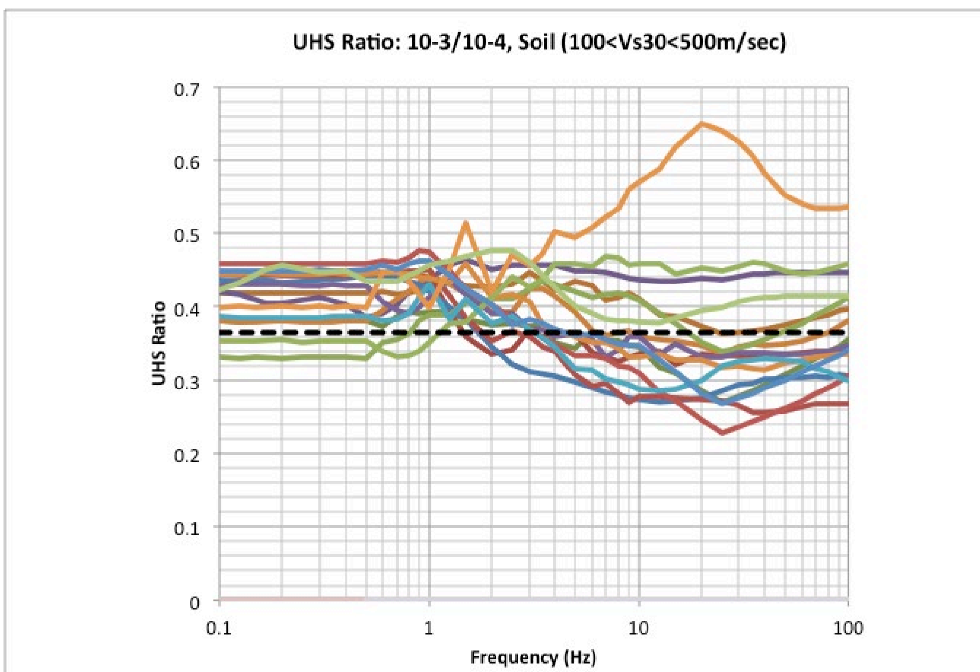


Figure 3-7 UHS spectral ratios between 1E-3 and 1E-4 from CENA soil site. Dashed black line is the average PGA (i.e., 100 Hz) value.

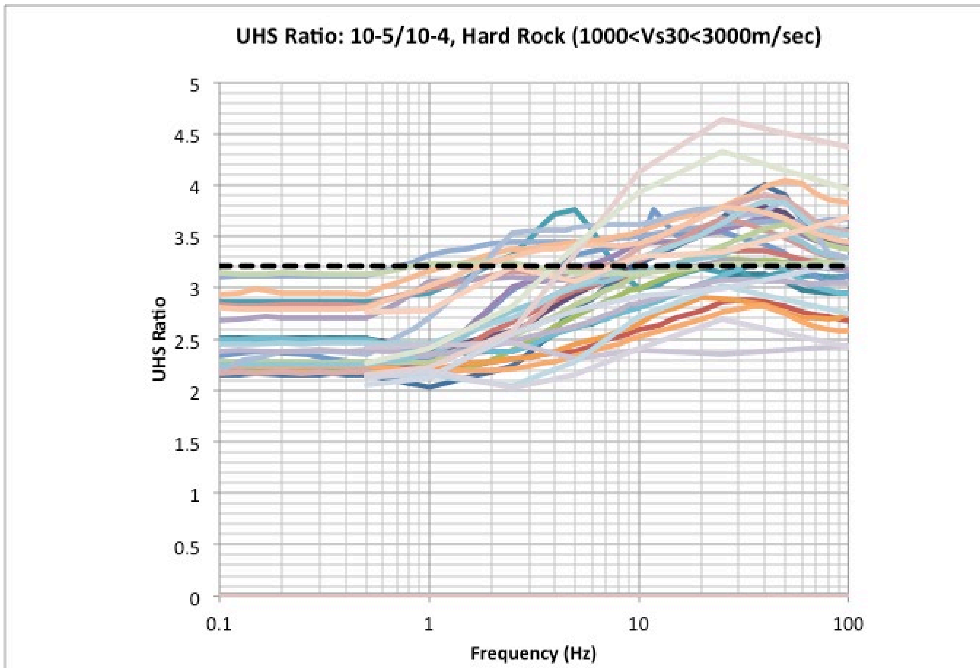


Figure 3-8 UHS spectral ratios between 1E-5 and 1E-4 from CENA hard rock site. Dashed black line is the average PGA (i.e., 100 Hz) value.

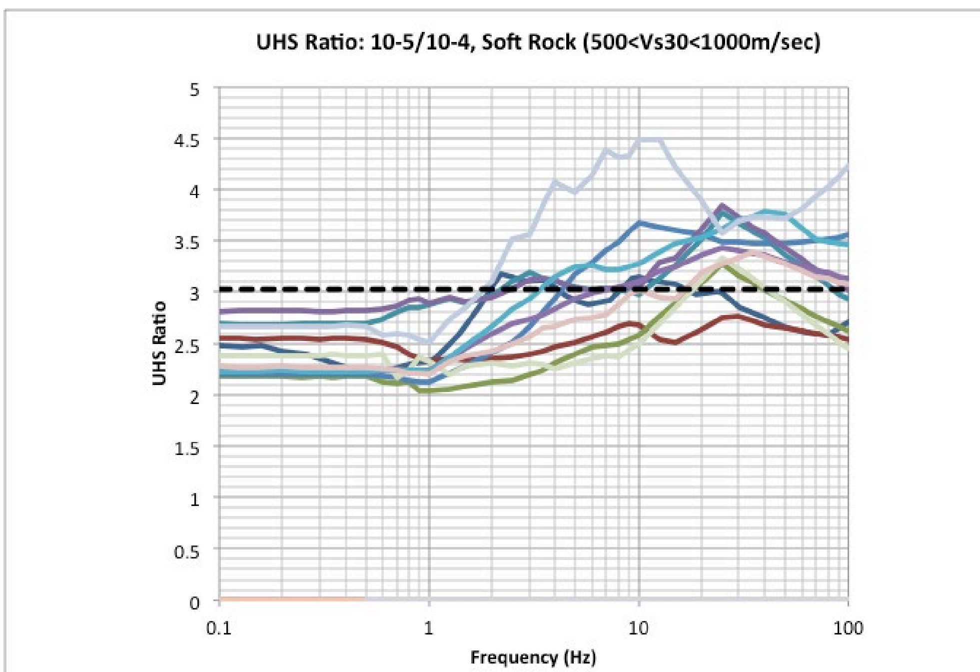


Figure 3-9 UHS spectral ratios between 1E-5 and 1E-4 from CENA soft rock site. Dashed black line is the average PGA (i.e., 100 Hz) value.

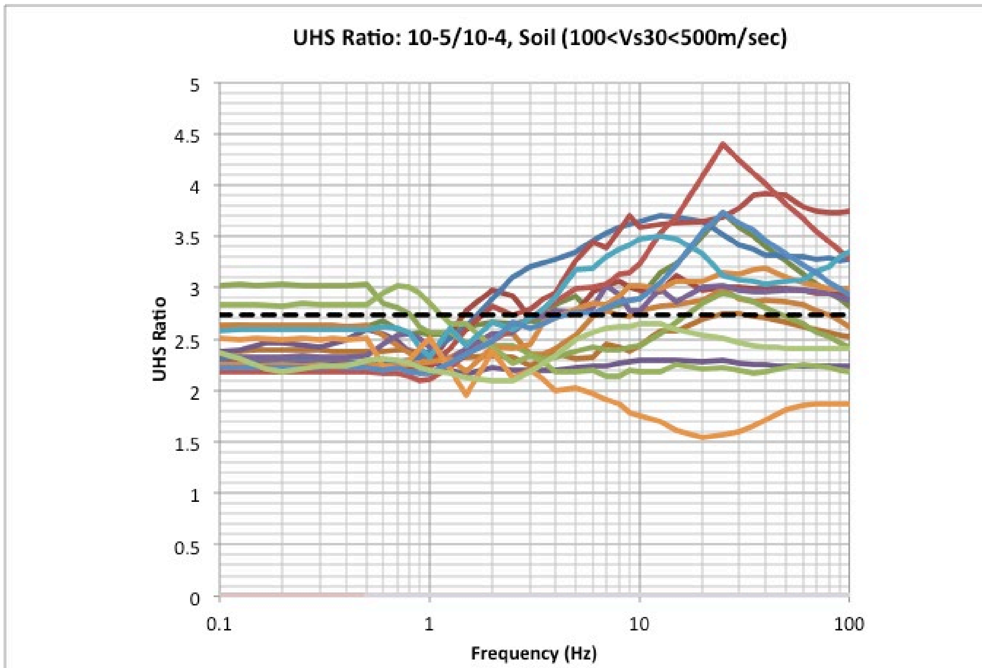


Figure 3-10 UHS spectral ratios between 1E-5 and 1E-4 from CENA soil site. Dashed black line is the average PGA (i.e., 100 Hz) value.

Table 3-5 Average scaling factors for CENA sites 1E-3 and 1E-5 hazard levels.

Case	**Average All Site Conditions**	**Hard Rock**	**Soft Rock**	**Soil**
[1E-3/1E-4]	0.32	0.29	0.33	0.37
[1E-5/1E-4]	3.04	3.21	3.03	2.74

3.4 WUS Scaling Factors for 1E-3 and 1E-5 UHS

The same methodology was applied to the three WUS sites and their respective UHS. The results are summarized in Table 3-6 and similarly it is recommended that the results from the three sites be used for application of scaling for the 1E-3 and 1E-5 hazard levels. Scale factors for other hazard levels can be estimated based on a linear interpolation of the log of the hazard level and log of the scale factors given the values provided in Table 3-6 and the desired interpolation hazard level.

Table 3-6 Average scaling factors for WUS sites 1E-3 and 1E-5 hazard levels.

Case	**Average All Site Conditions**	**Soft Rock**	**Soil**
[1E-3/1E-4]	0.37	0.36	0.40
[1E-5/1E-4]	2.38	2.32	2.52

4 Conclusion

Based on the analyses of PSHA results for sites located in the CENA and WUS, scaling factors for representative scenario earthquakes have been developed. For the CENA sites, these scaling factors are based on the selection of three scenario events. Three separate site classifications are developed for the CENA sites (i.e., hard rock, soft rock and soil). For the WUS, two scenario events are recommended and defined for two site classifications (soft rock and soil). An optimization procedure was implemented to estimate scaling factors for application with the scenario spectral shapes for the horizontal component. For the vertical component, applicable V/H scaling factors are developed separately for the CENA and WUS cases based on the scenario events. For the 1E-4 hazard level a ranking distribution of these PGA factors is computed and presented along with recommended scaling factors for the 1E-3 and 1E-5 hazard levels. Scale factors for other hazard levels can be interpolated based on a log-log interpolation. As part of this study which will be presented in a later report, spectrum compatible time histories will be developed for each of the scenario spectra.

5 References

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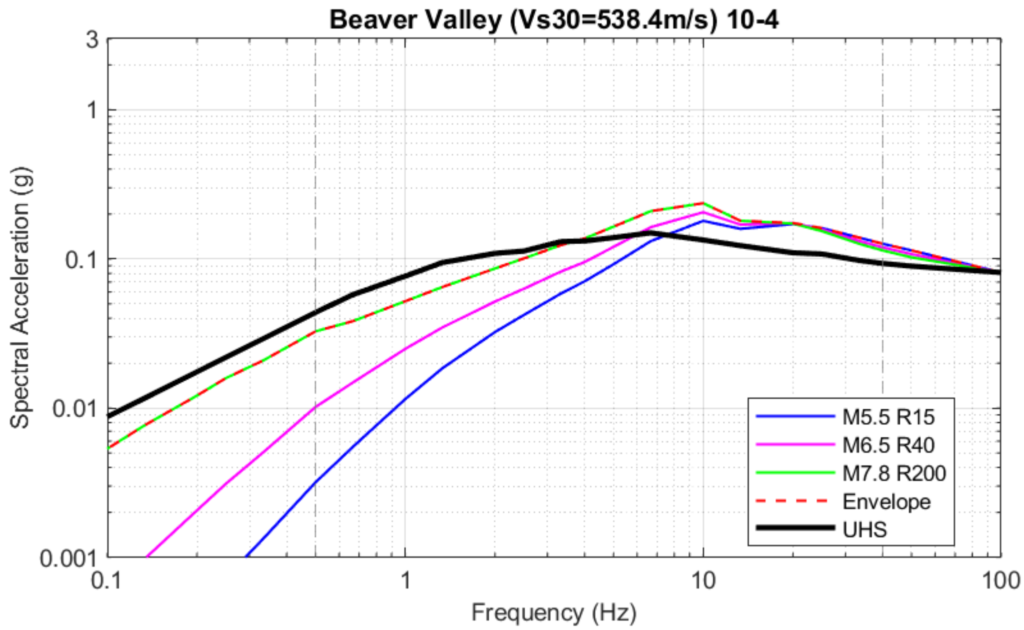
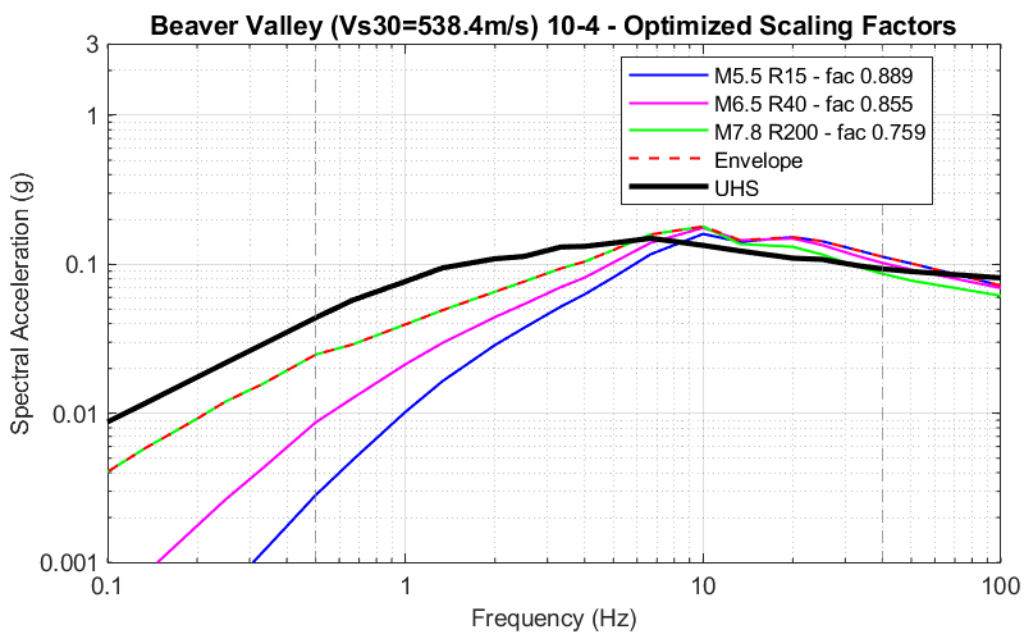
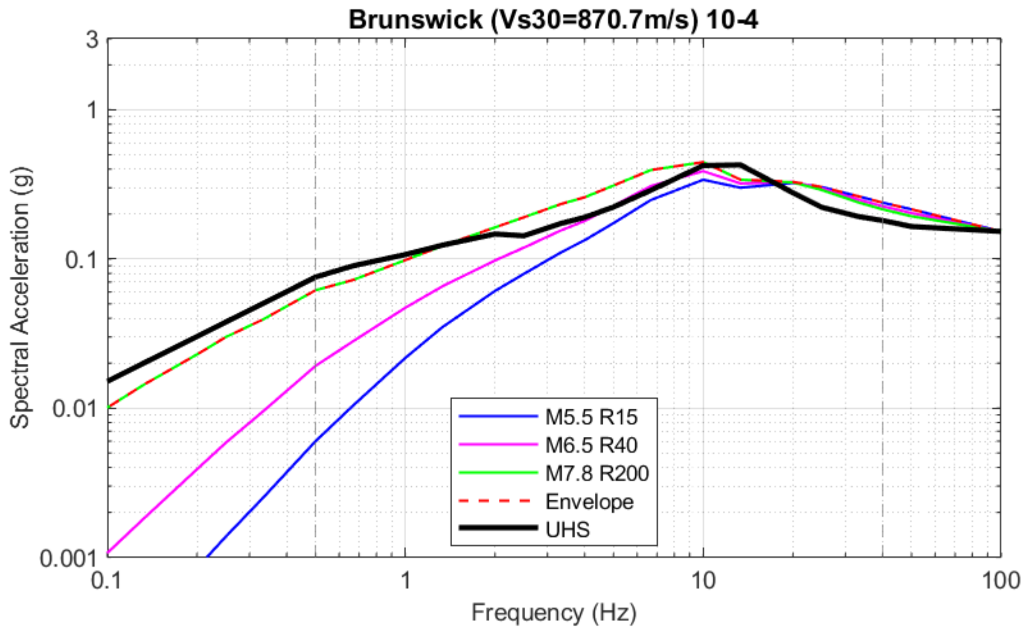
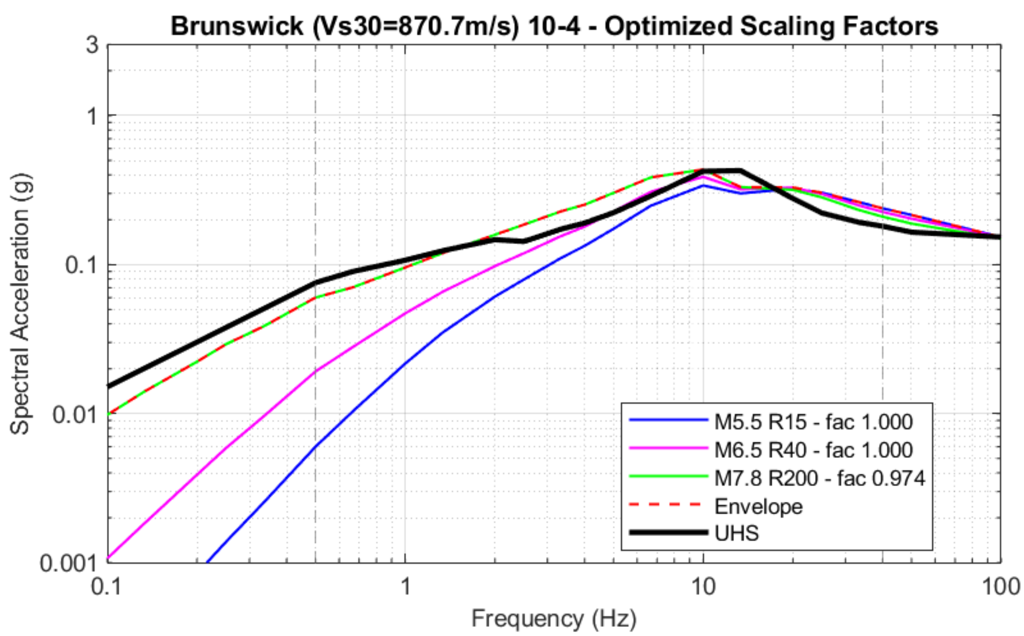
Appendix A
Scaling Plots for 1E-4 UHS



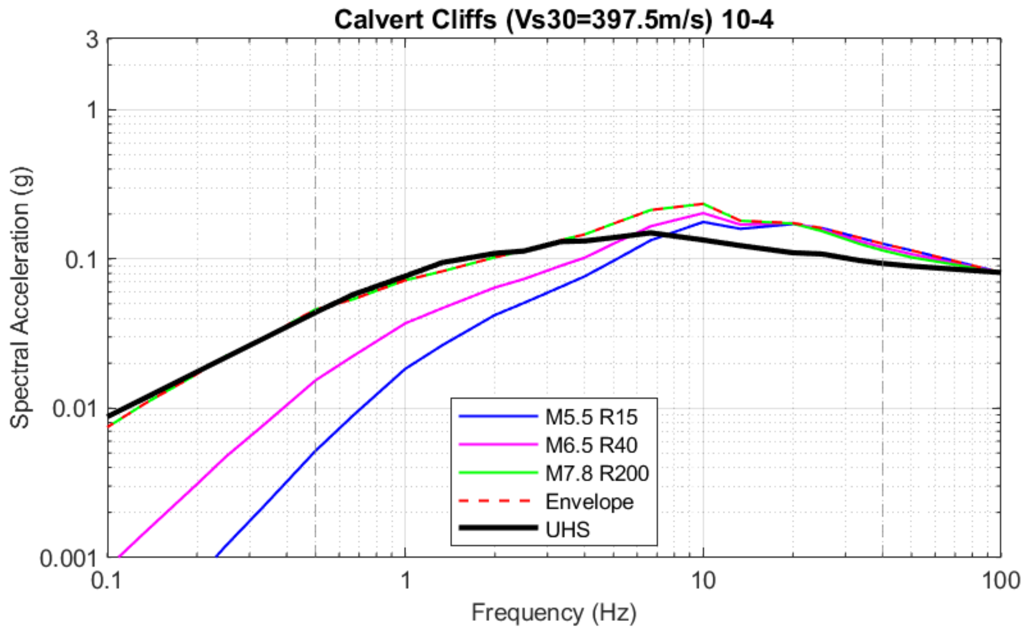


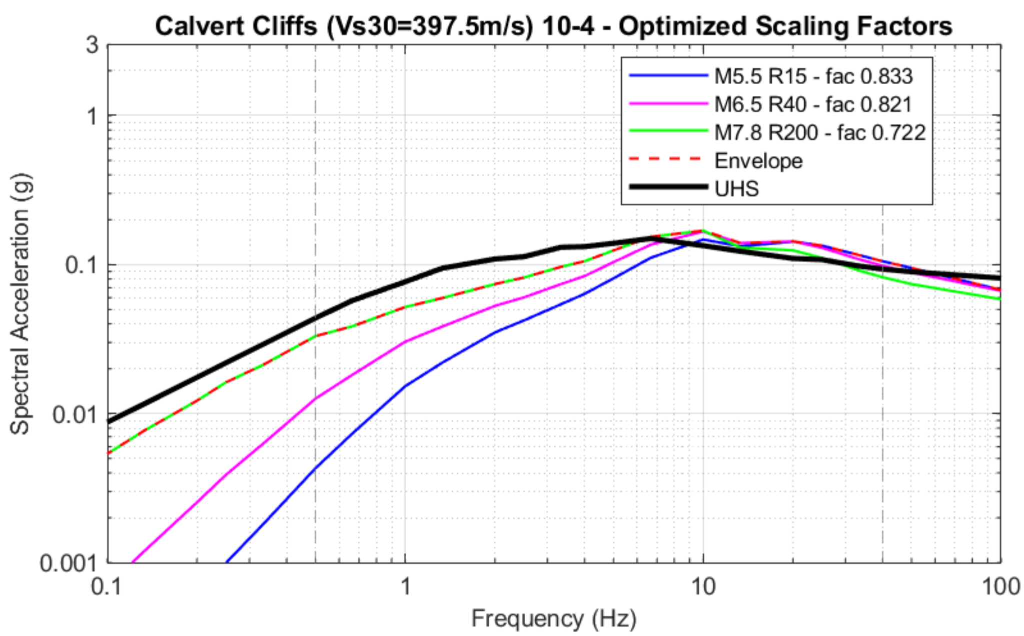
Appendix Figure A-1 Comparison of the scaled scenario spectra to the Beaver Valley (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



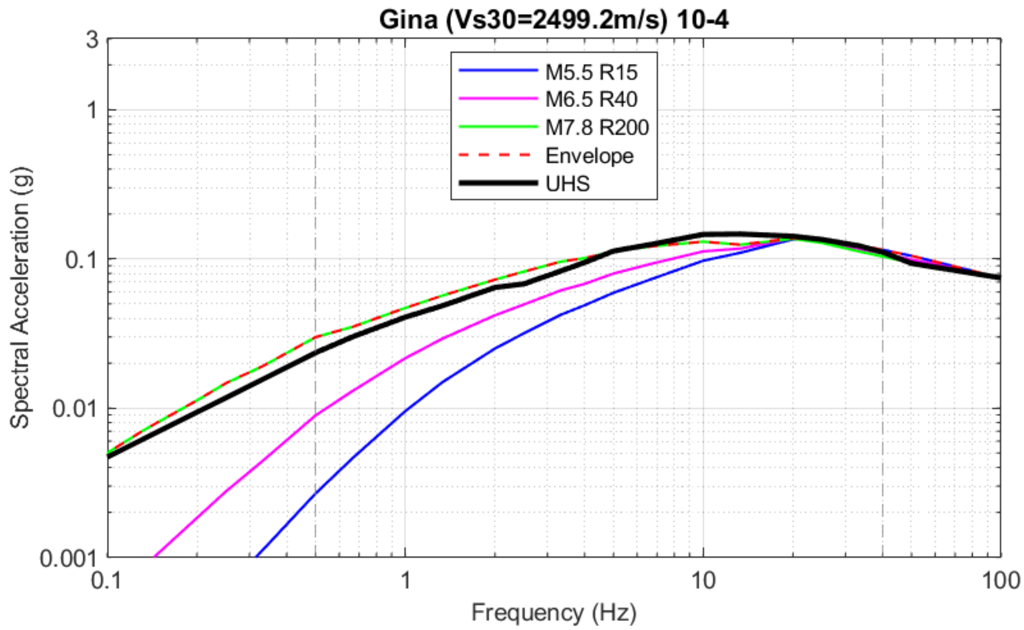


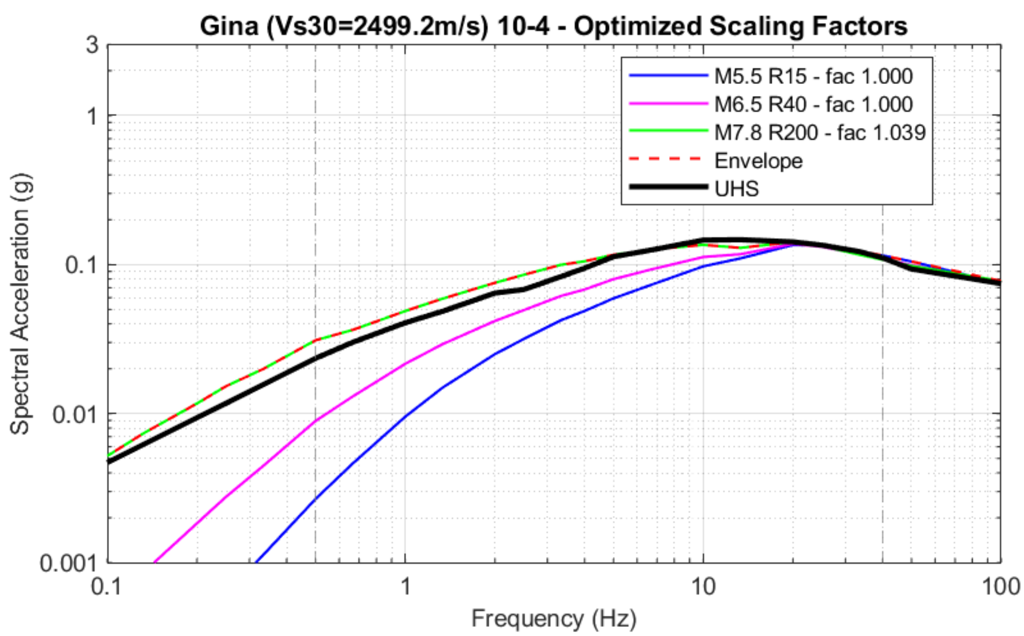
Appendix Figure A-2 Comparison of the scaled scenario spectra to the Brunswick (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



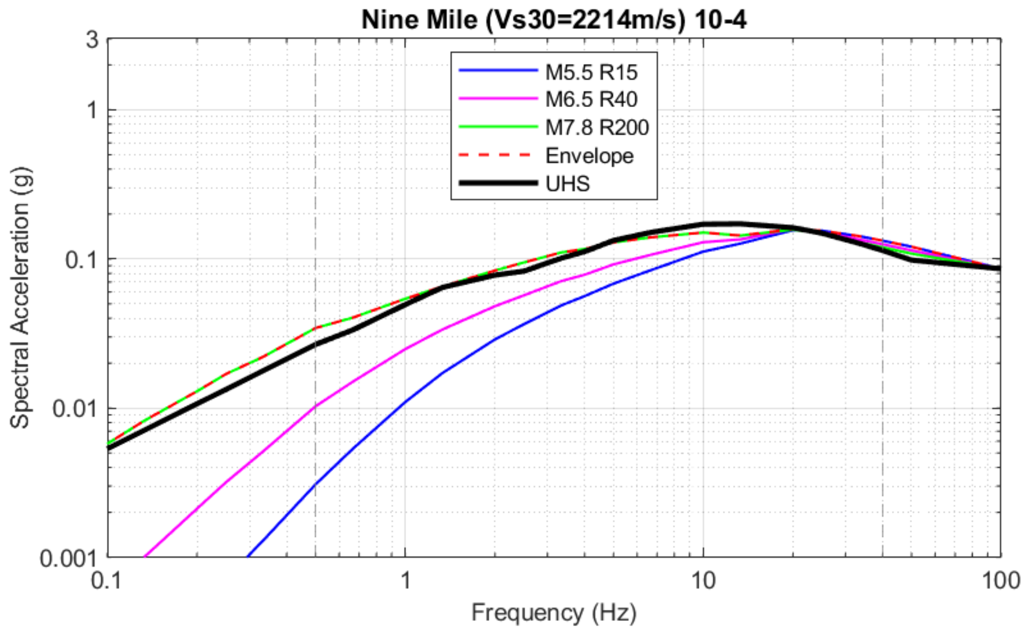


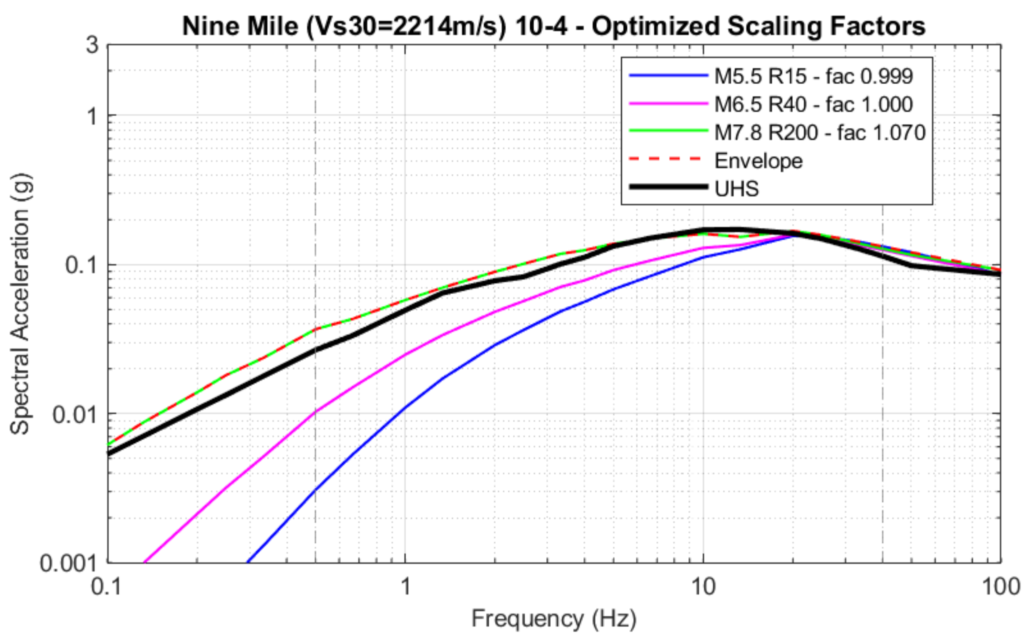
Appendix Figure A-3 Comparison of the scaled scenario spectra to the Calvert Cliffs (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



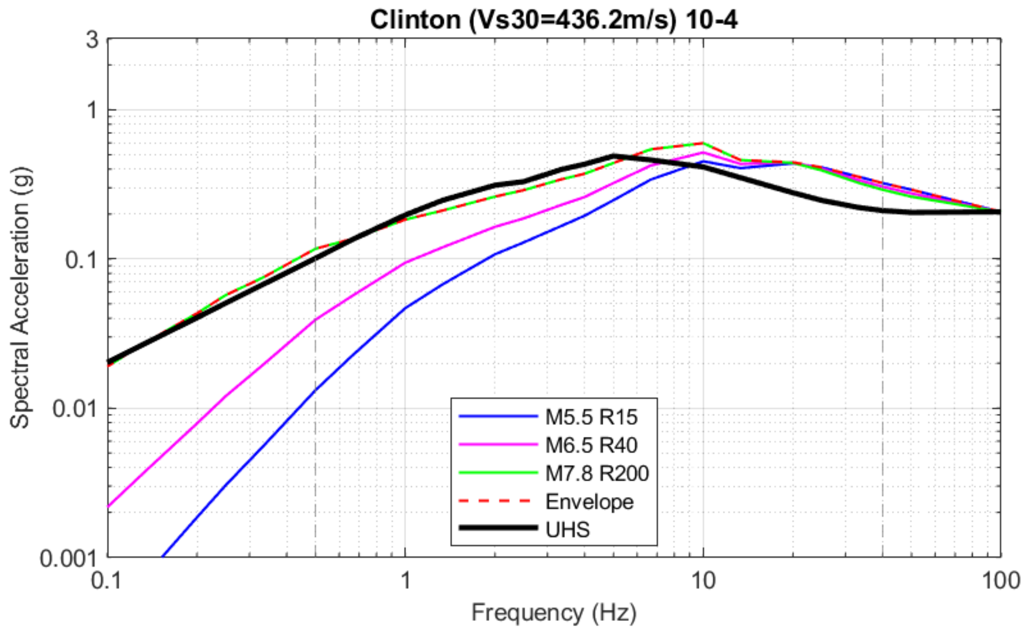


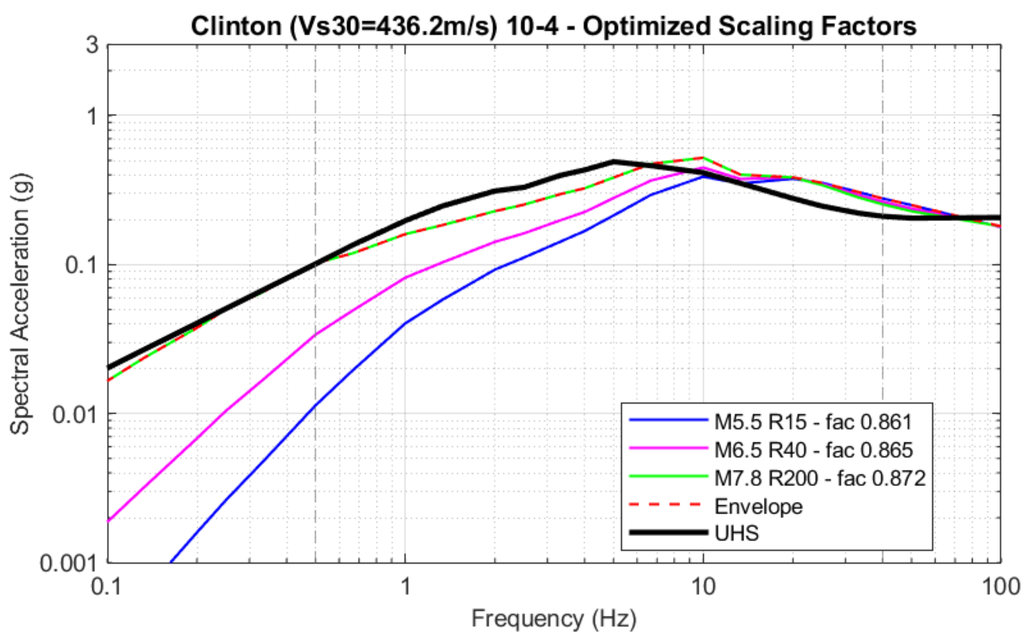
Appendix Figure A-4 Comparison of the scaled scenario spectra to the Gina (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



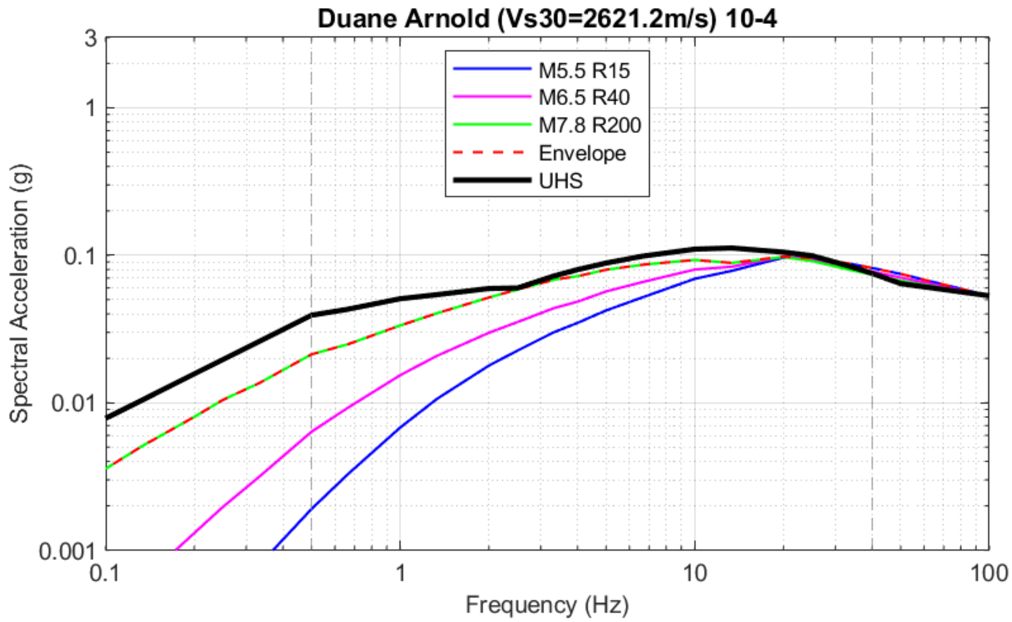


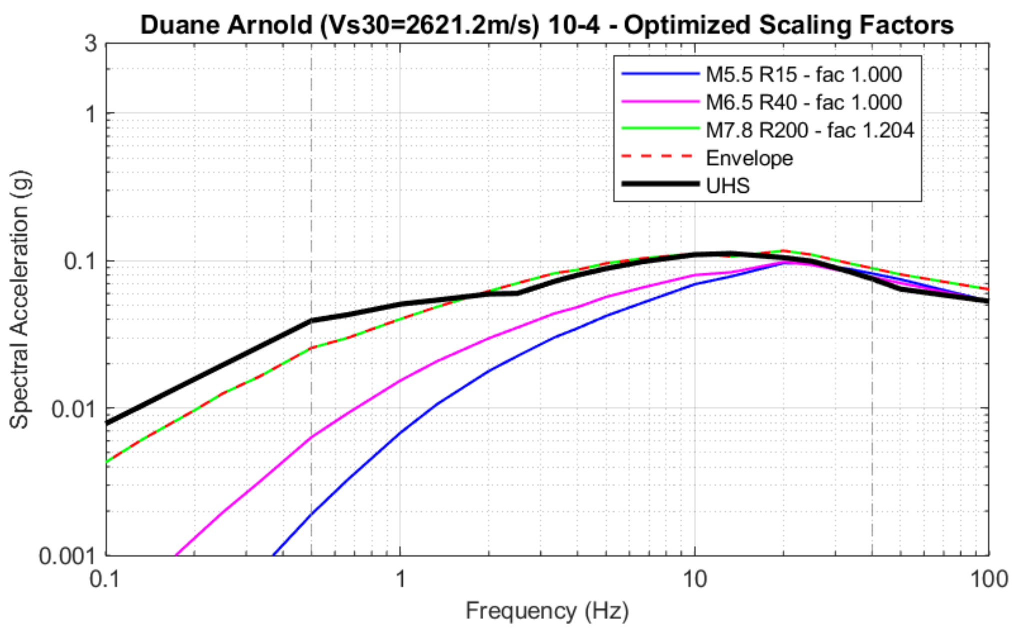
Appendix Figure A-5 Comparison of the scaled scenario spectra to the Nine Mile (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



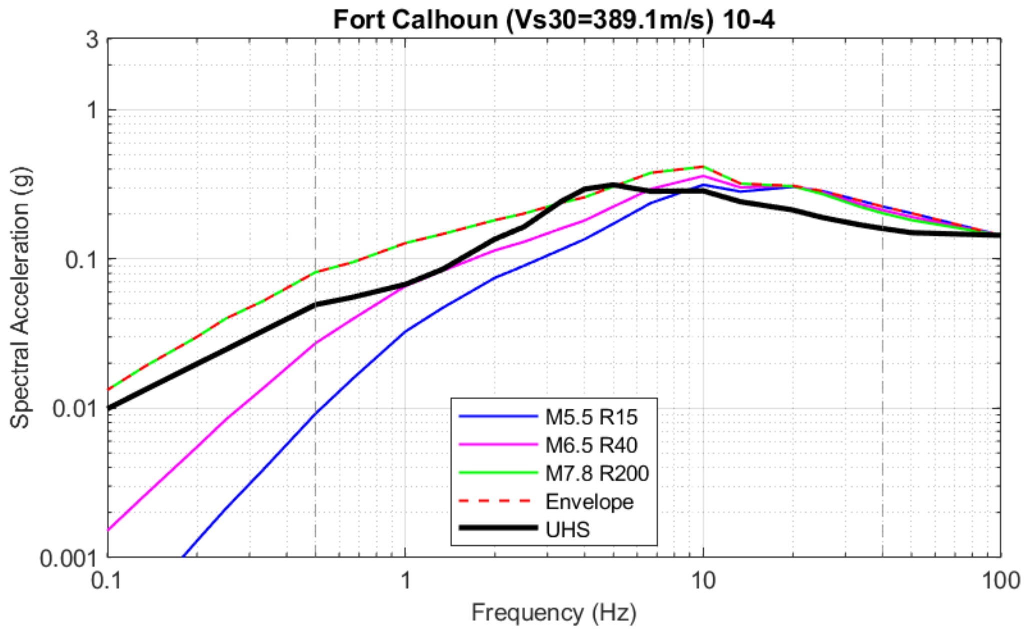


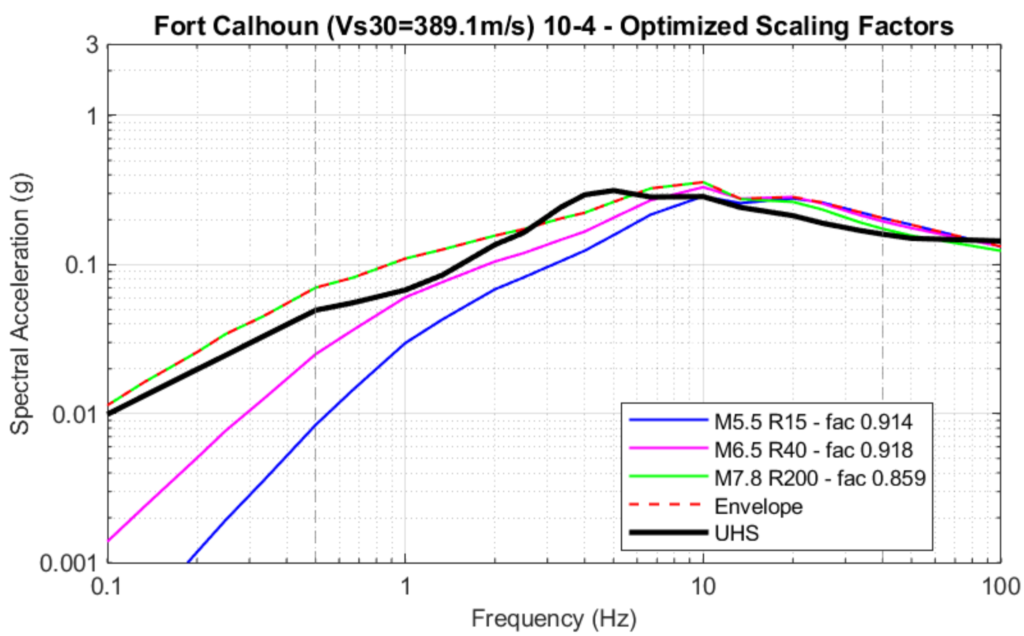
Appendix Figure A-6 Comparison of the scaled scenario spectra to the Clinton (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



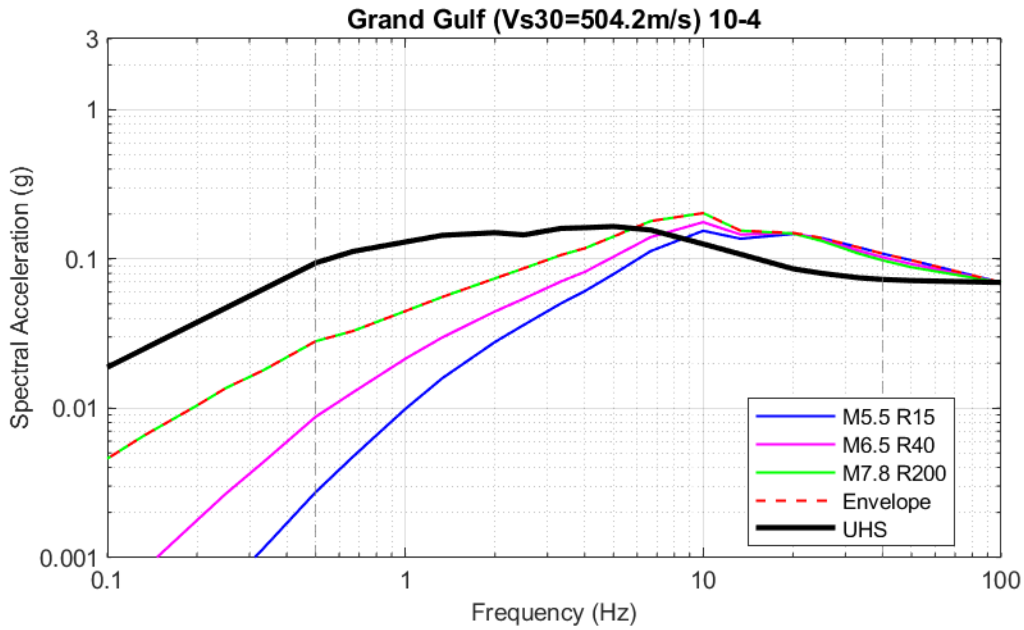


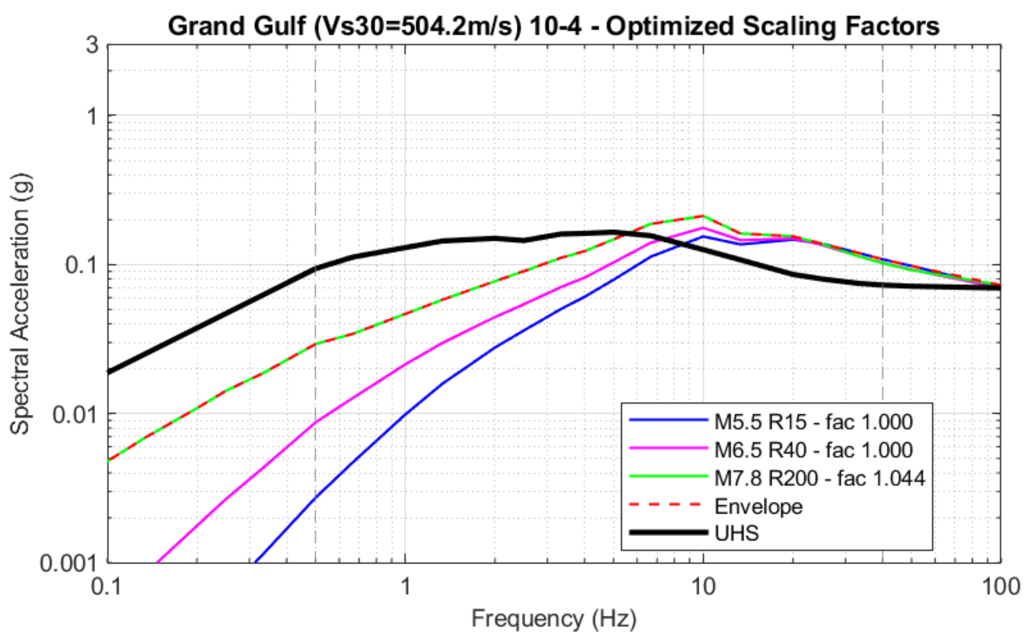
Appendix Figure A-7 Comparison of the scaled scenario spectra to the Duane Arnold (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



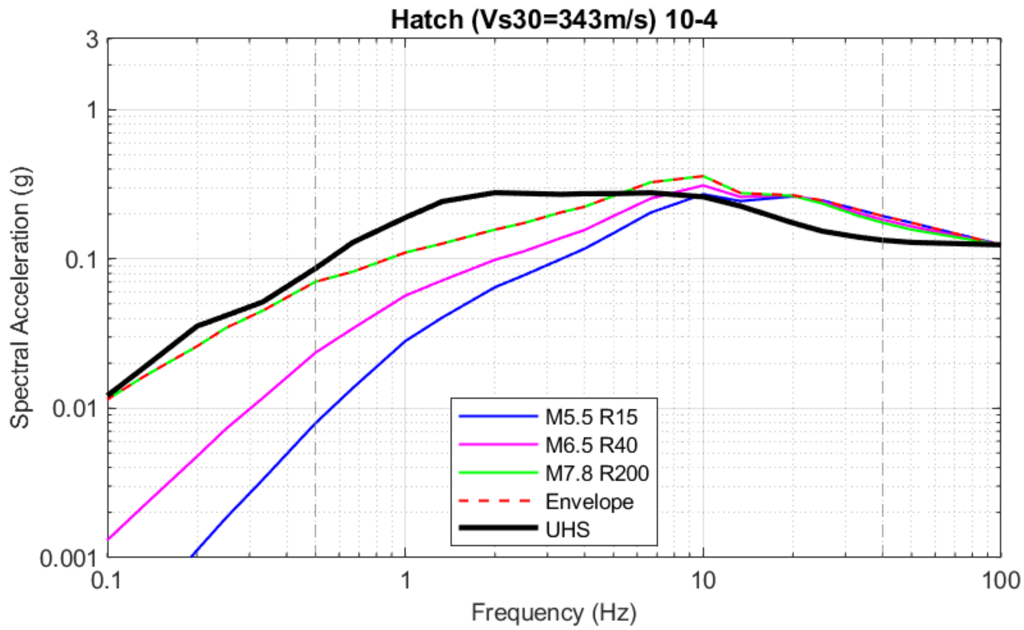


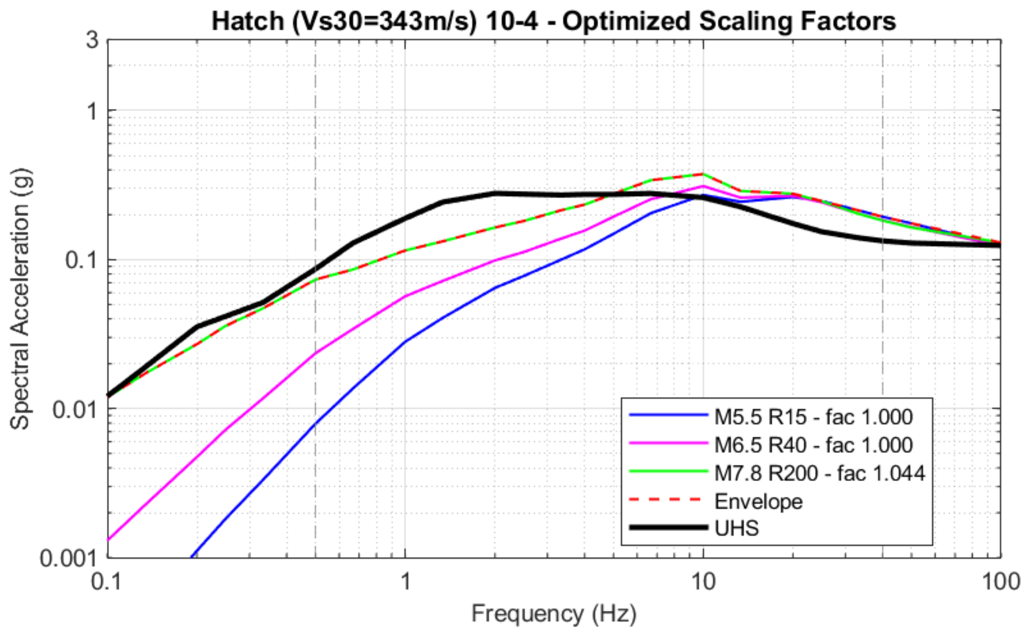
Appendix Figure A-8 Comparison of the scaled scenario spectra to the Fort Calhoun (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



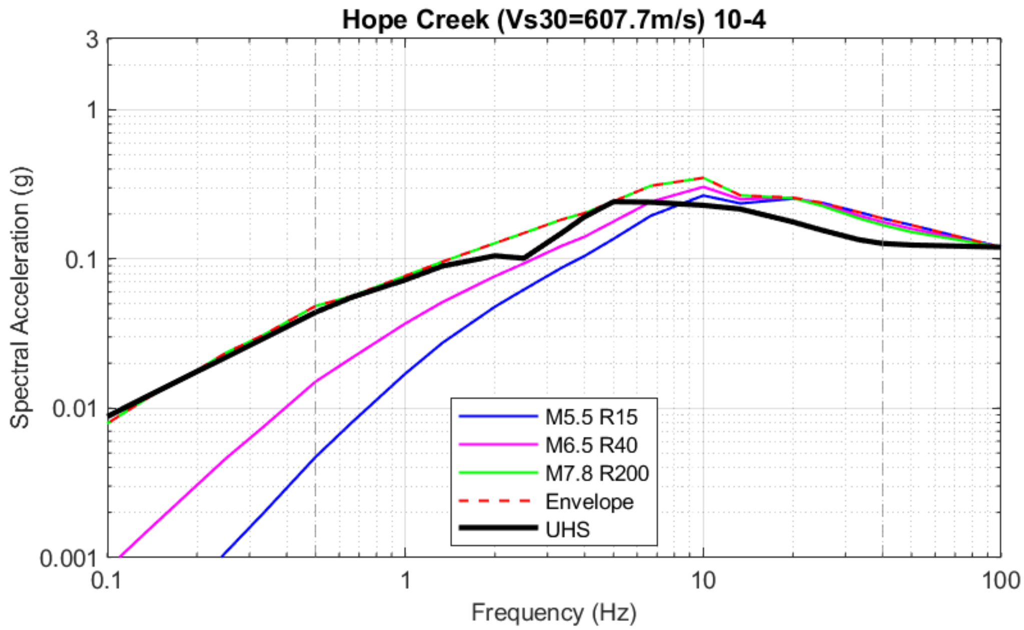


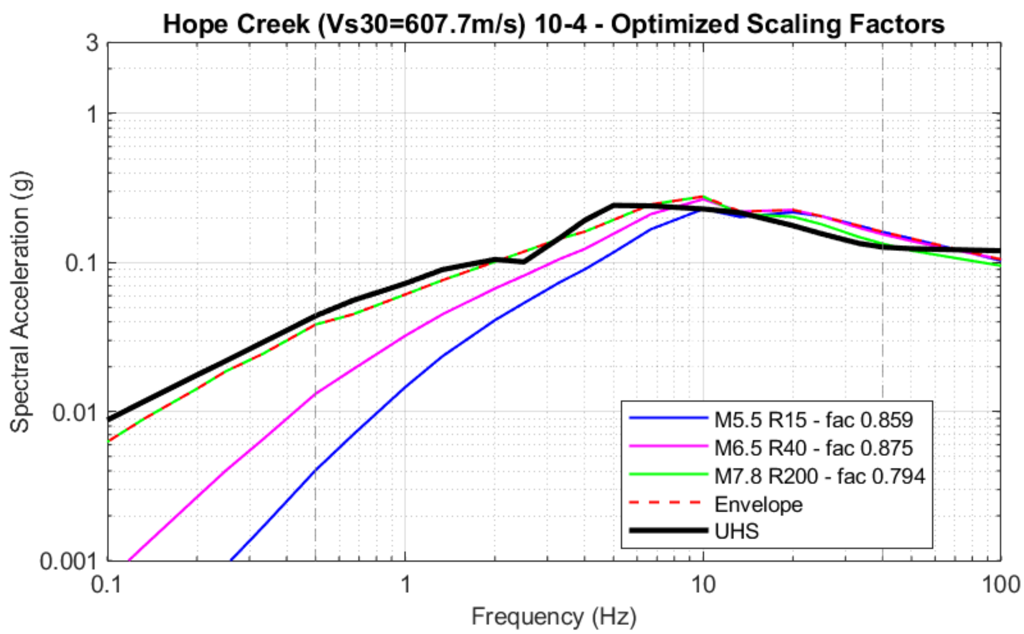
Appendix Figure A-9 Comparison of the scaled scenario spectra to the Grand Gulf (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



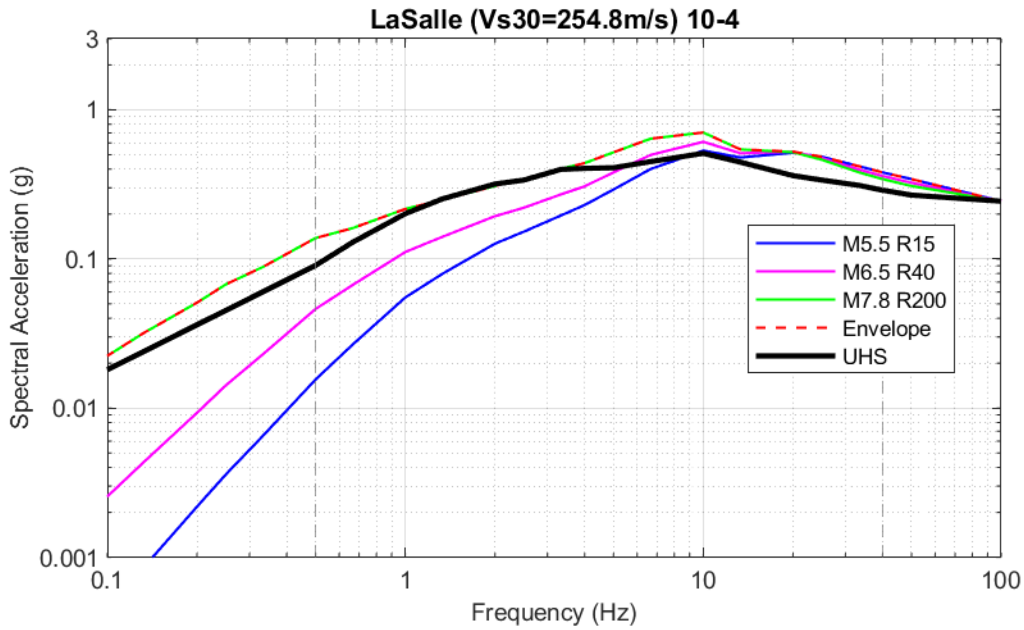


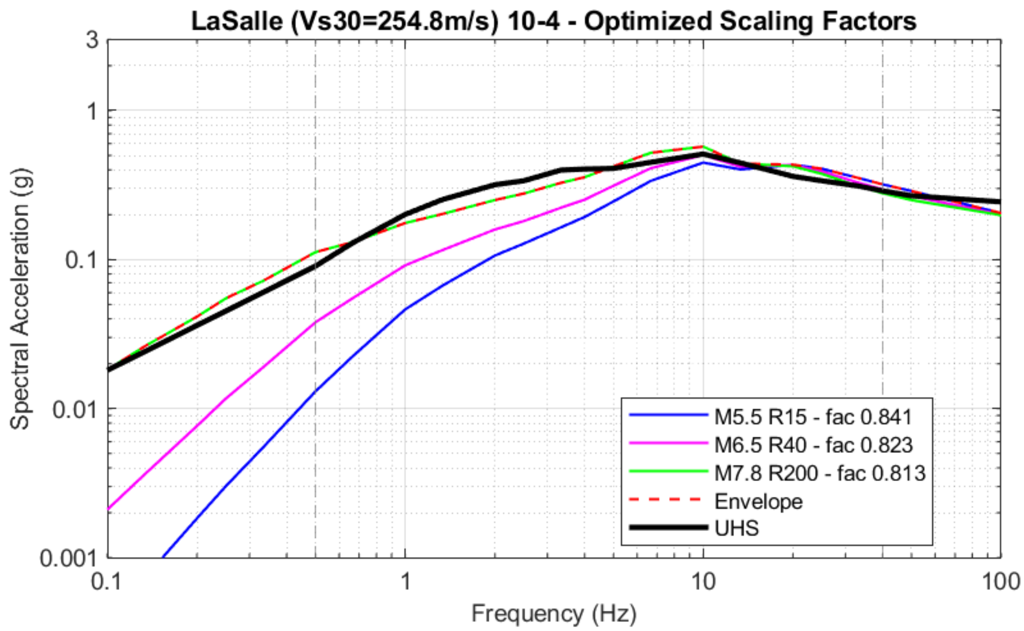
Appendix Figure A-10 Comparison of the scaled scenario spectra to the Hatch (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



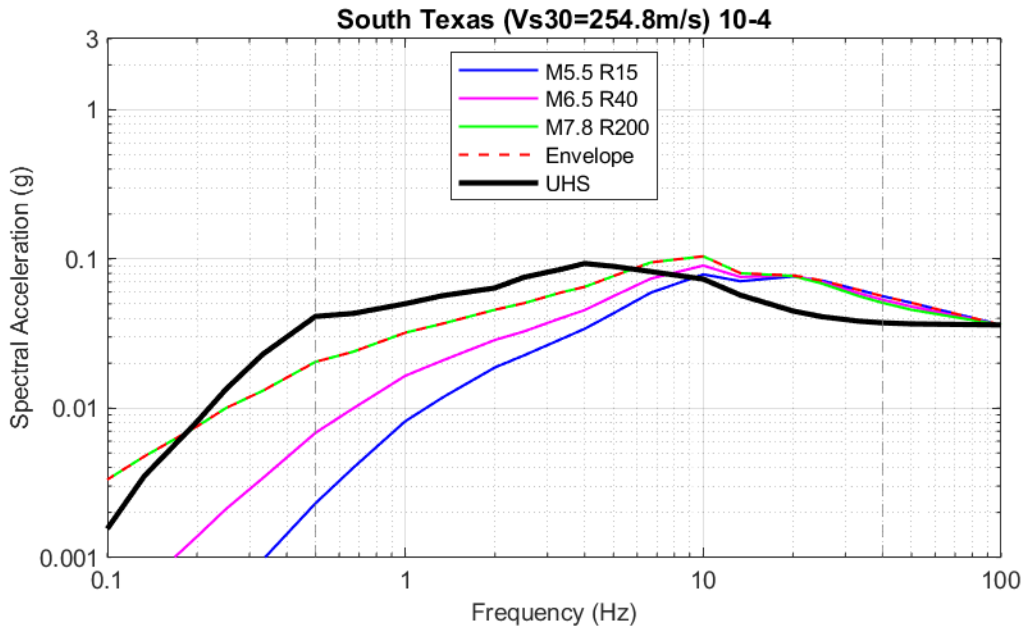


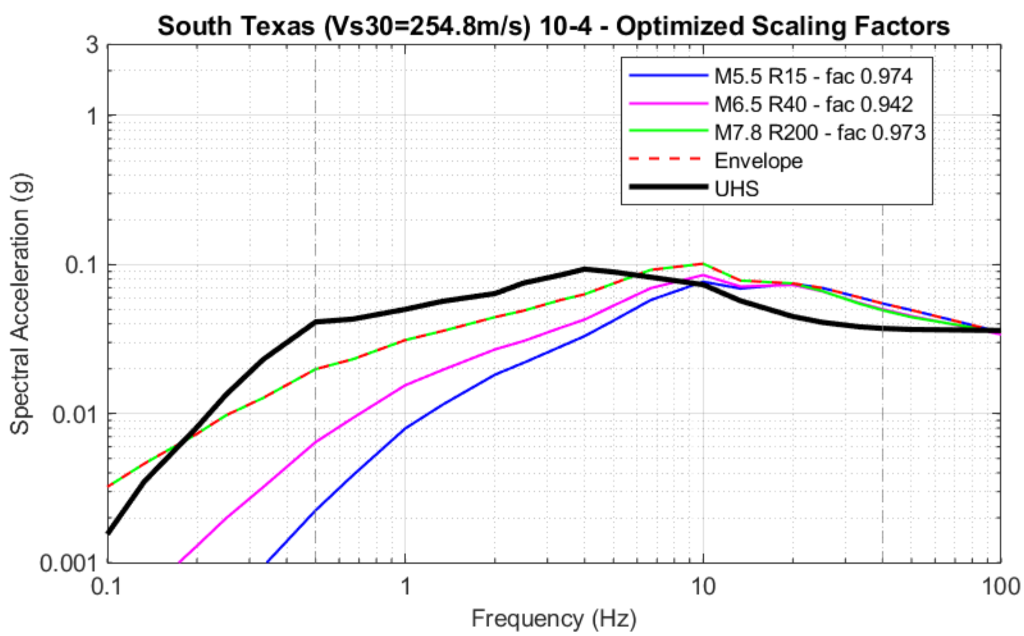
Appendix Figure A-11 Comparison of the scaled scenario spectra to the Hope Creek (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



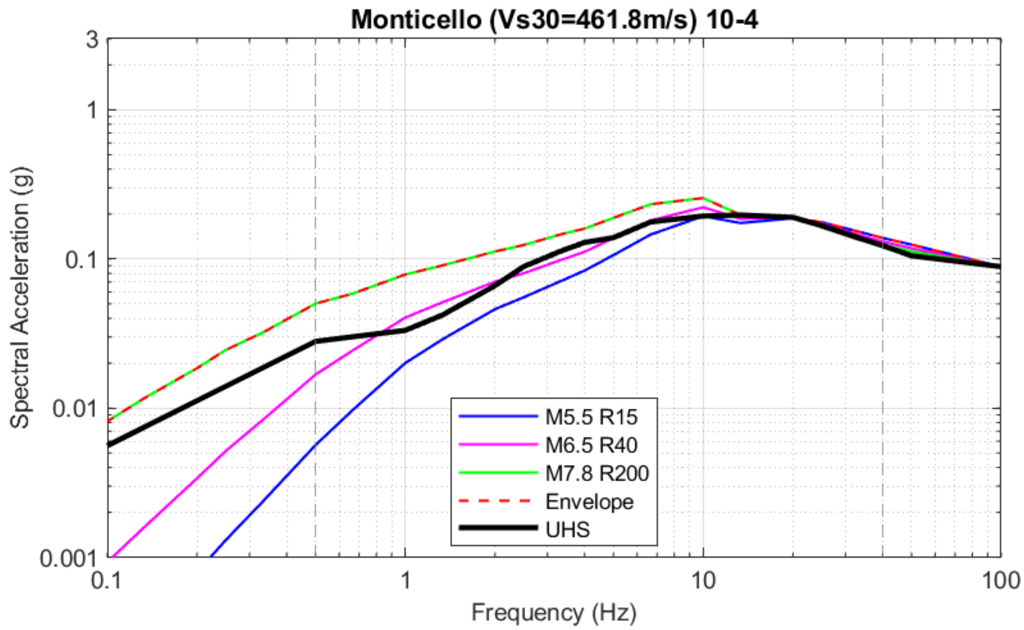


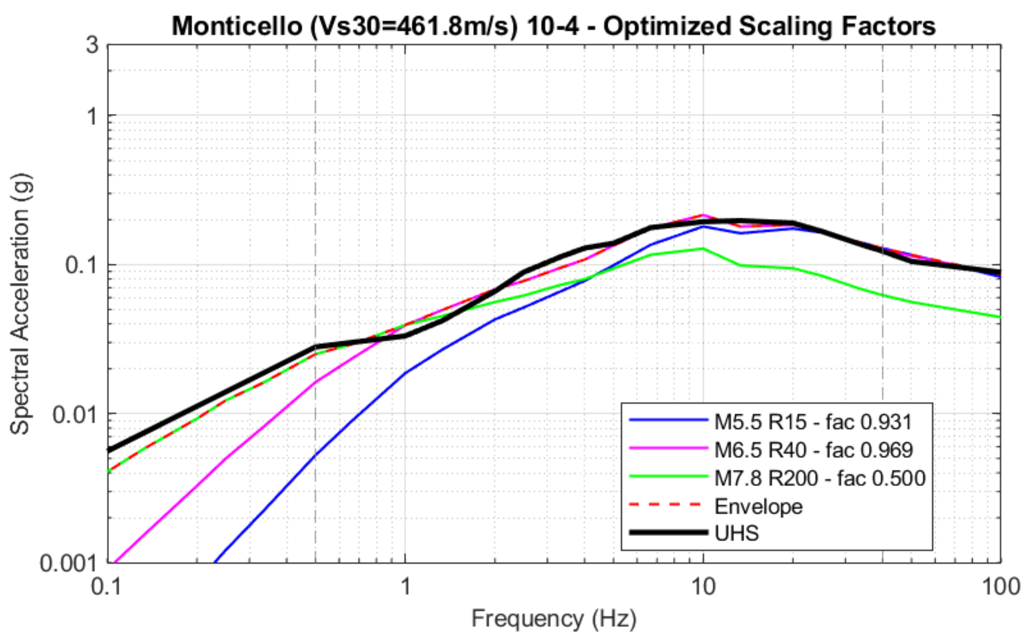
Appendix Figure A-12 Comparison of the scaled scenario spectra to the LaSalle (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



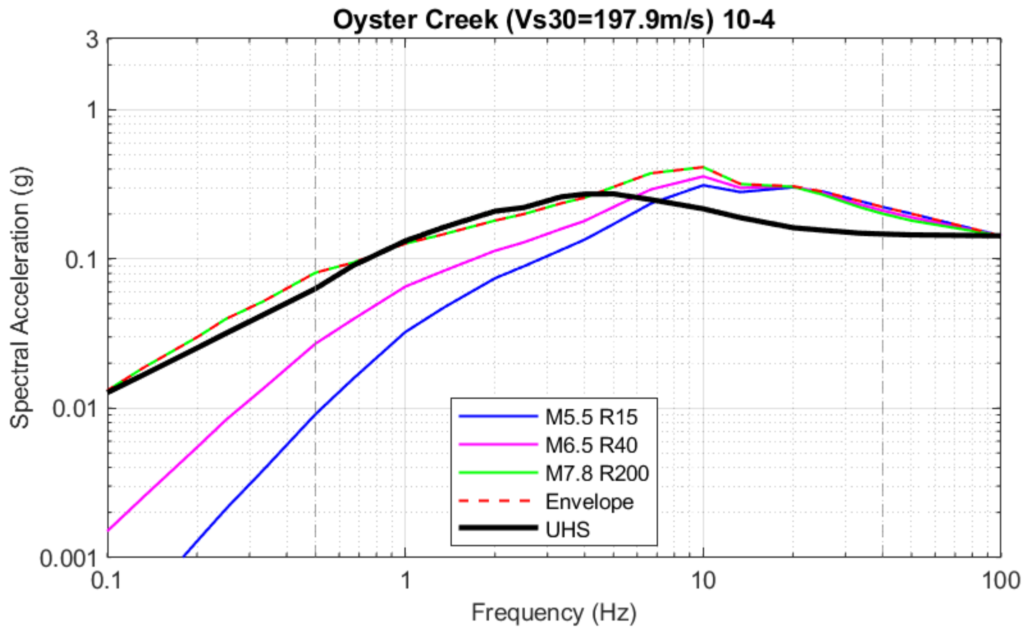


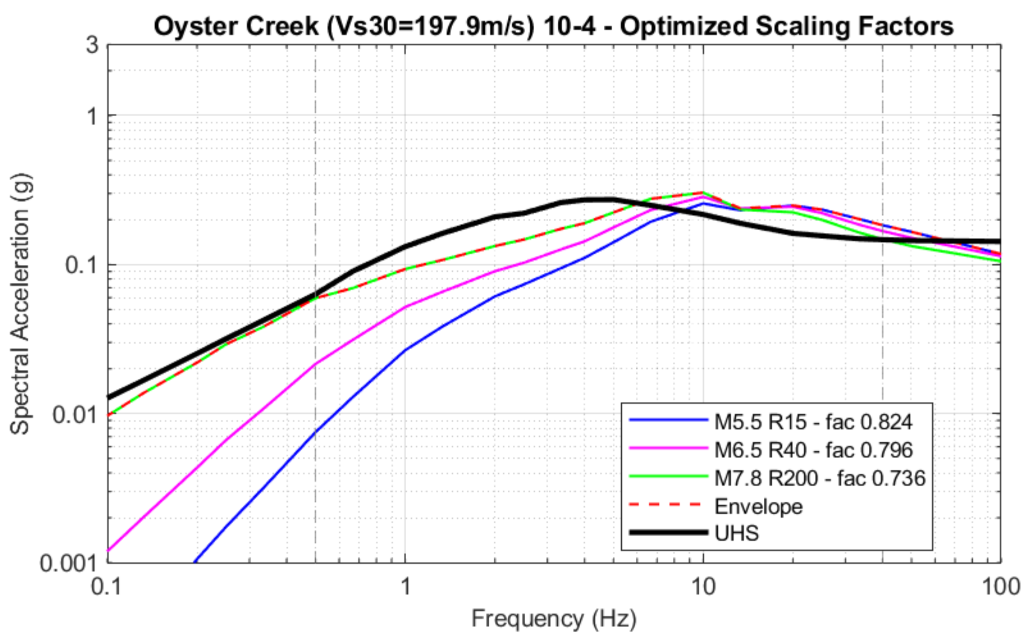
Appendix Figure A-13 Comparison of the scaled scenario spectra to the South Texas (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



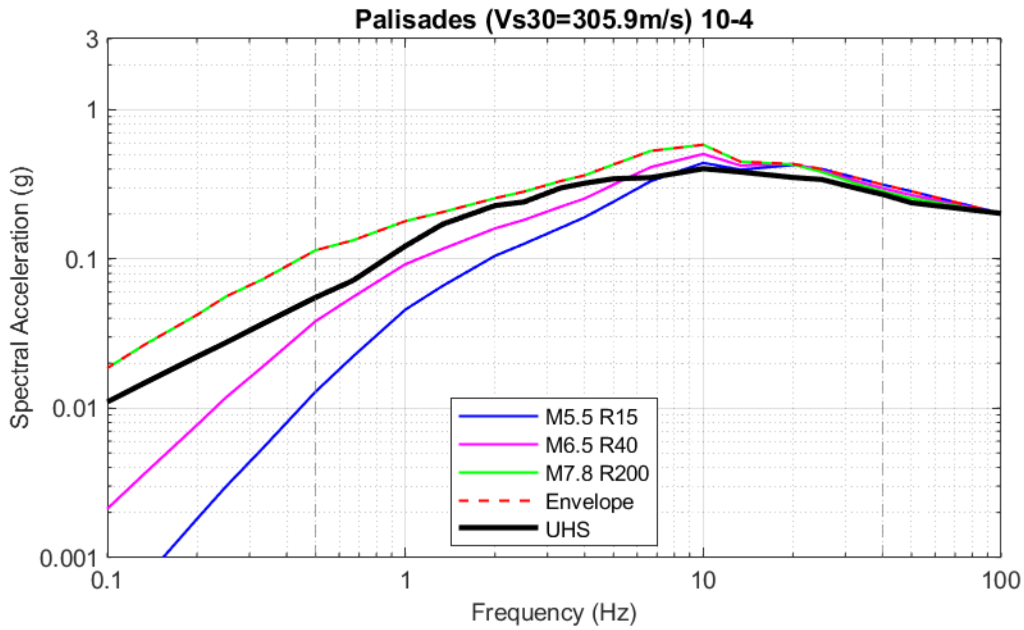


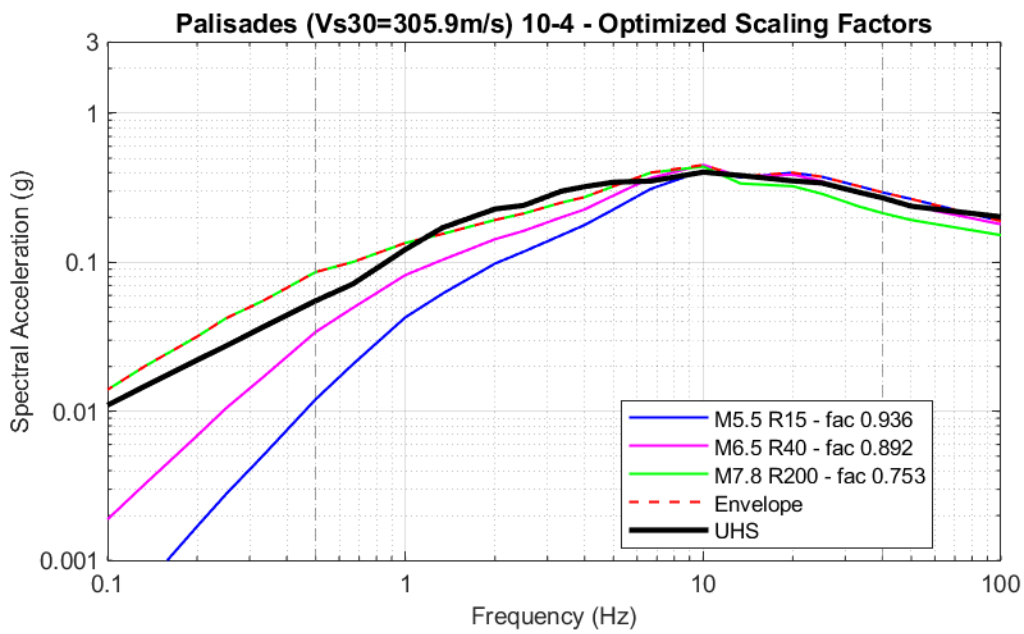
Appendix Figure A-14 Comparison of the scaled scenario spectra to the Monticello (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



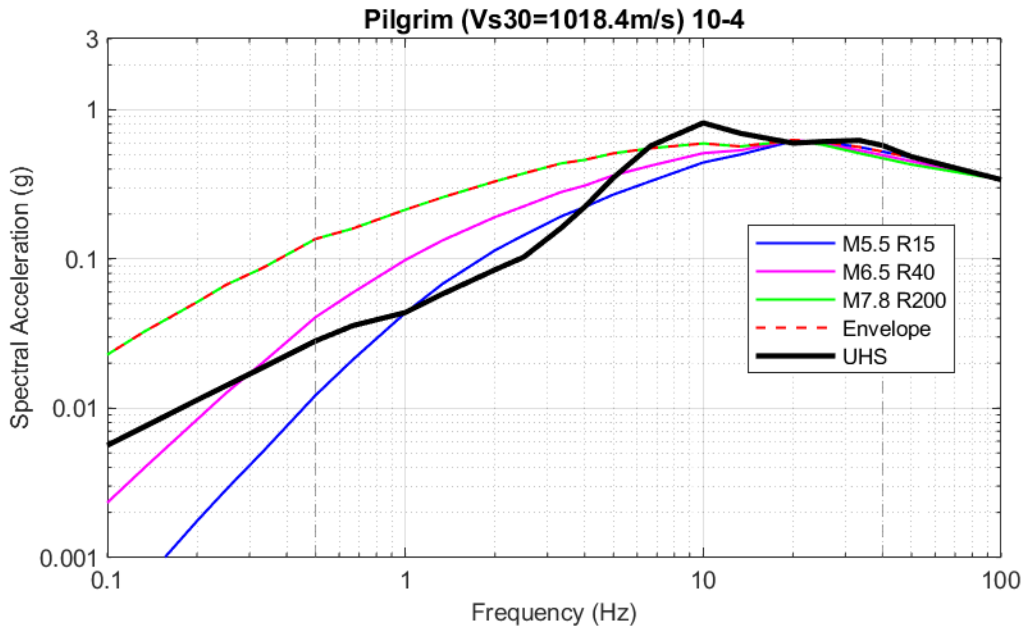


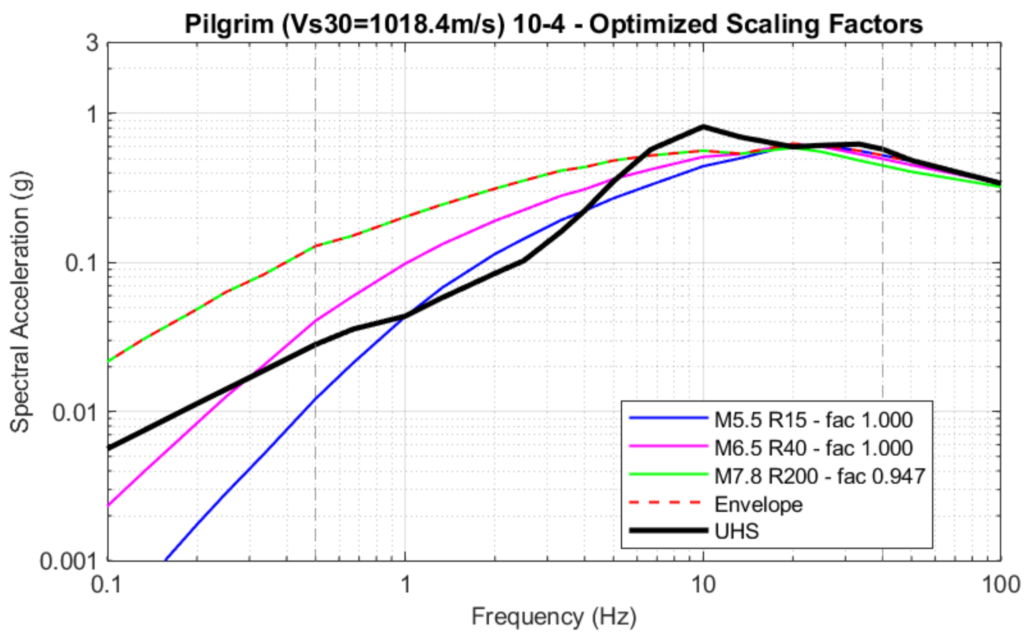
Appendix Figure A-15 Comparison of the scaled scenario spectra to the Oyster Creek (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



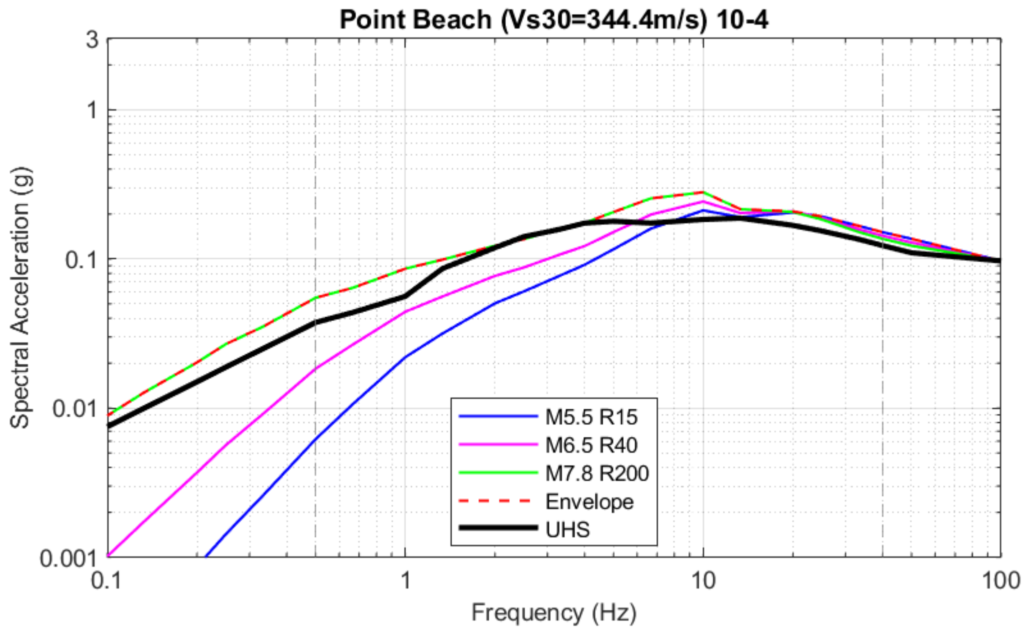


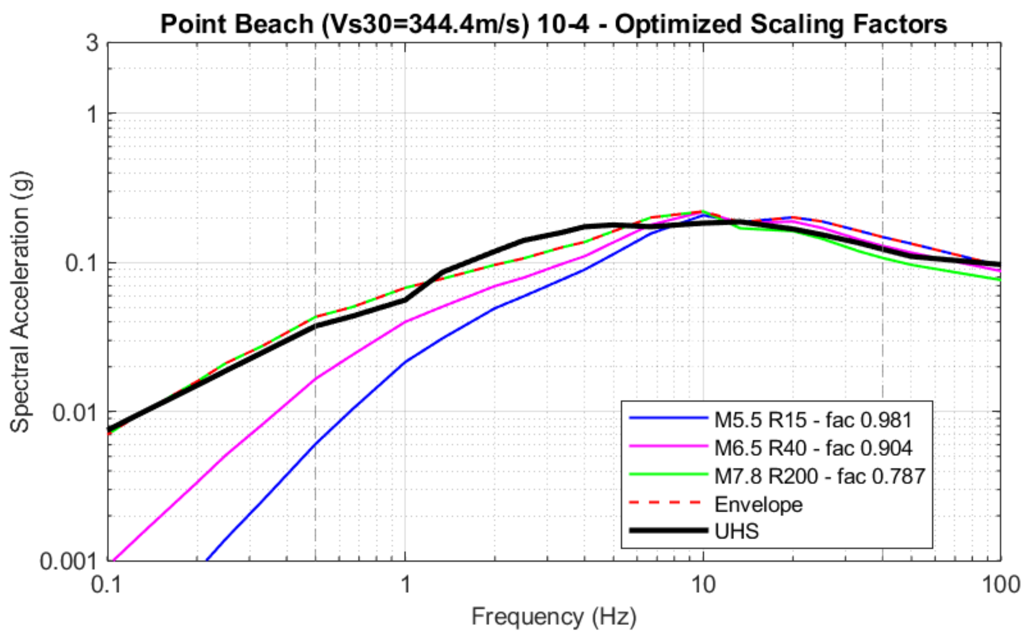
Appendix Figure A-16 Comparison of the scaled scenario spectra to the Palisades (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



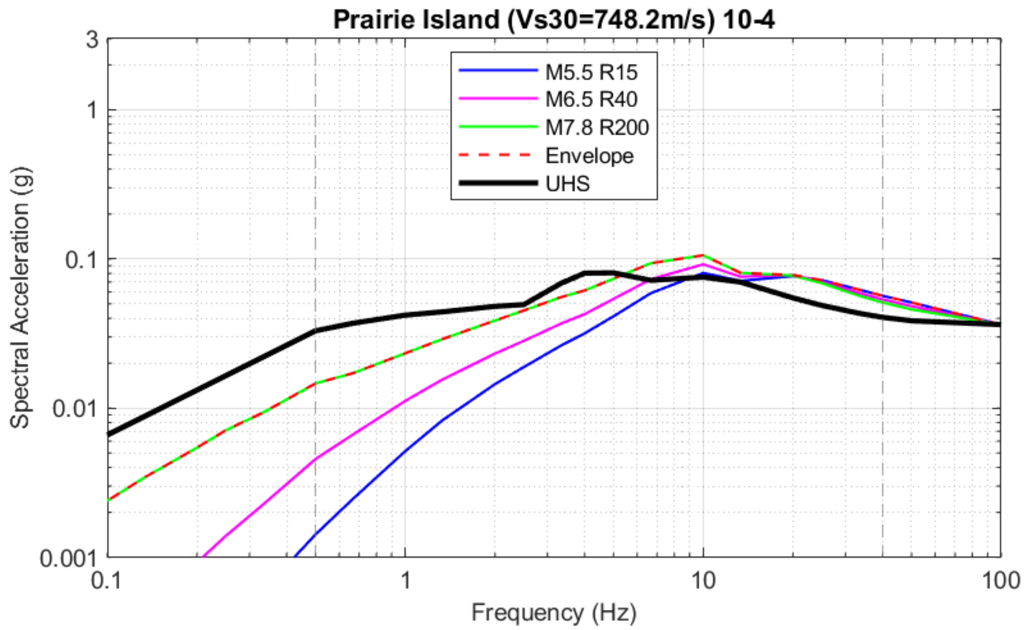


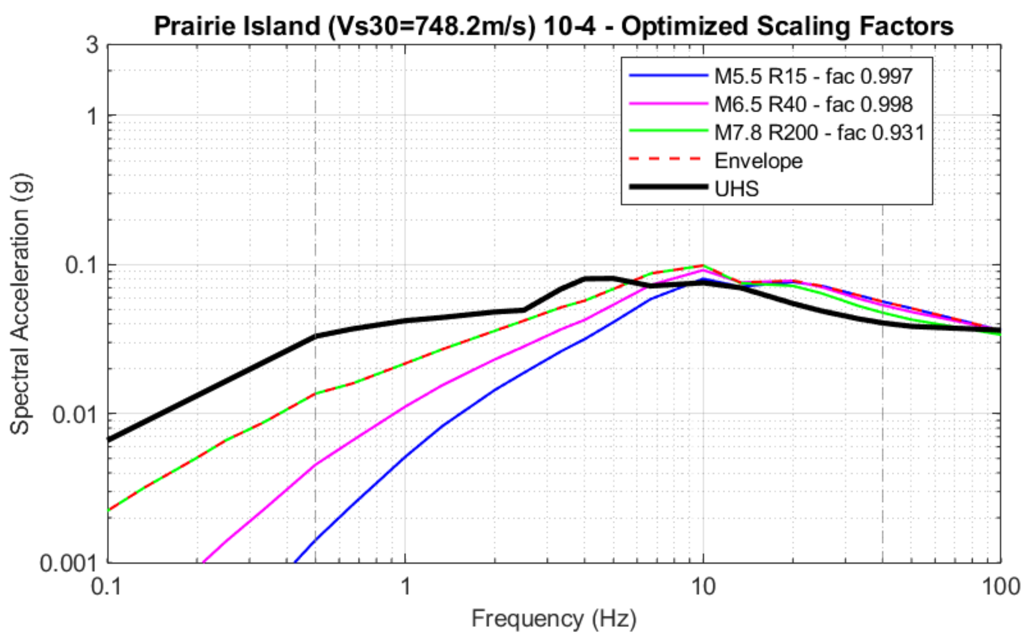
Appendix Figure A-17 Comparison of the scaled scenario spectra to the Pilgrim (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



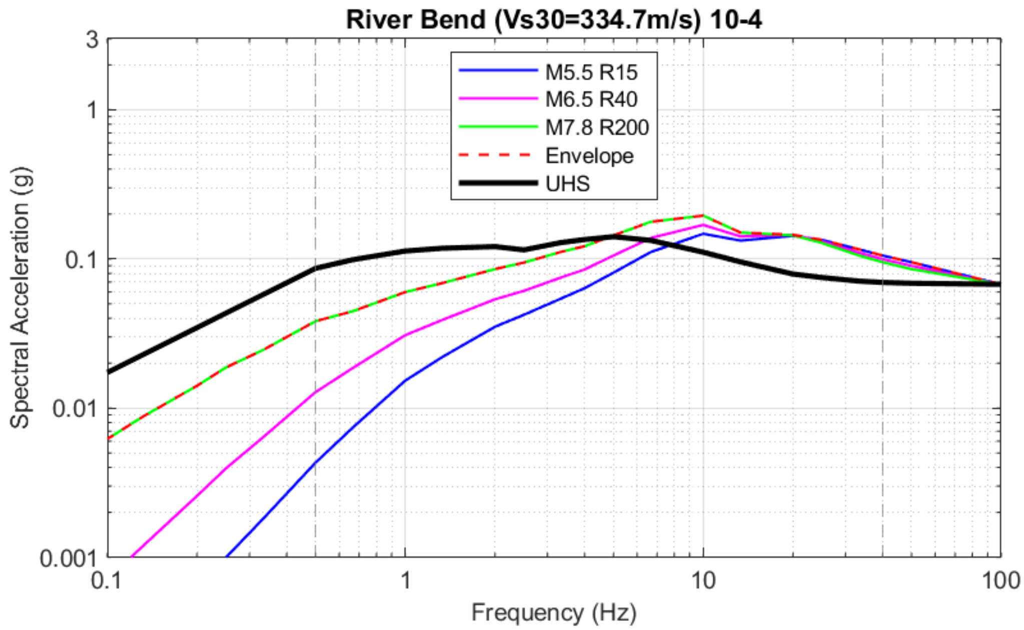


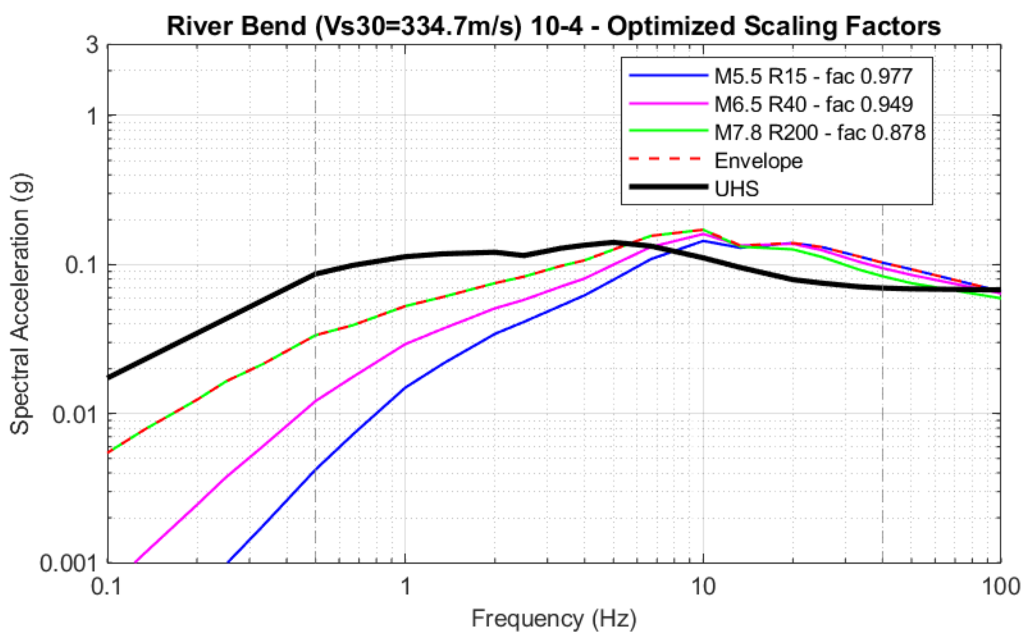
Appendix Figure A-18 Comparison of the scaled scenario spectra to the Point Beach (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



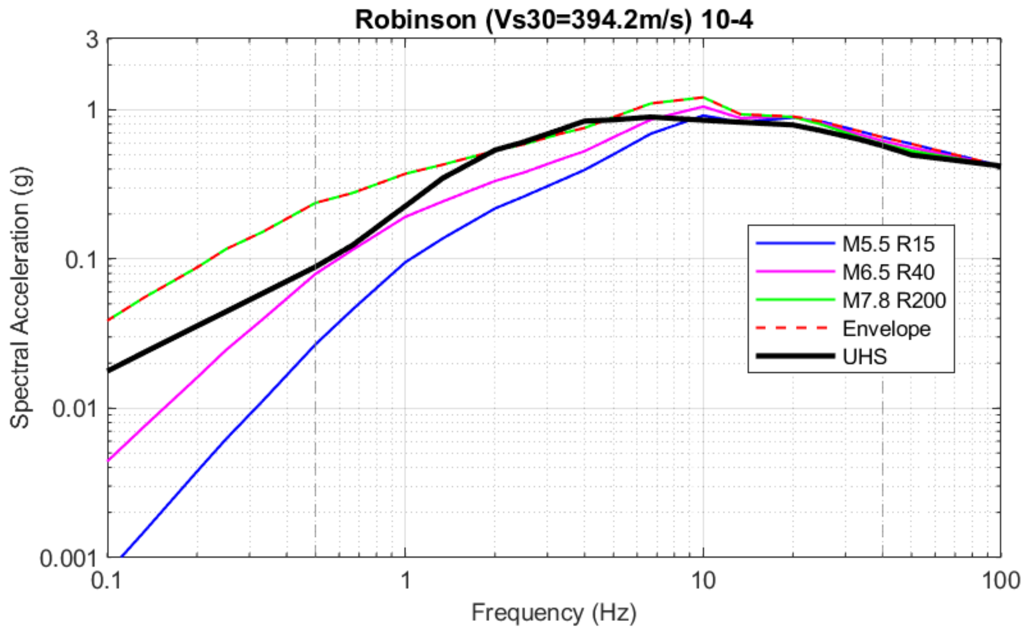


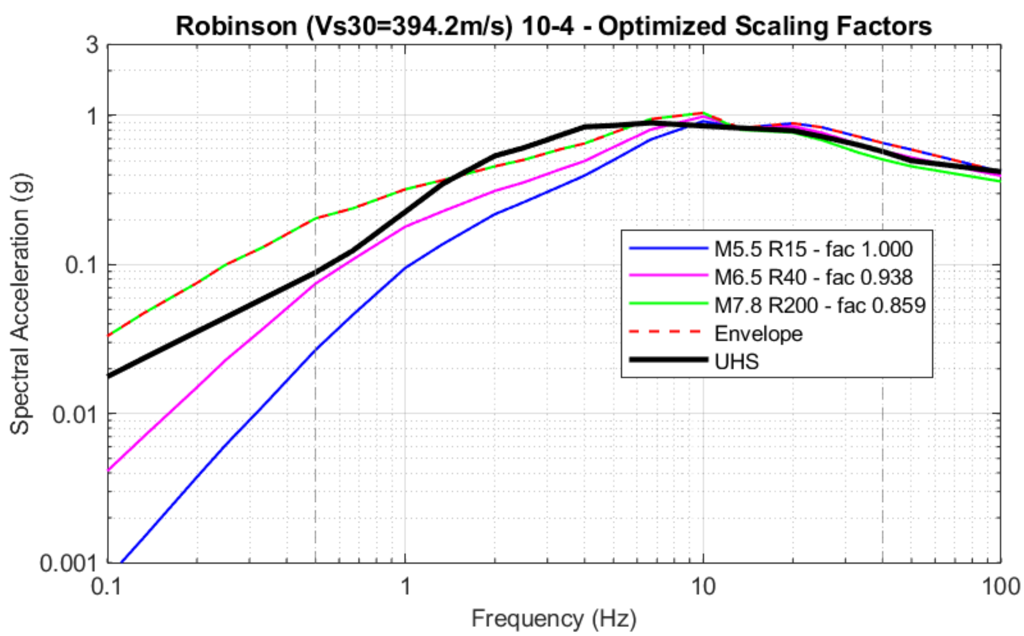
Appendix Figure A-19 Comparison of the scaled scenario spectra to the Prairie Island (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



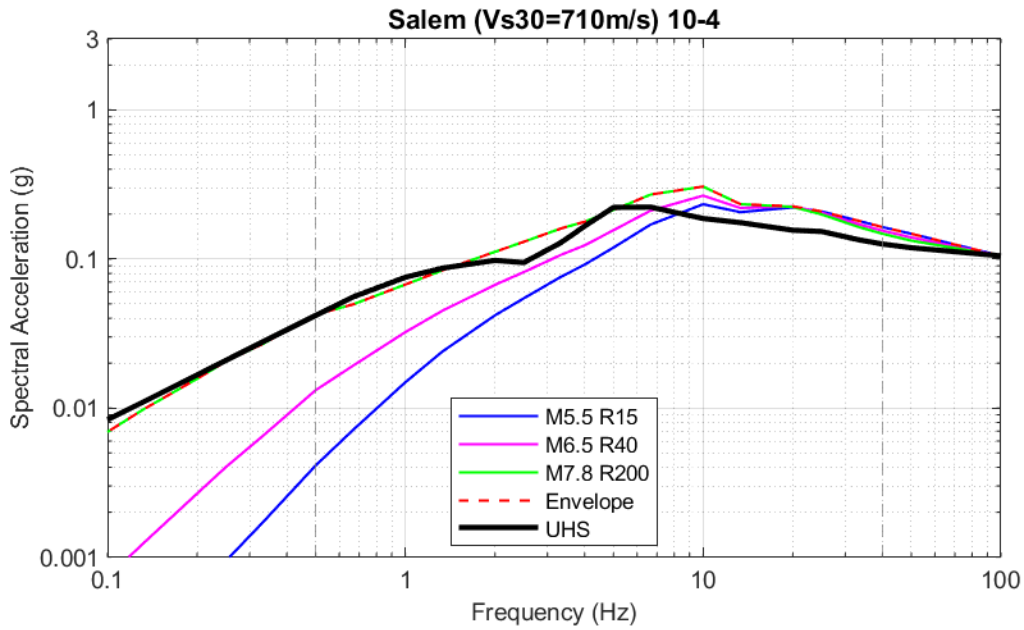


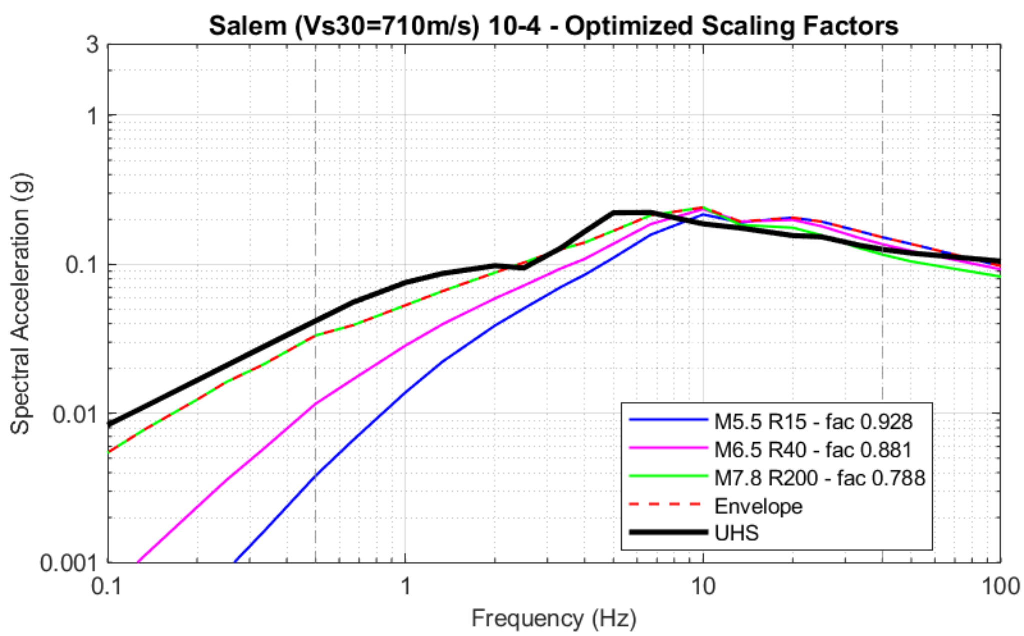
Appendix Figure A-20 Comparison of the scaled scenario spectra to the River Bend (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



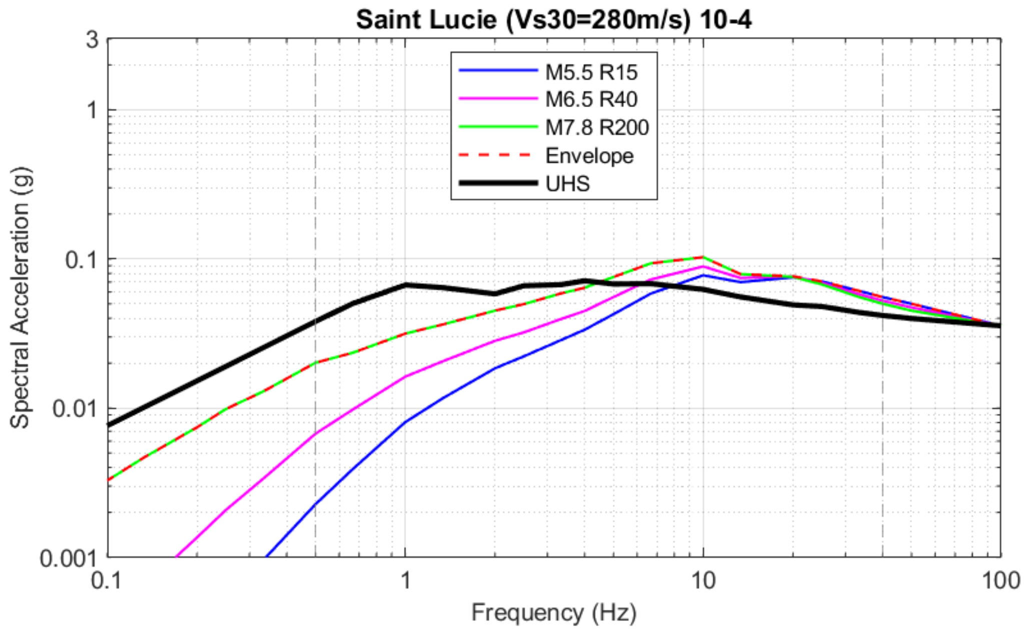


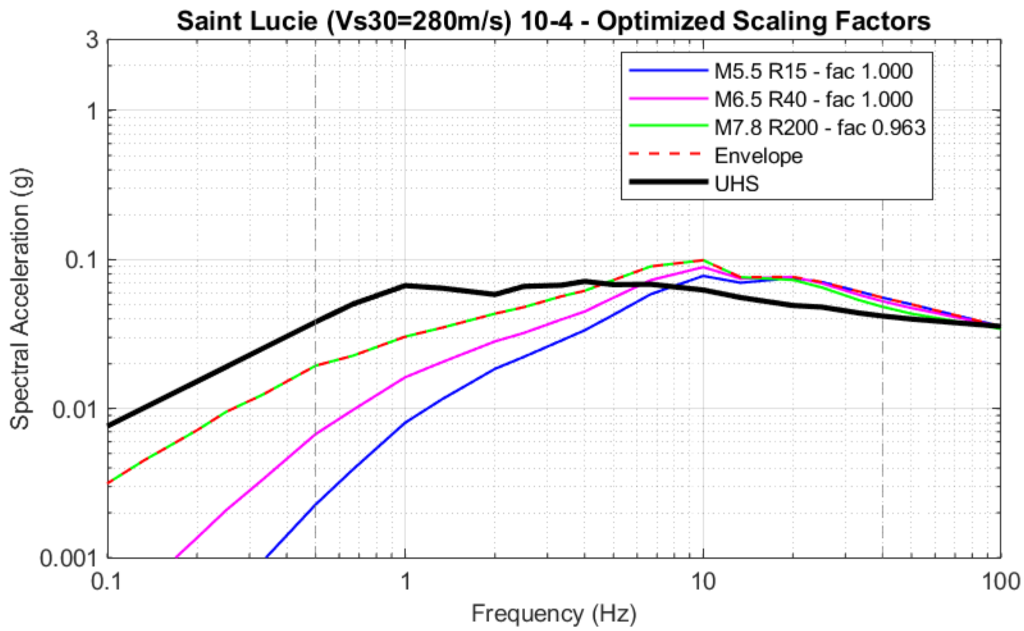
Appendix Figure A-21 Comparison of the scaled scenario spectra to the Robinson (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



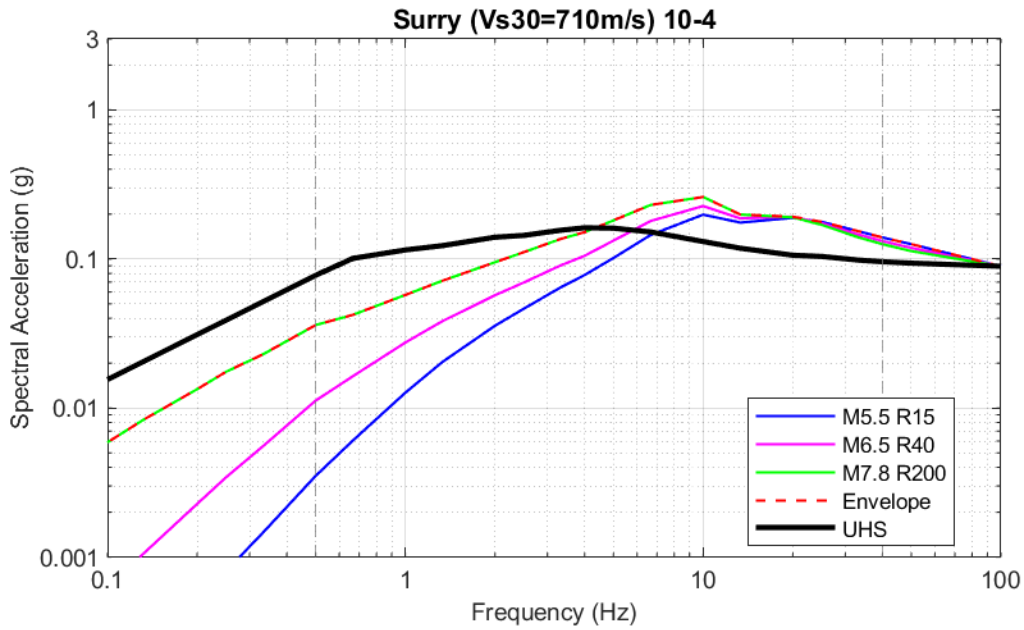


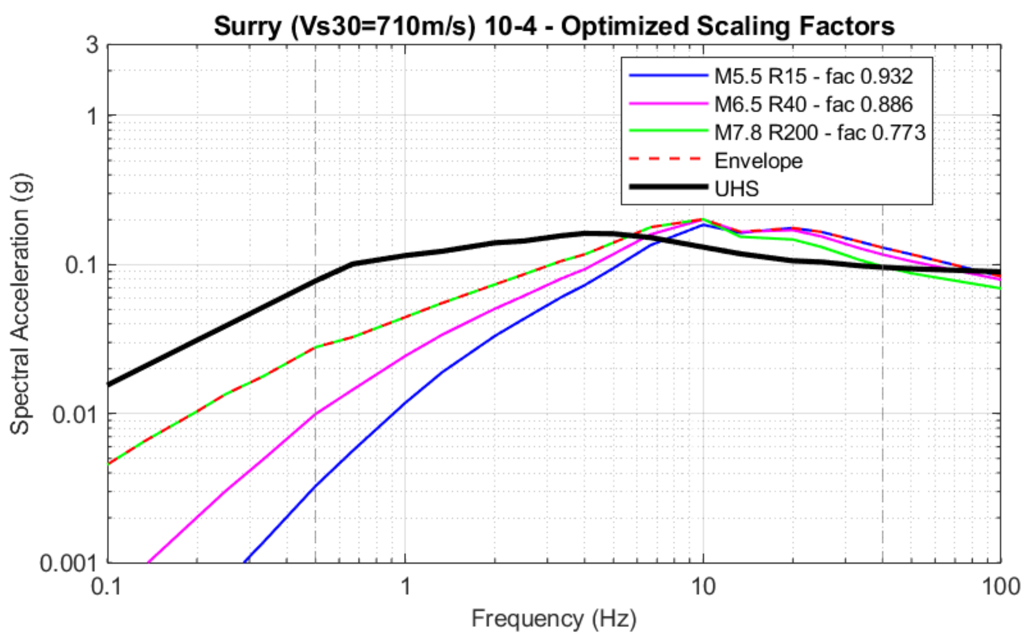
Appendix Figure A-22 Comparison of the scaled scenario spectra to the Salem (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



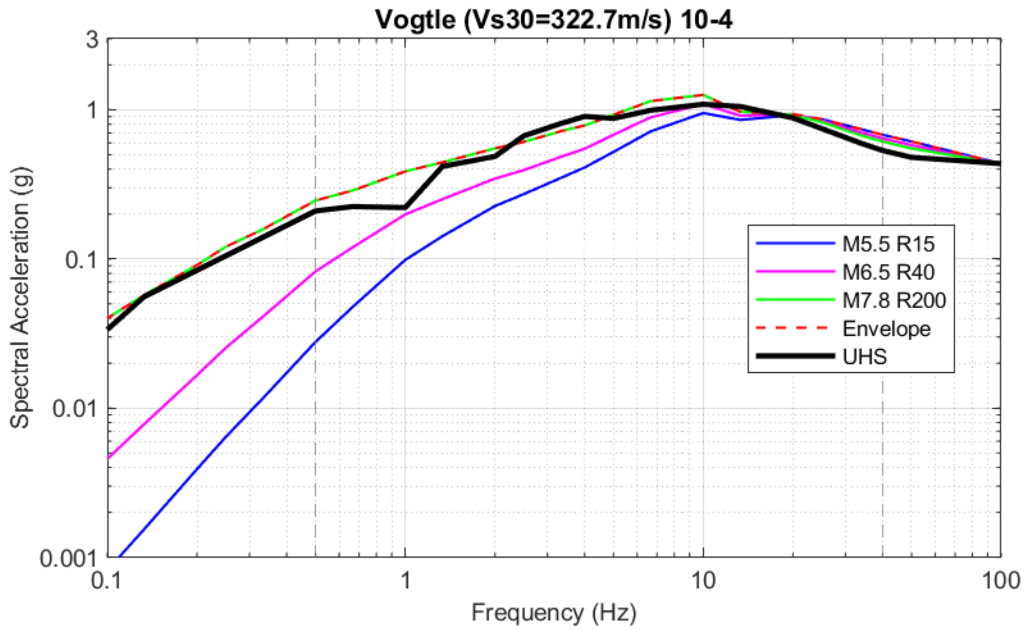


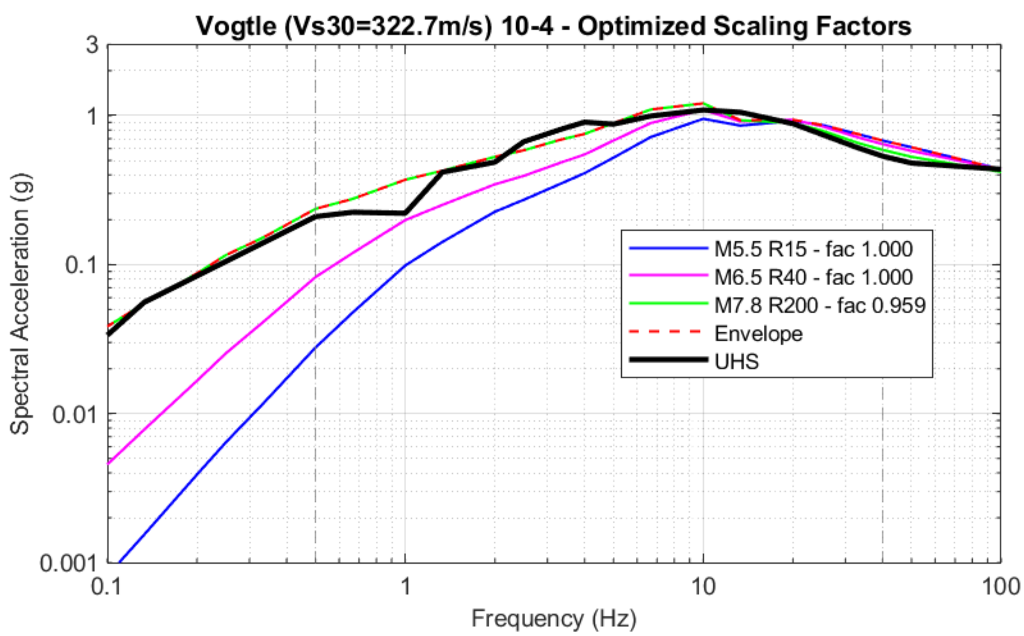
Appendix Figure A-23 Comparison of the scaled scenario spectra to the St. Lucie (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



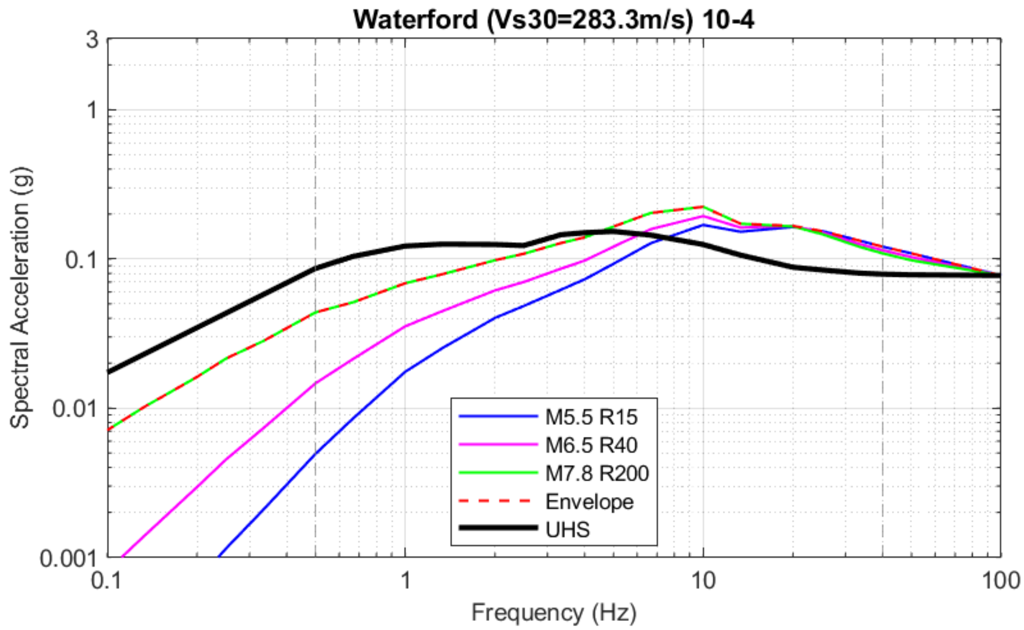


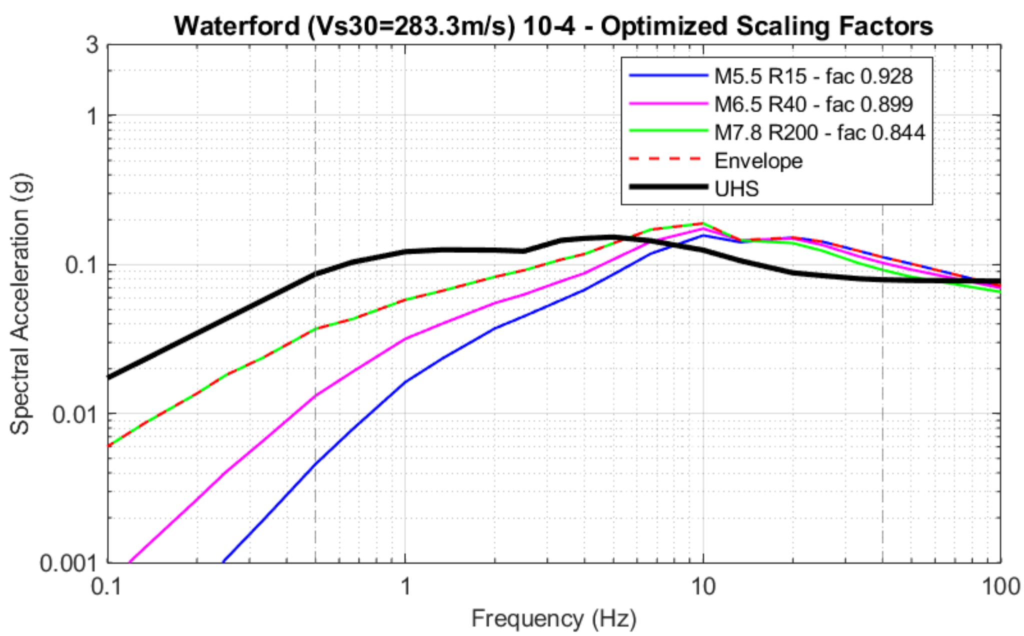
Appendix Figure A-24 Comparison of the scaled scenario spectra to the Surry (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



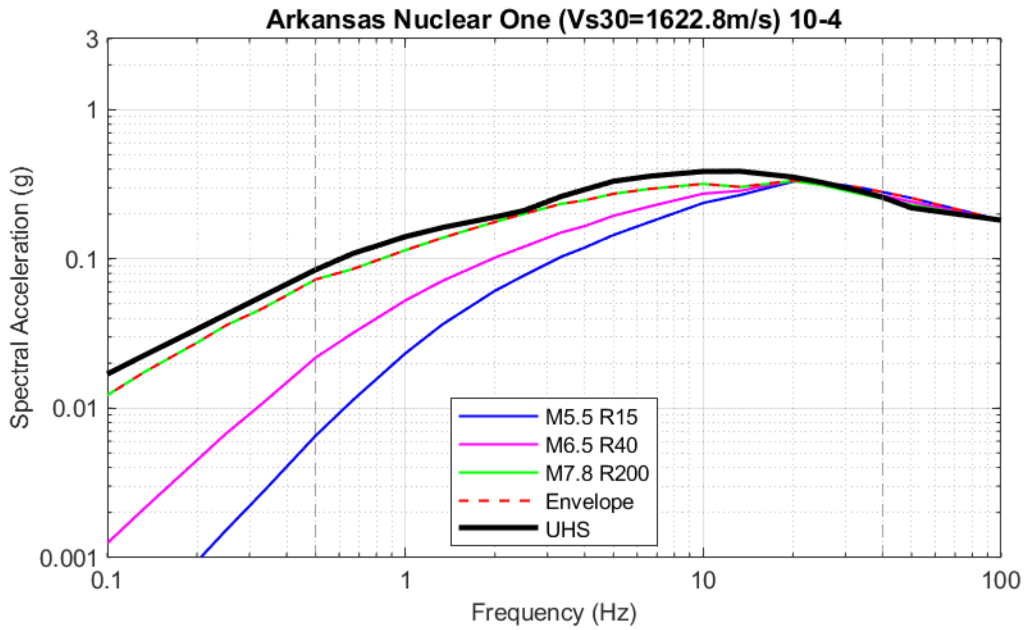


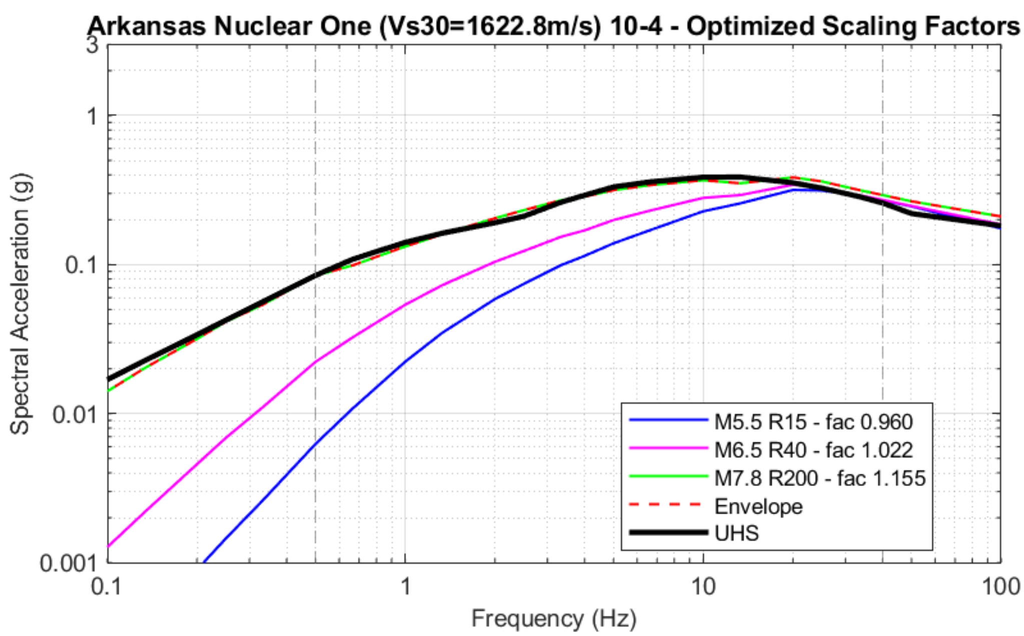
Appendix Figure A-25 Comparison of the scaled scenario spectra to the Vogtle (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



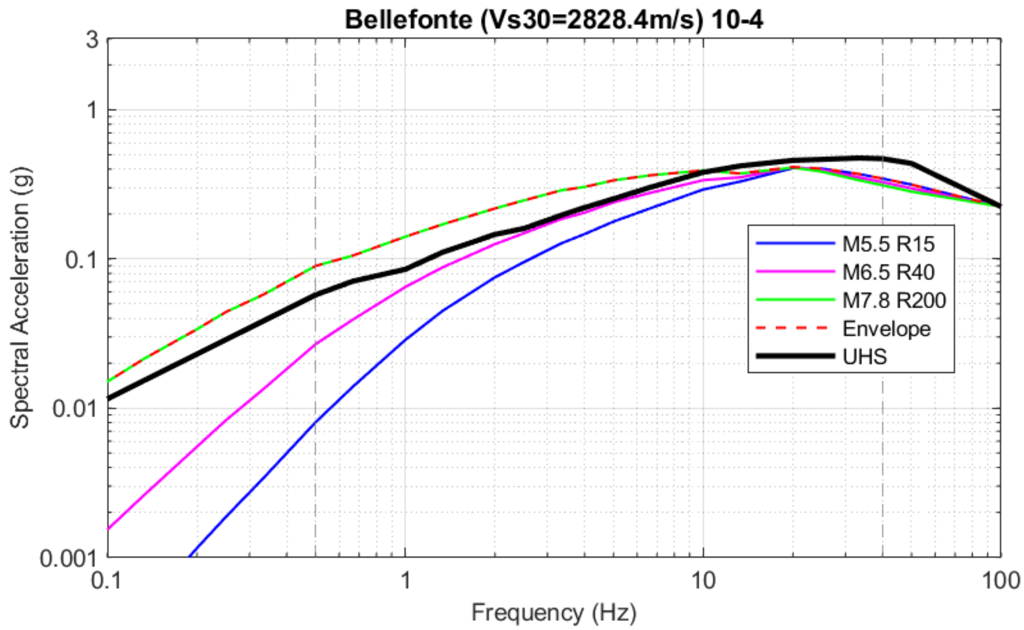


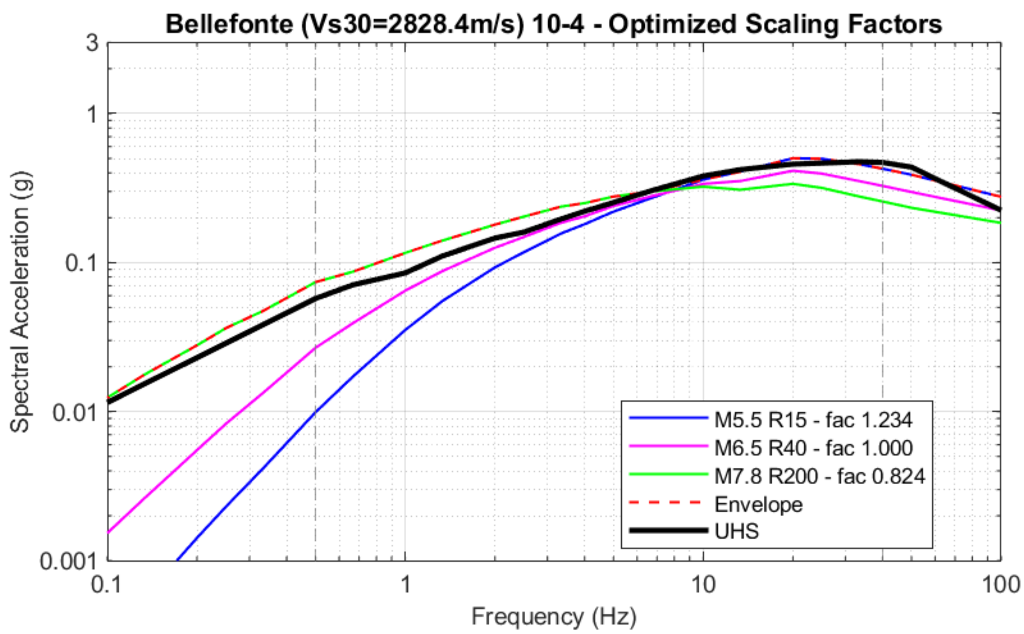
Appendix Figure A-26 Comparison of the scaled scenario spectra to the Waterford (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



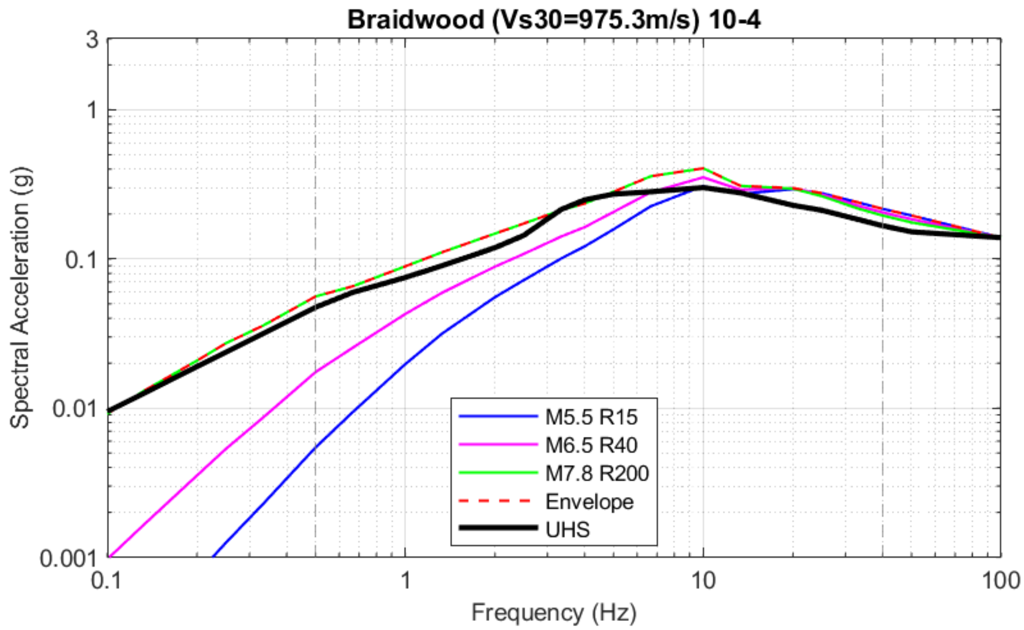


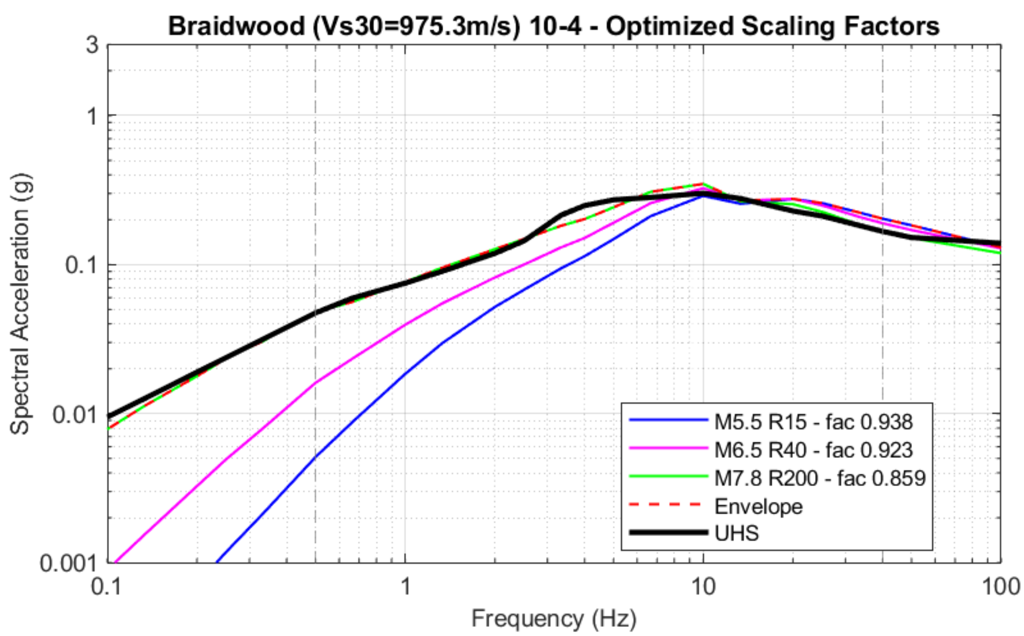
Appendix Figure A-27 Comparison of the scaled scenario spectra to the Arkansas Nuclear One (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



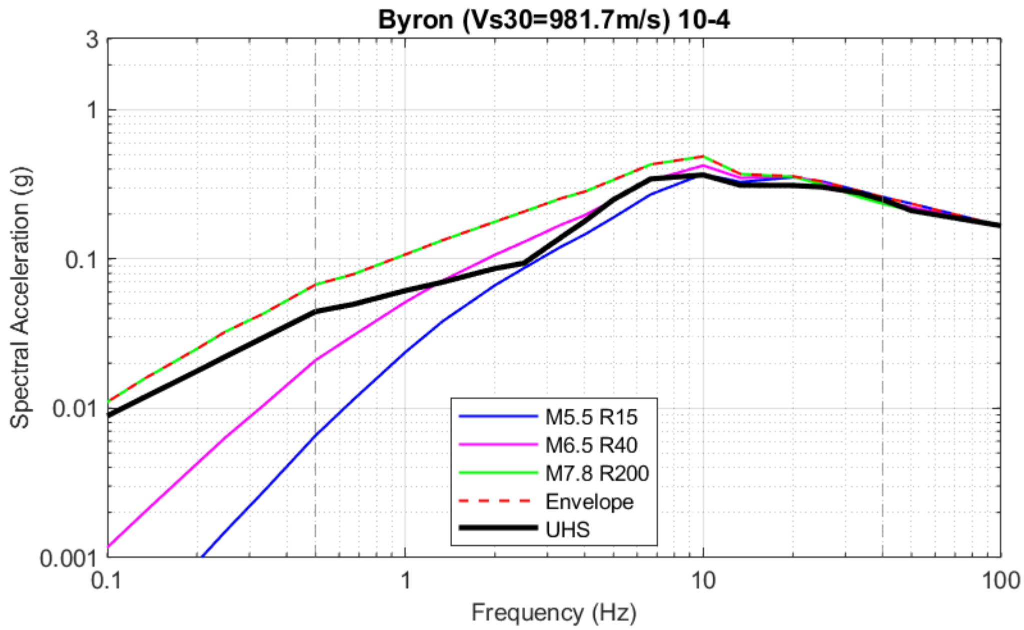


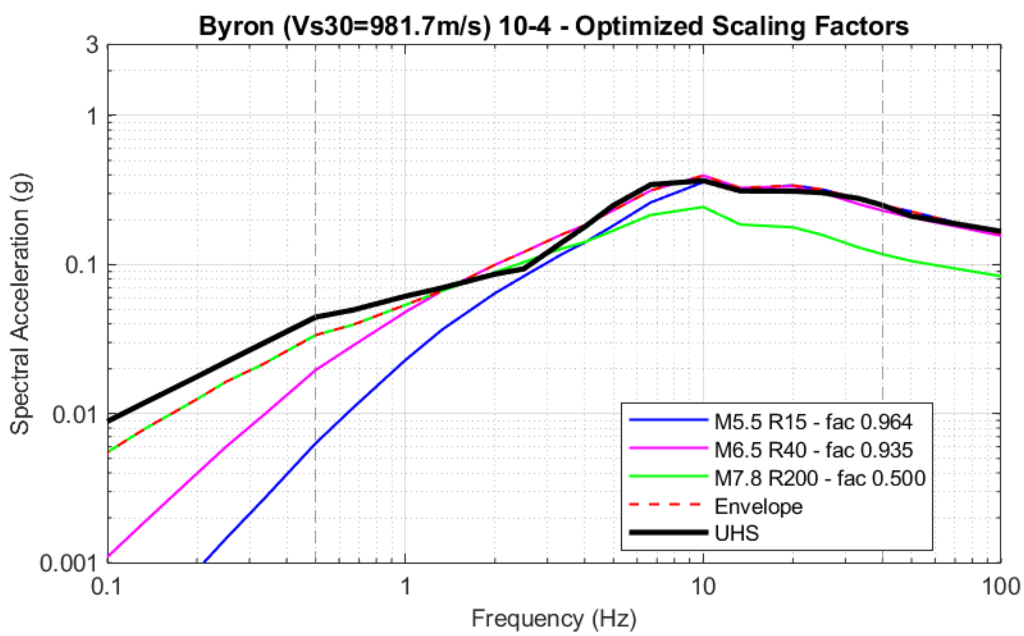
Appendix Figure A-28 Comparison of the scaled scenario spectra to the Bellefonte (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



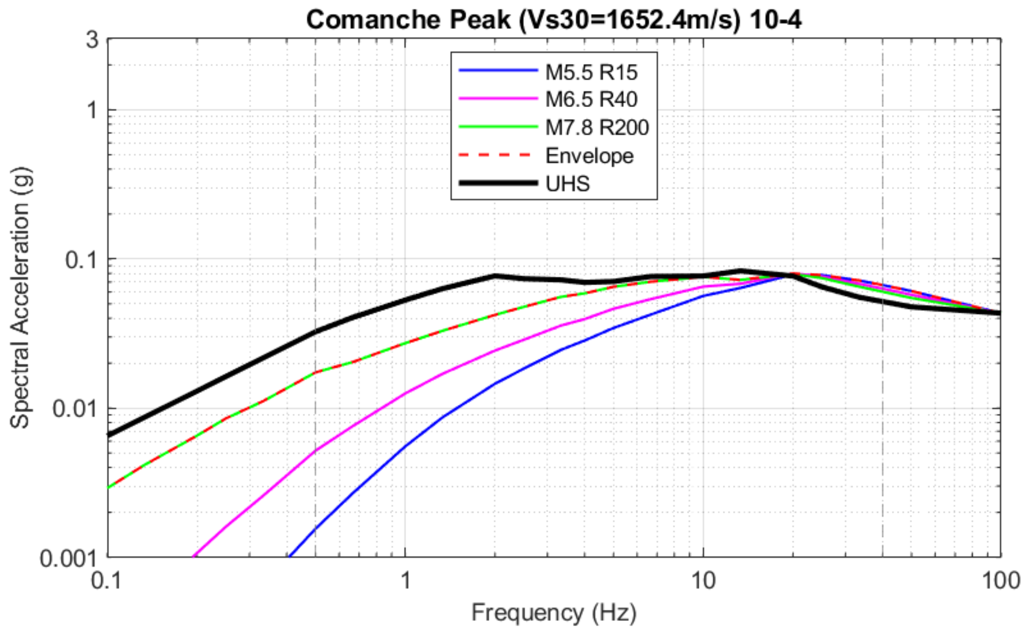


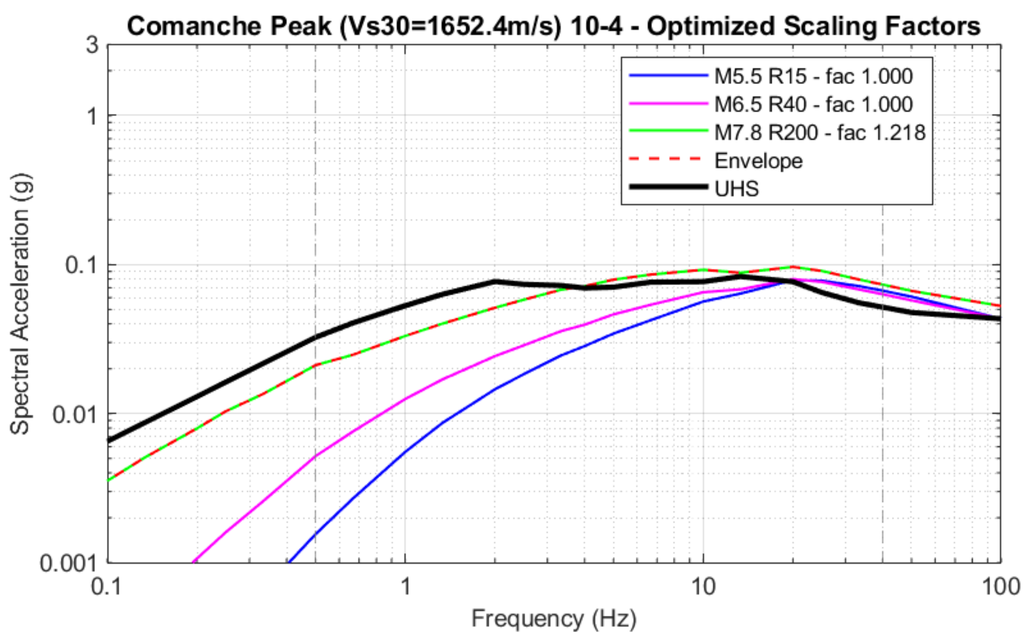
Appendix Figure A-29 Comparison of the scaled scenario spectra to the Braidwood (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



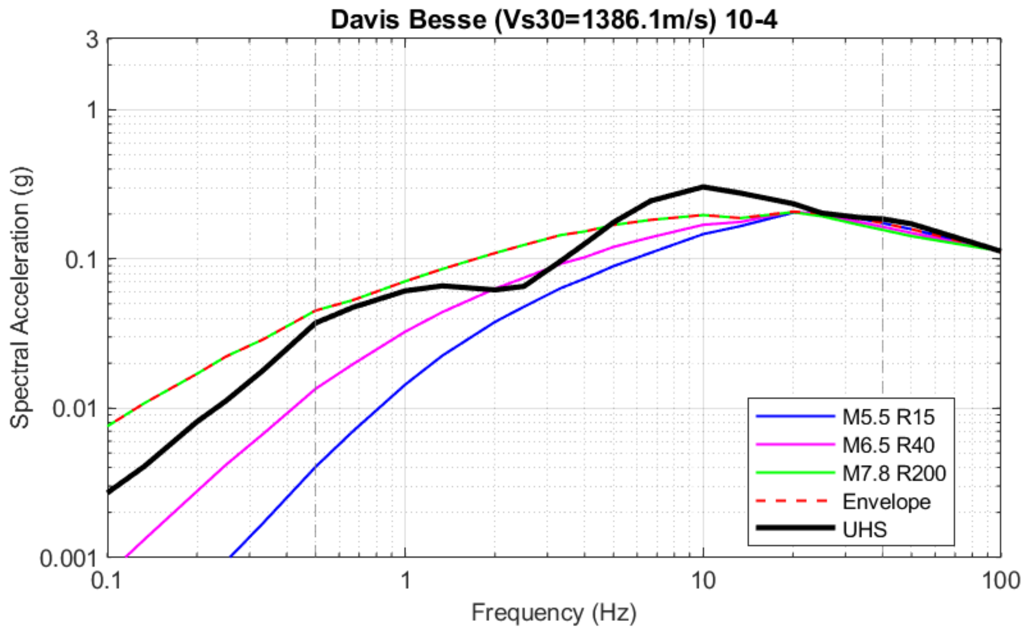


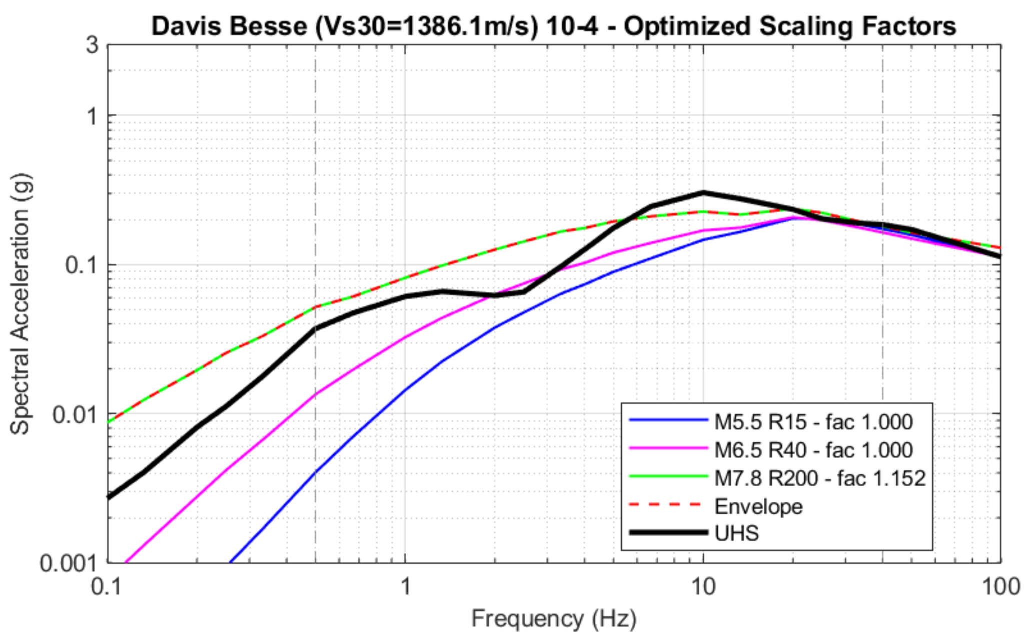
Appendix Figure A-30 Comparison of the scaled scenario spectra to the Byron (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



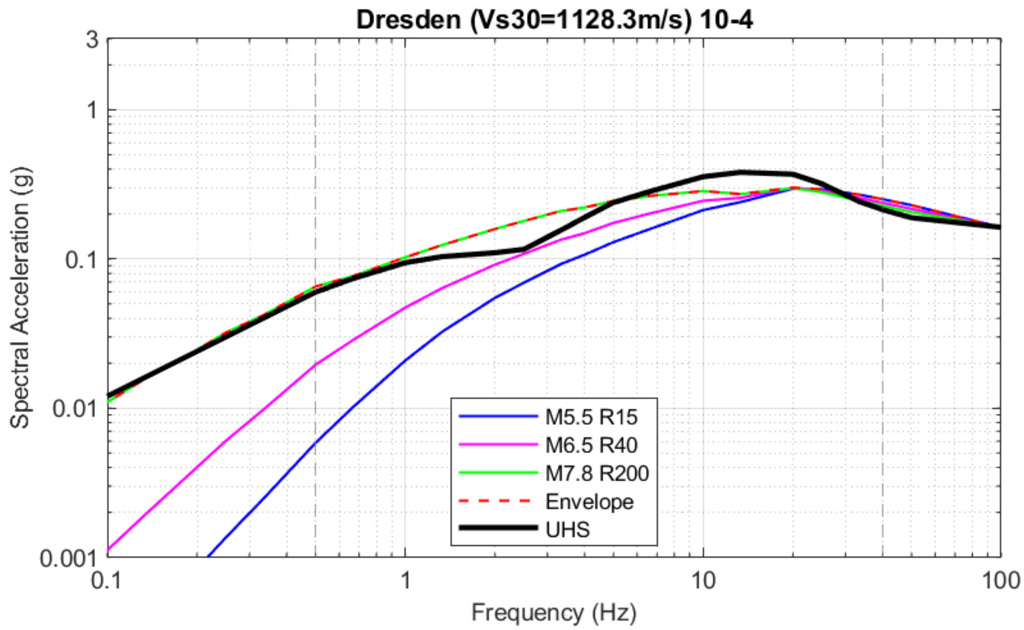


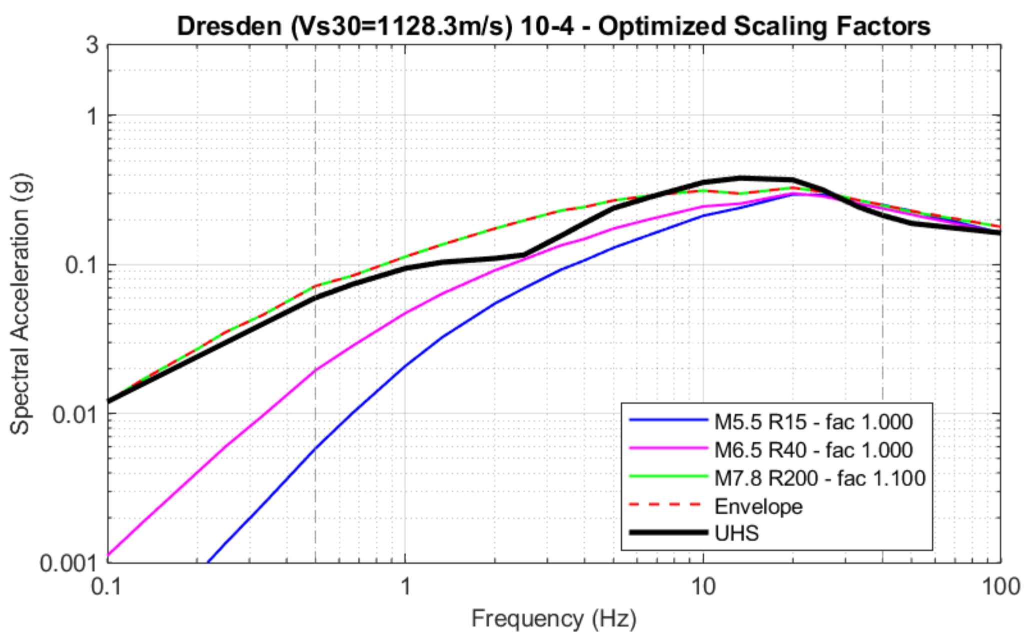
Appendix Figure A-31 Comparison of the scaled scenario spectra to the Comanche Peak (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



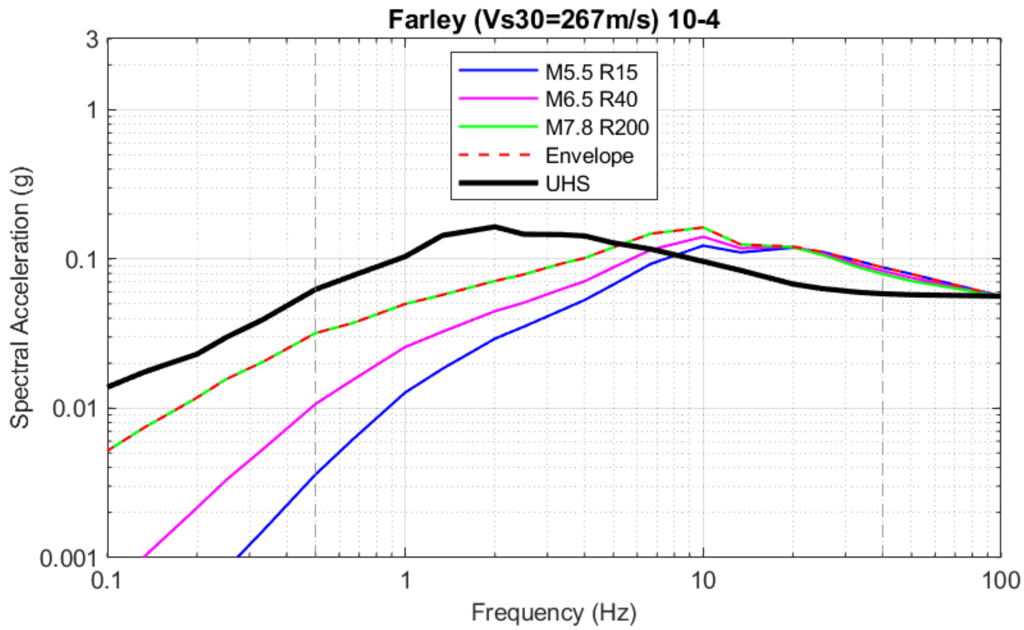


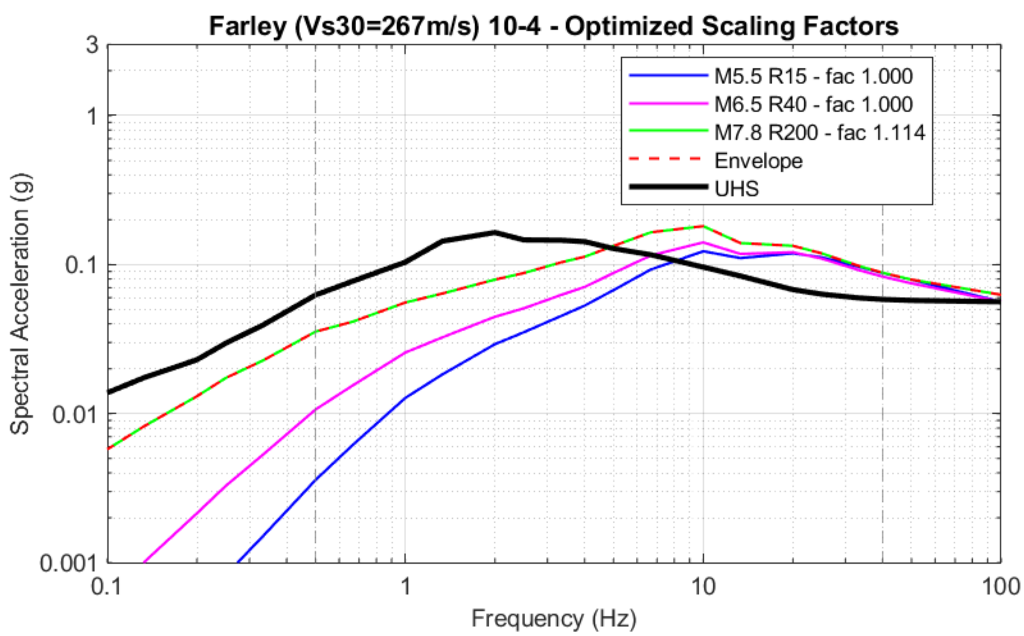
Appendix Figure A-32 Comparison of the scaled scenario spectra to the Davis Besse (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



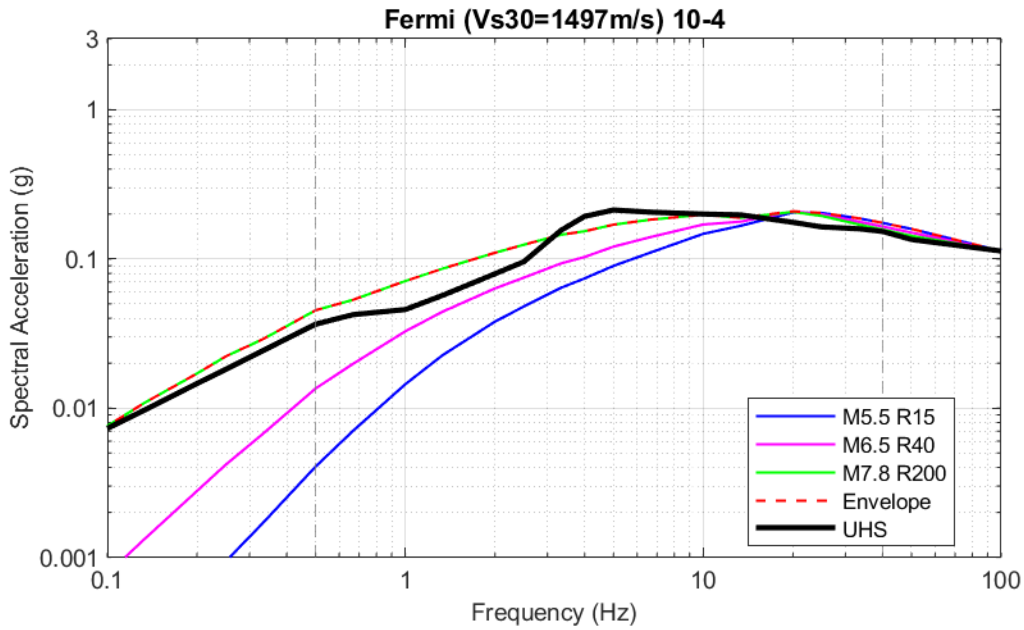


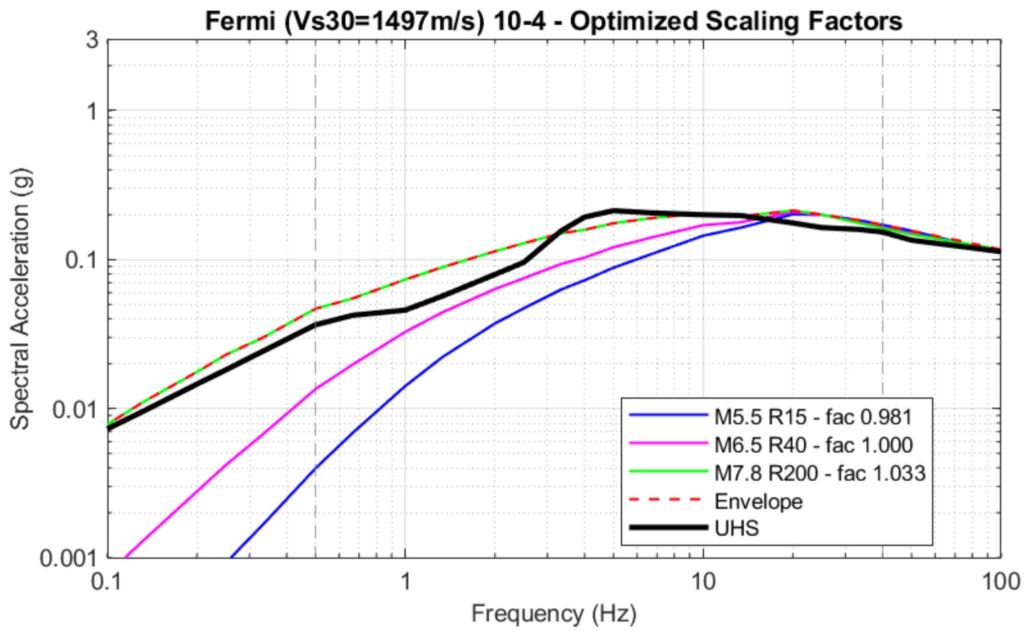
Appendix Figure A-33 Comparison of the scaled scenario spectra to the Dresden (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



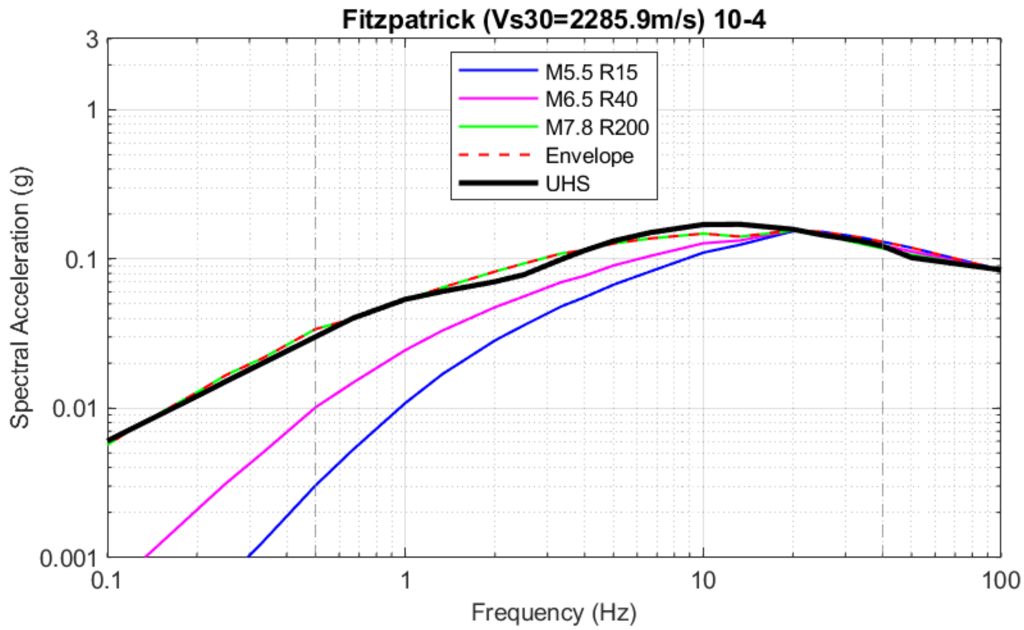


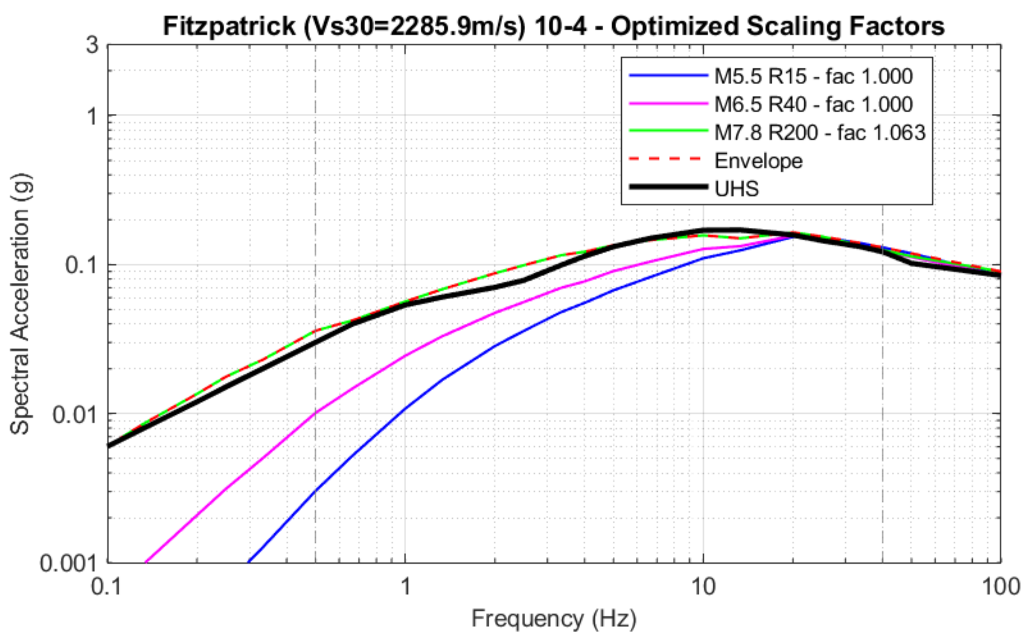
Appendix Figure A-34 Comparison of the scaled scenario spectra to the Farley (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



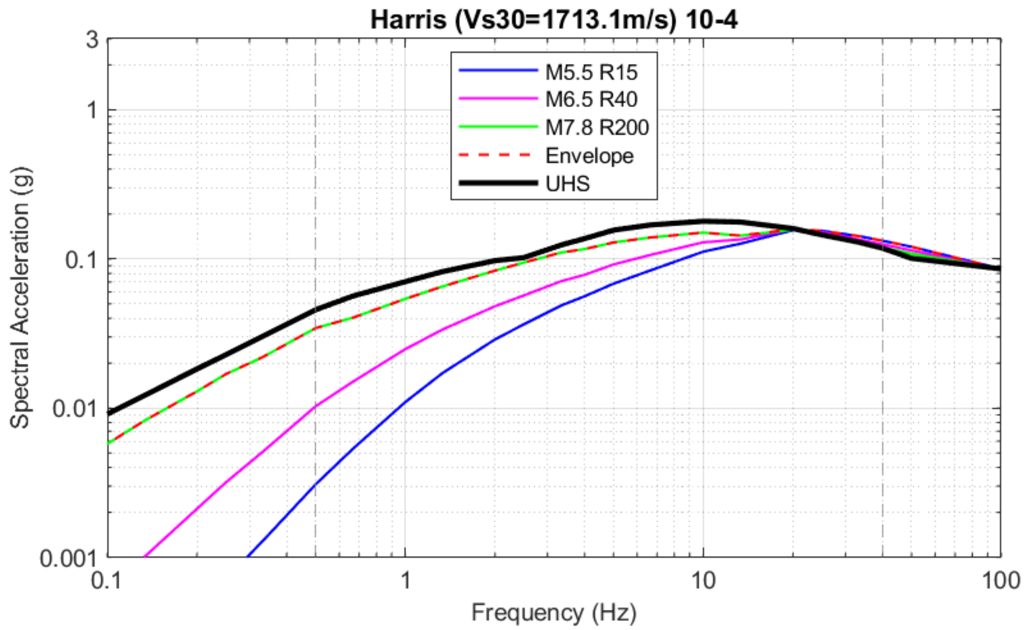


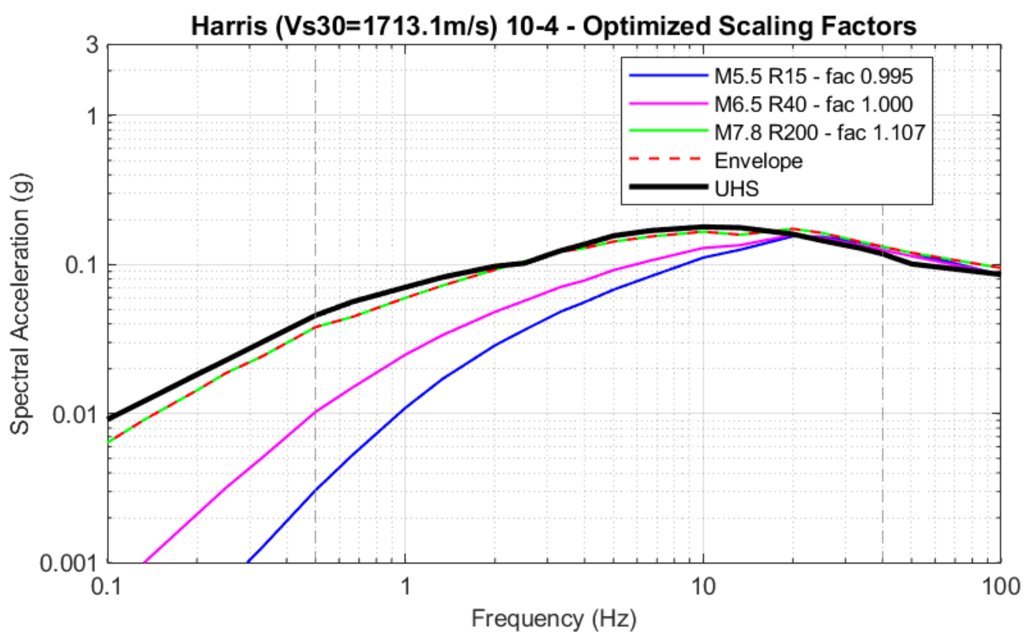
Appendix Figure A-35 Comparison of the scaled scenario spectra to the Fermi (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



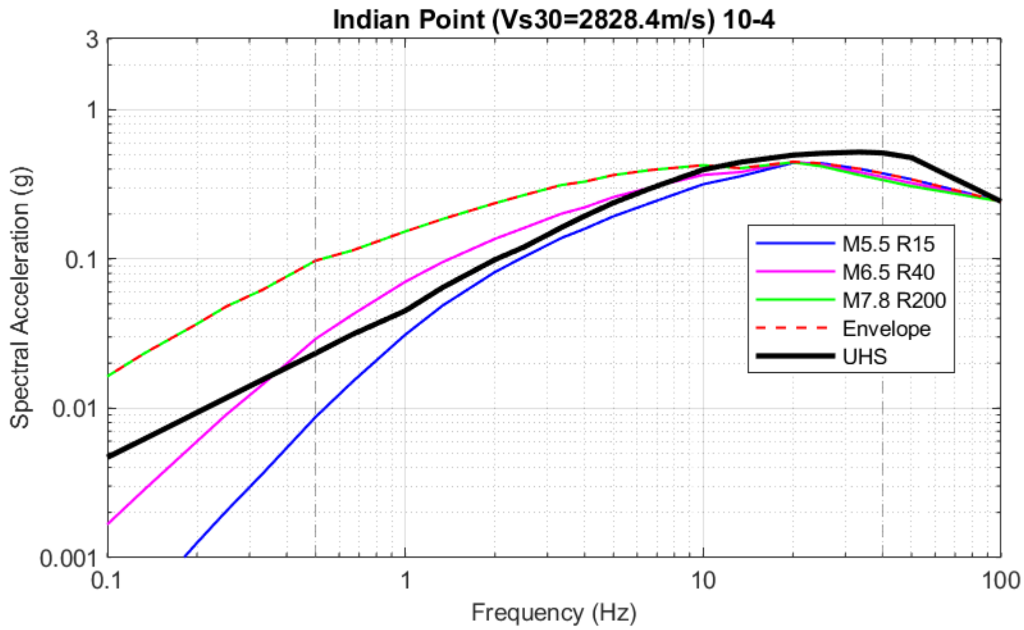


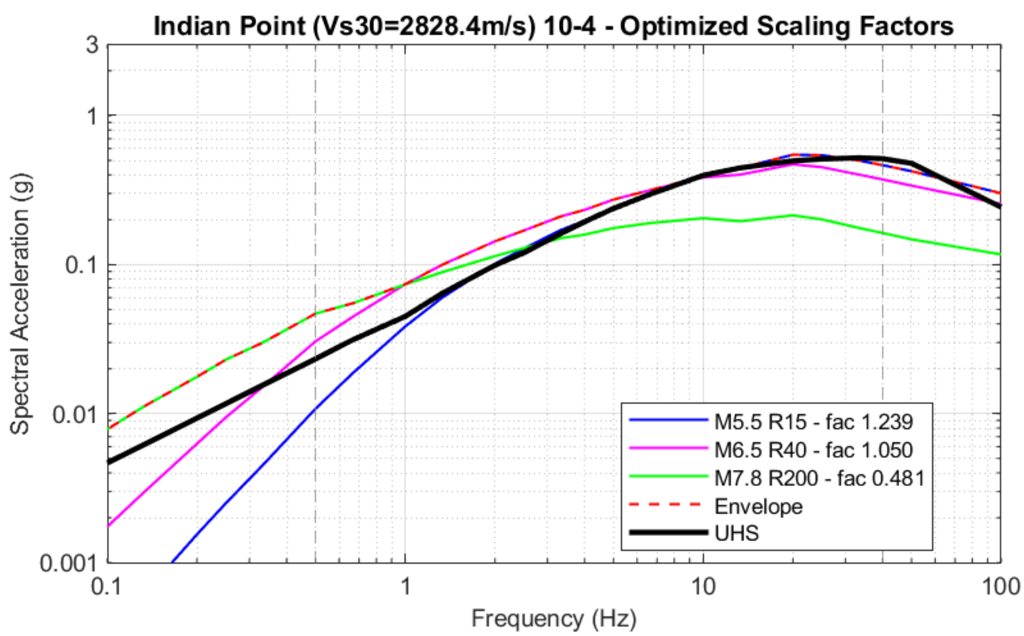
Appendix Figure A-36 Comparison of the scaled scenario spectra to the Fitzpatrick (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



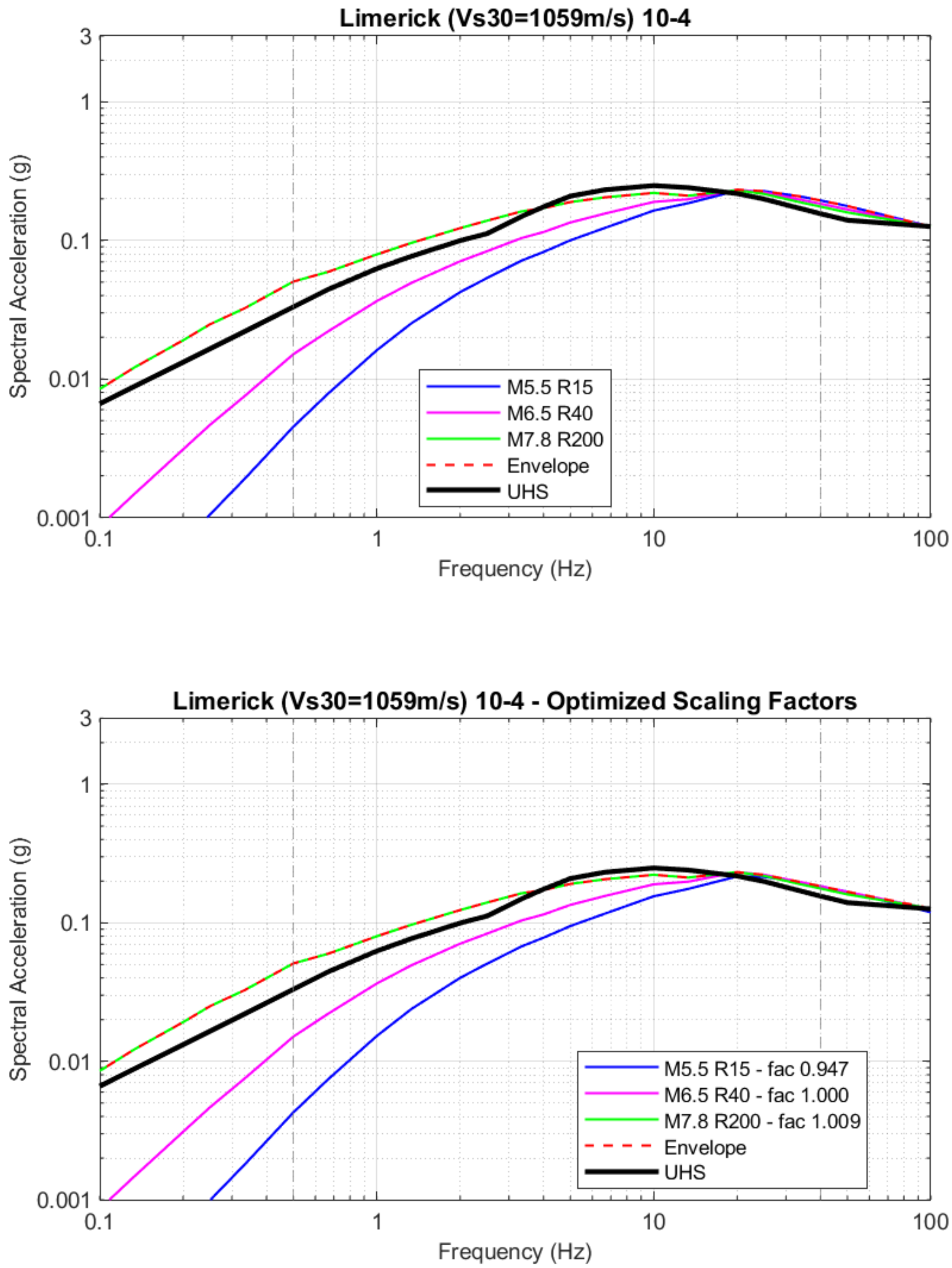


Appendix Figure A-37 Comparison of the scaled scenario spectra to the Harris (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

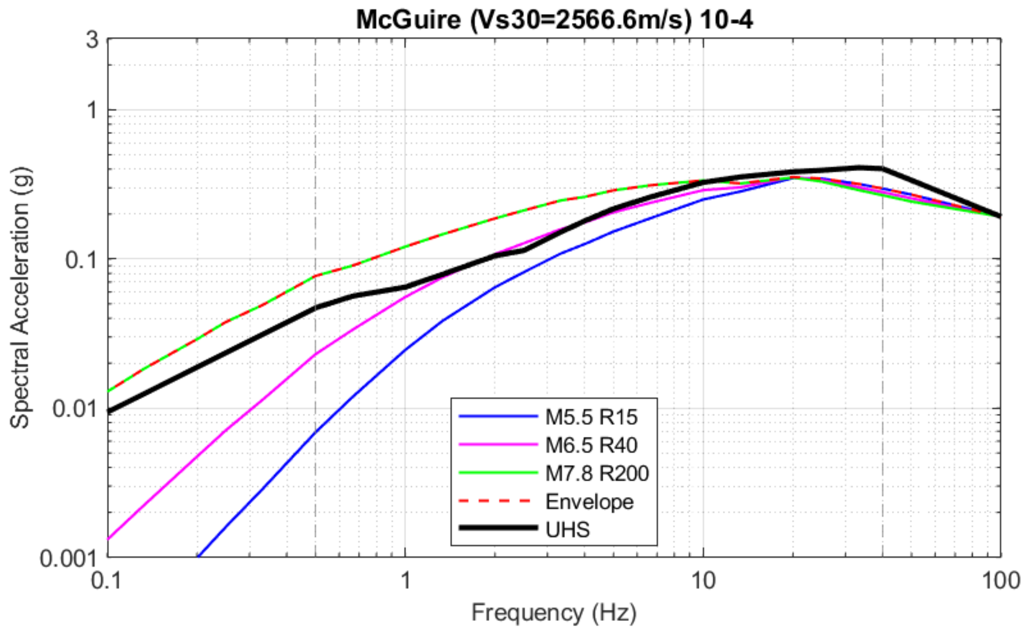


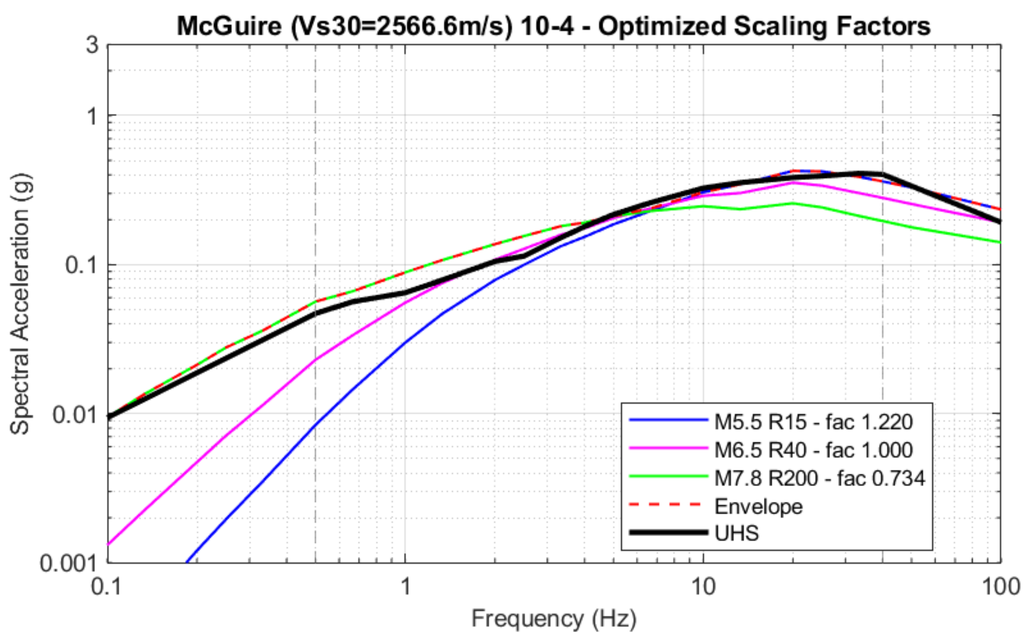


Appendix Figure A-38 Comparison of the scaled scenario spectra to the Indian Pt. (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

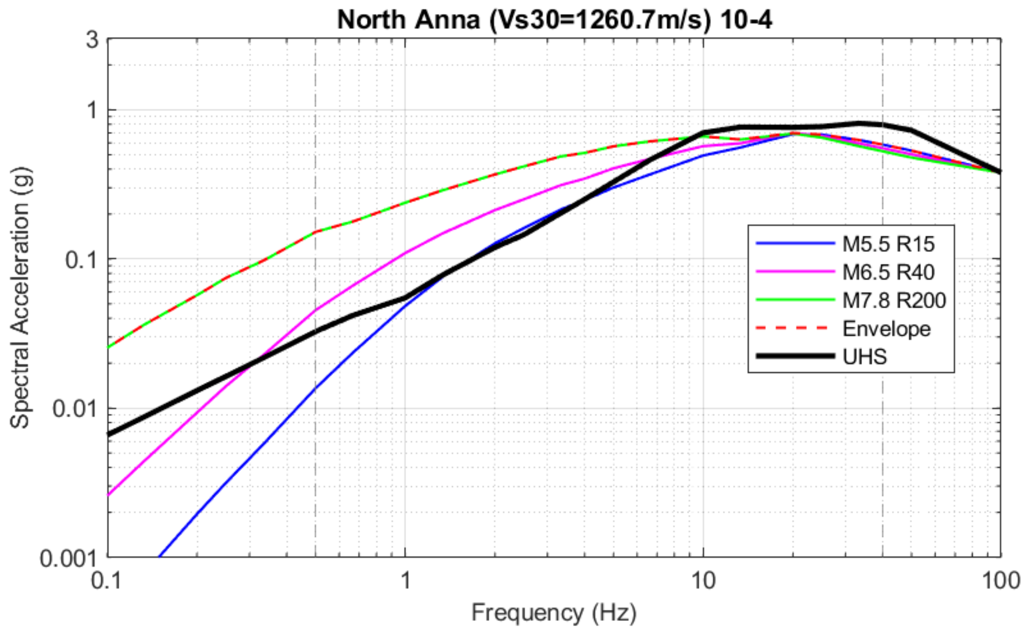


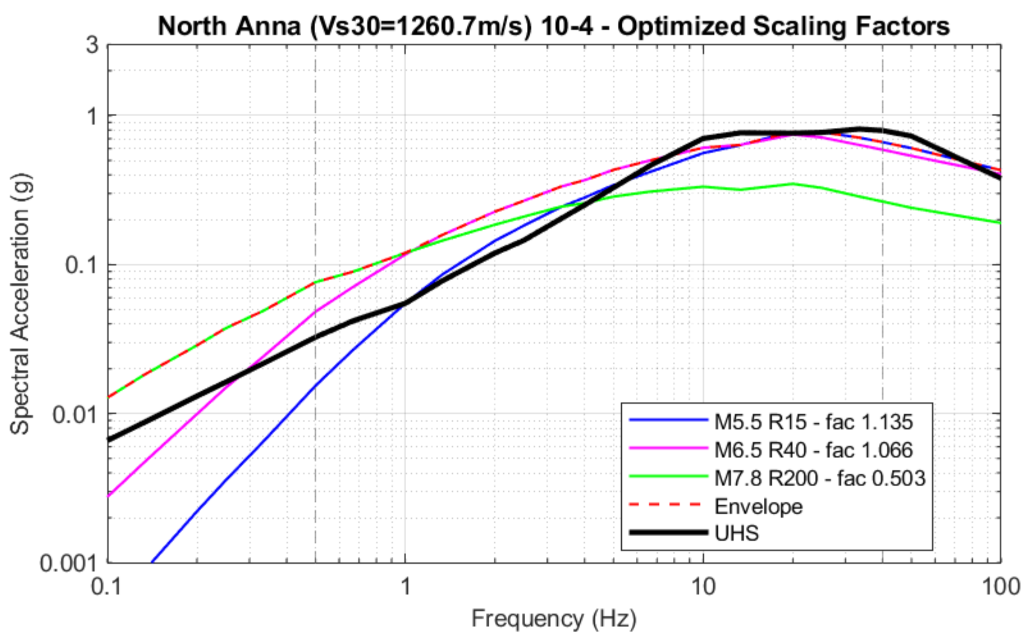
Appendix Figure A-39 Comparison of the scaled scenario spectra to the Limerick (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



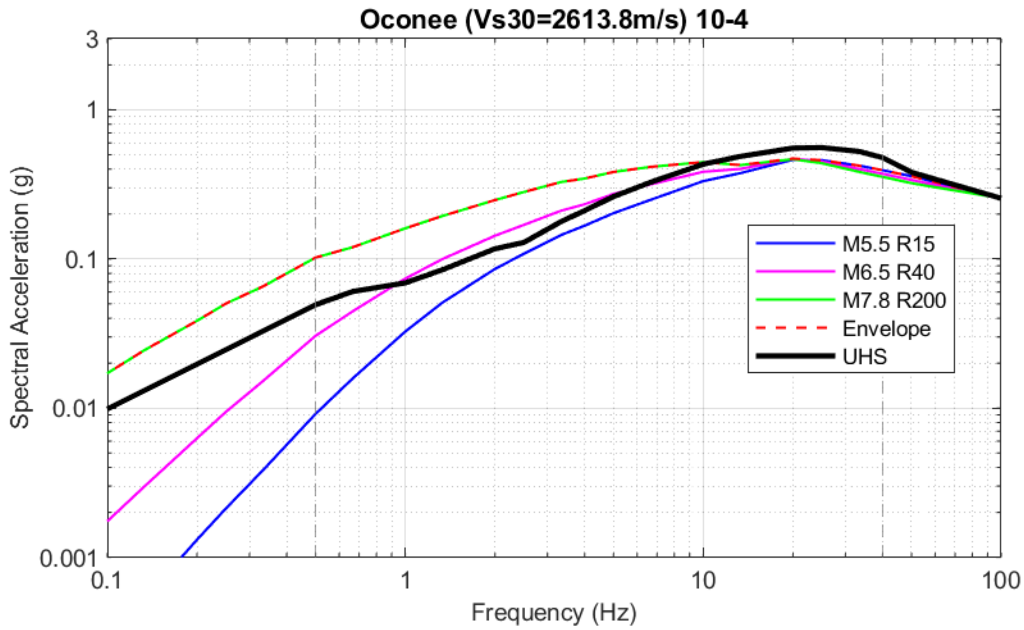


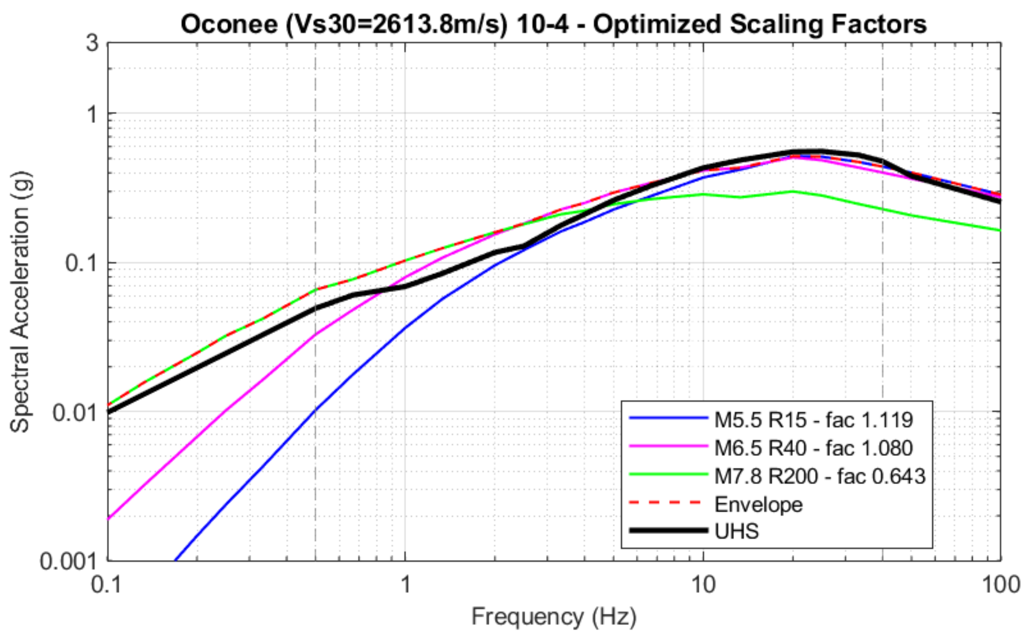
Appendix Figure A-40 Comparison of the scaled scenario spectra to the McGuire (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



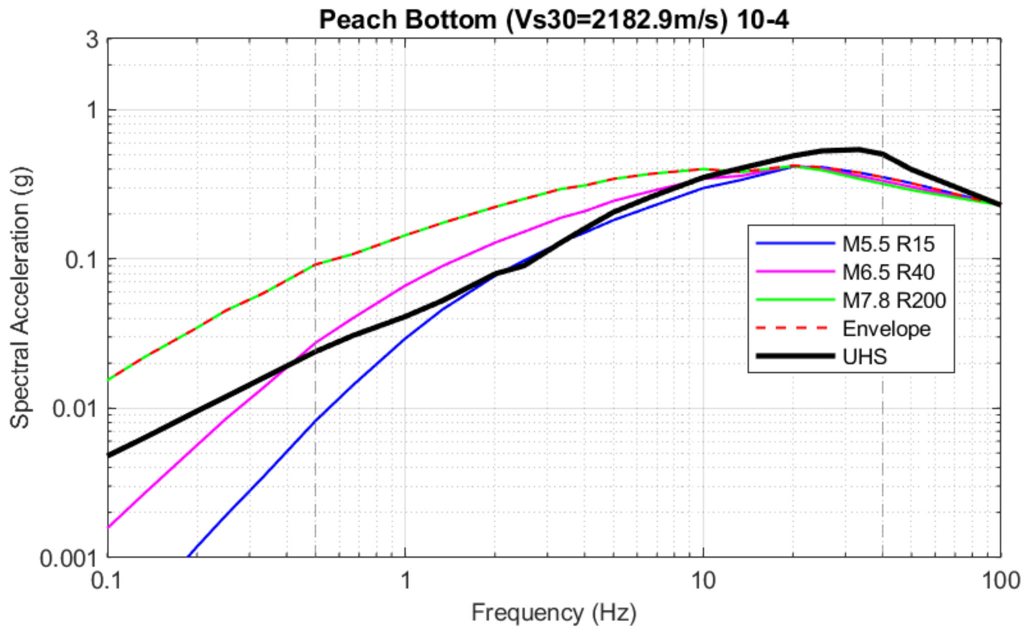


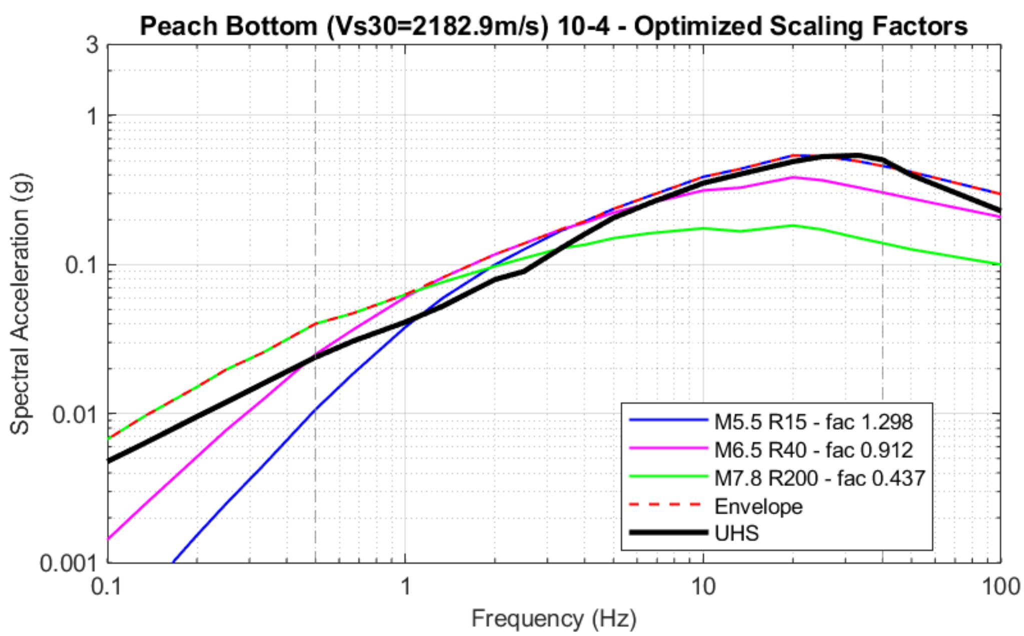
Appendix Figure A-41 Comparison of the scaled scenario spectra to the North Anna (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



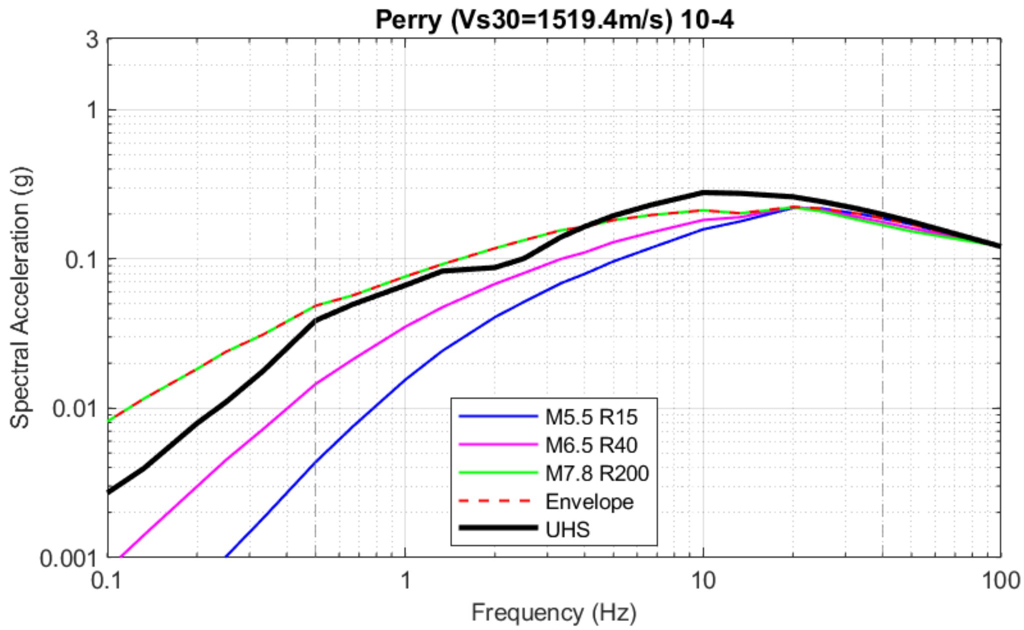


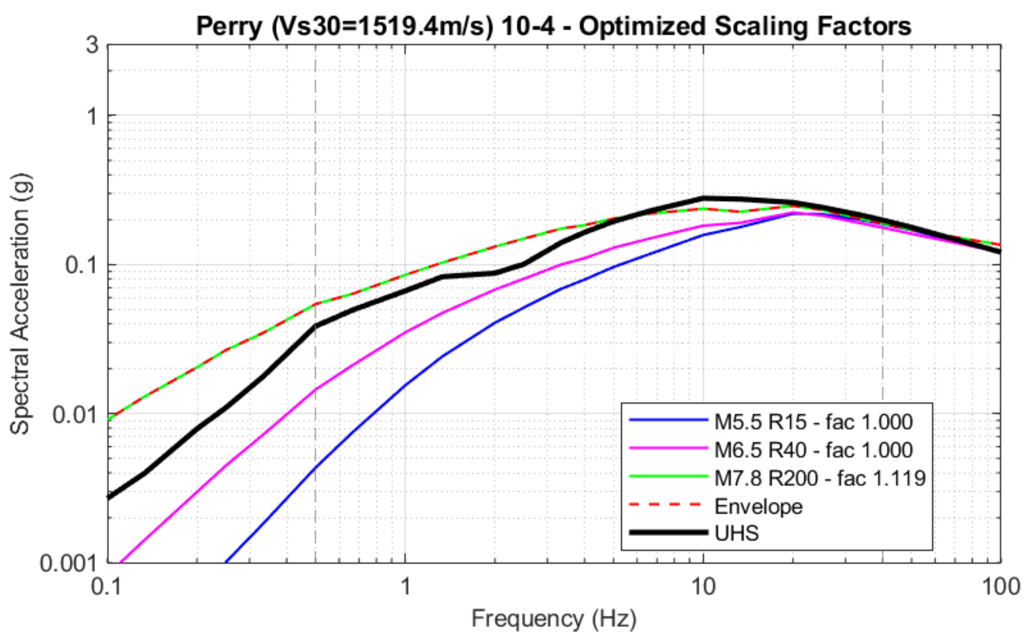
Appendix Figure A-42 Comparison of the scaled scenario spectra to the Oconee (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



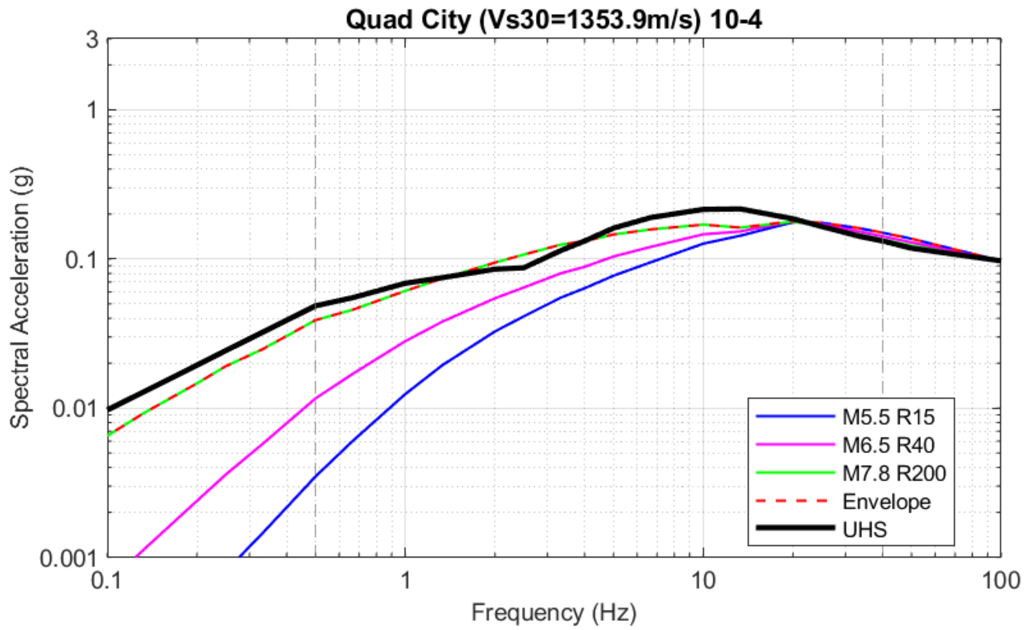


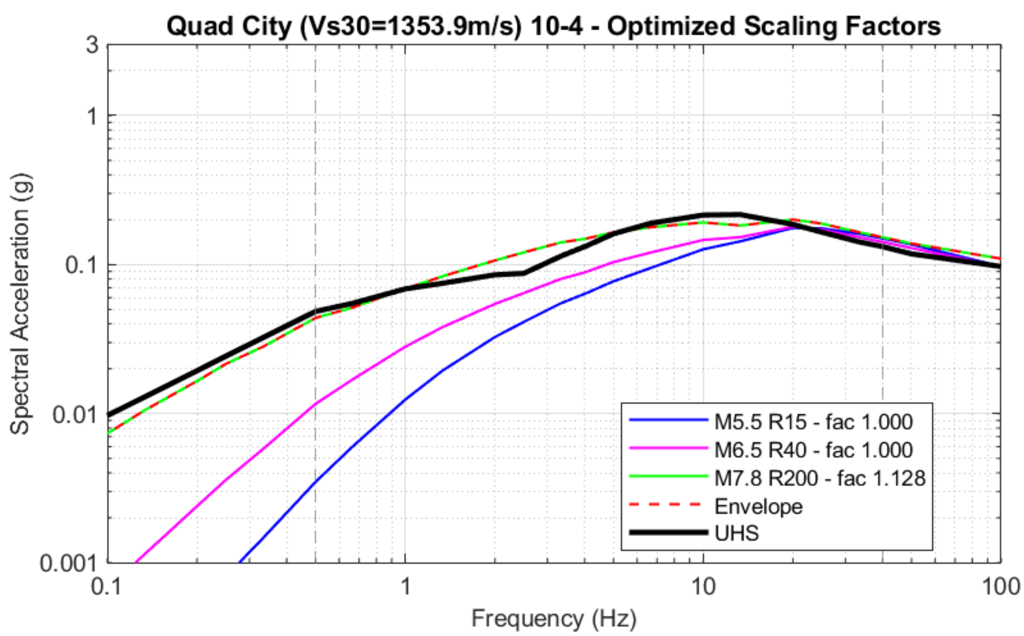
Appendix Figure A-43 Comparison of the scaled scenario spectra to the Peach Bottom (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



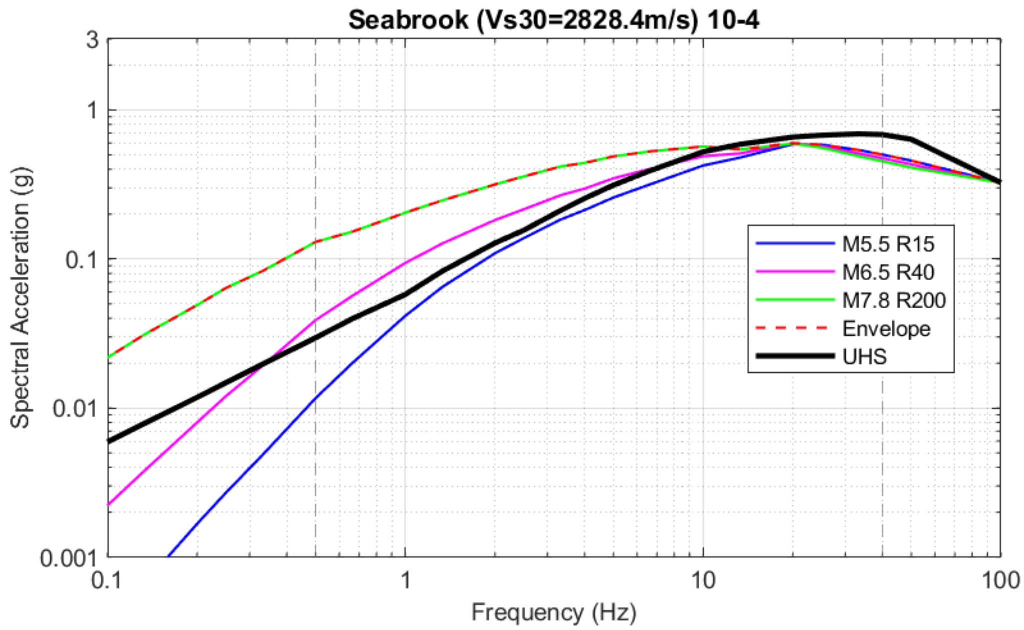


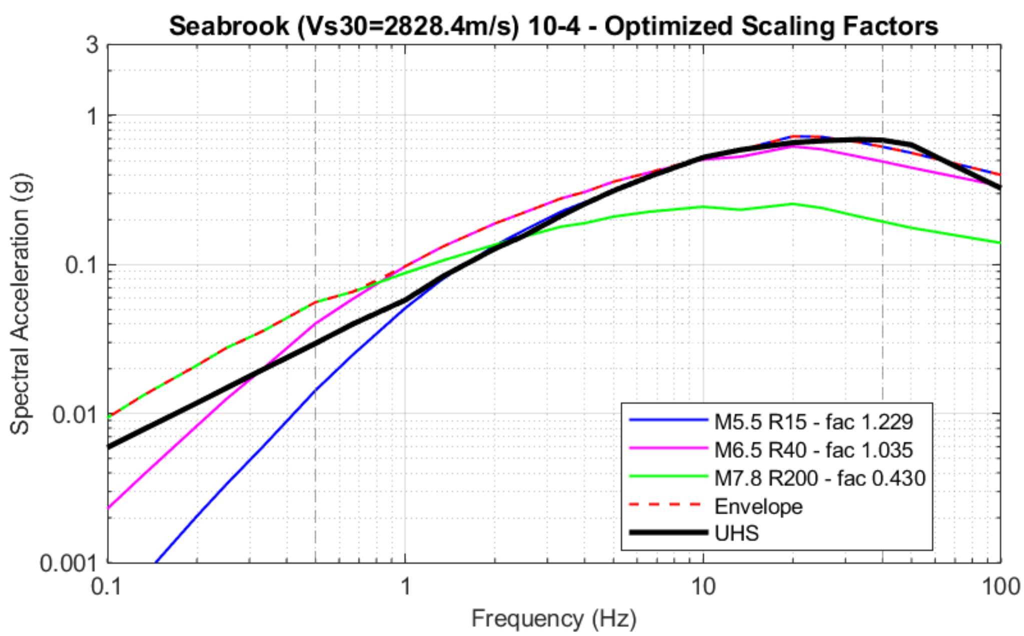
Appendix Figure A-44 Comparison of the scaled scenario spectra to the Perry (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



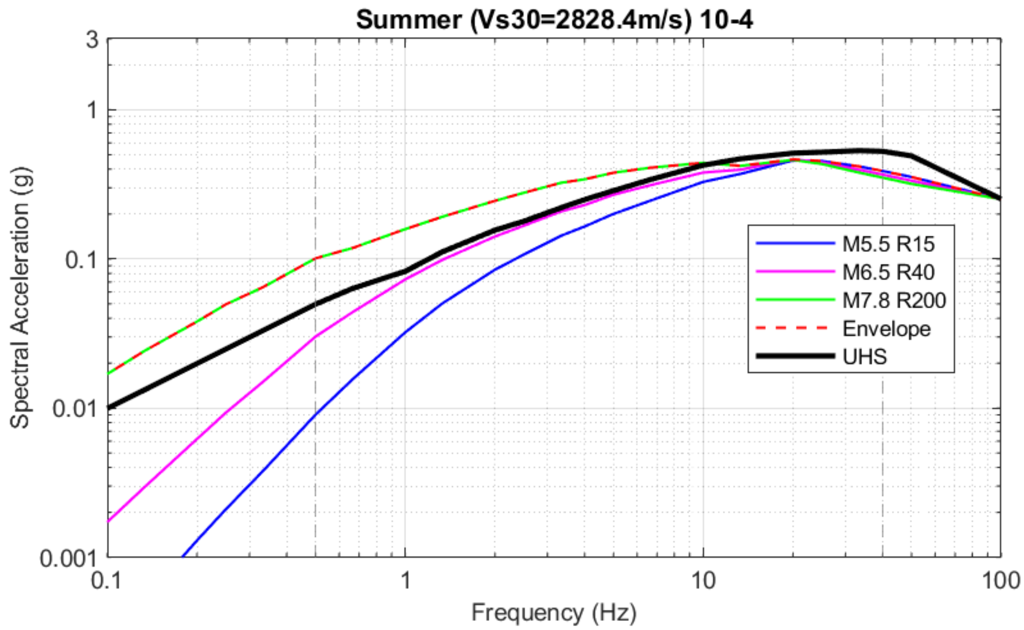


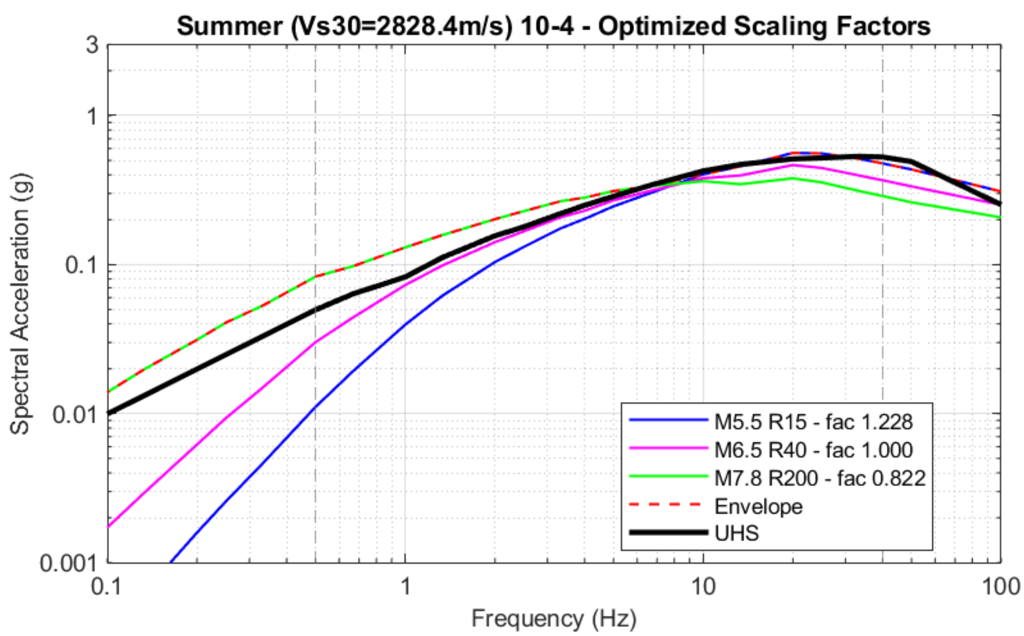
Appendix Figure A-45 Comparison of the scaled scenario spectra to the Quad City (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



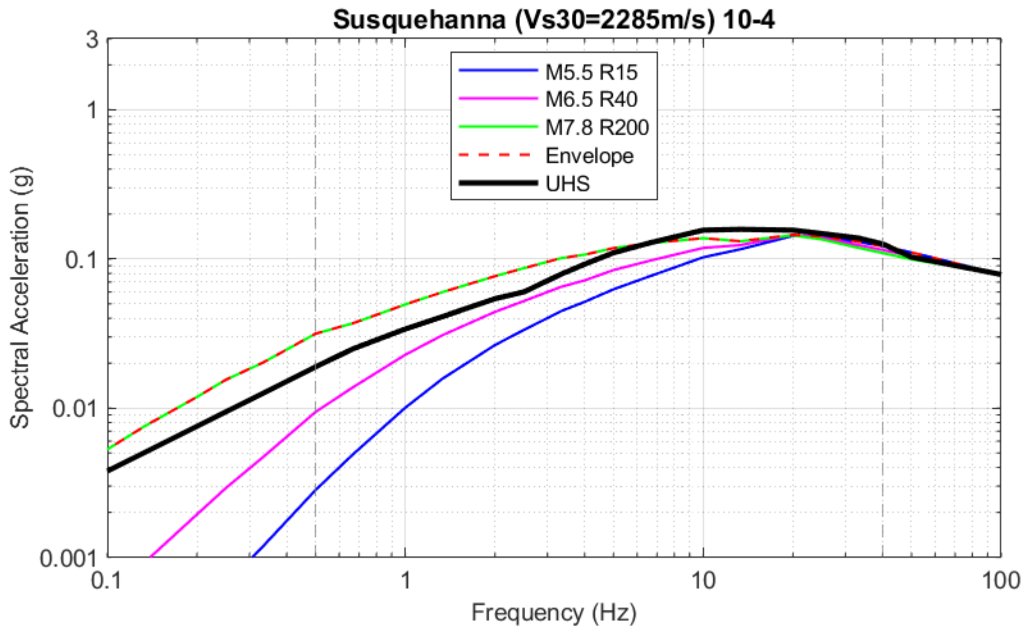


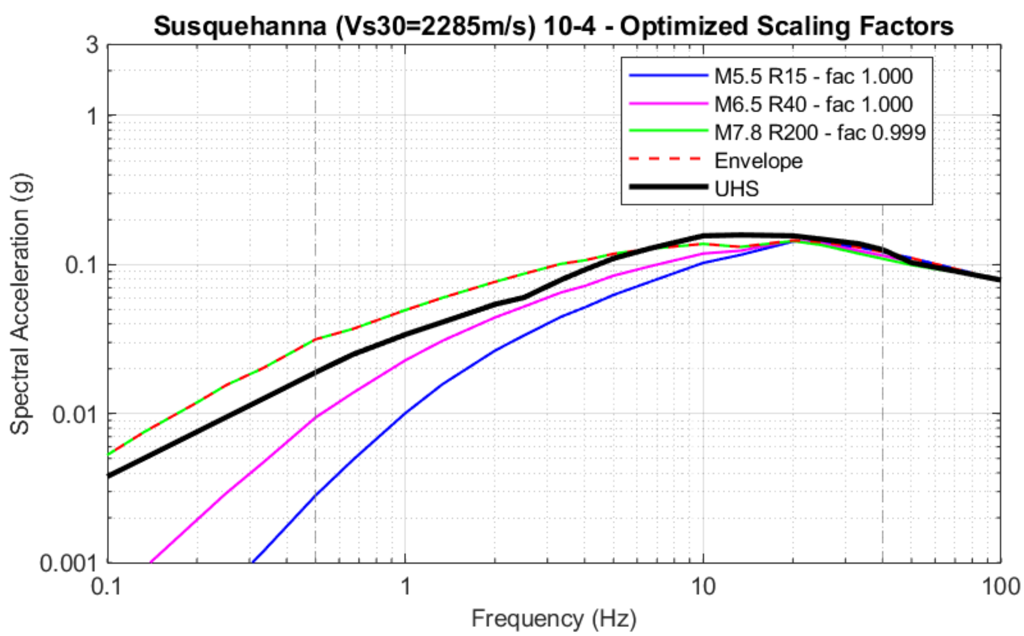
Appendix Figure A-46 Comparison of the scaled scenario spectra to the Seabrook (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



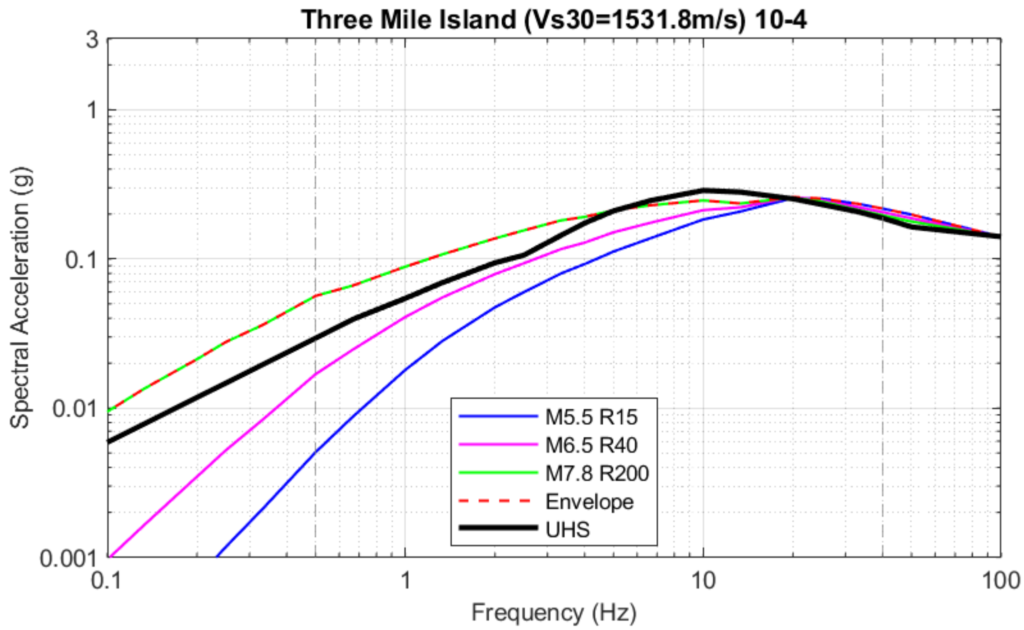


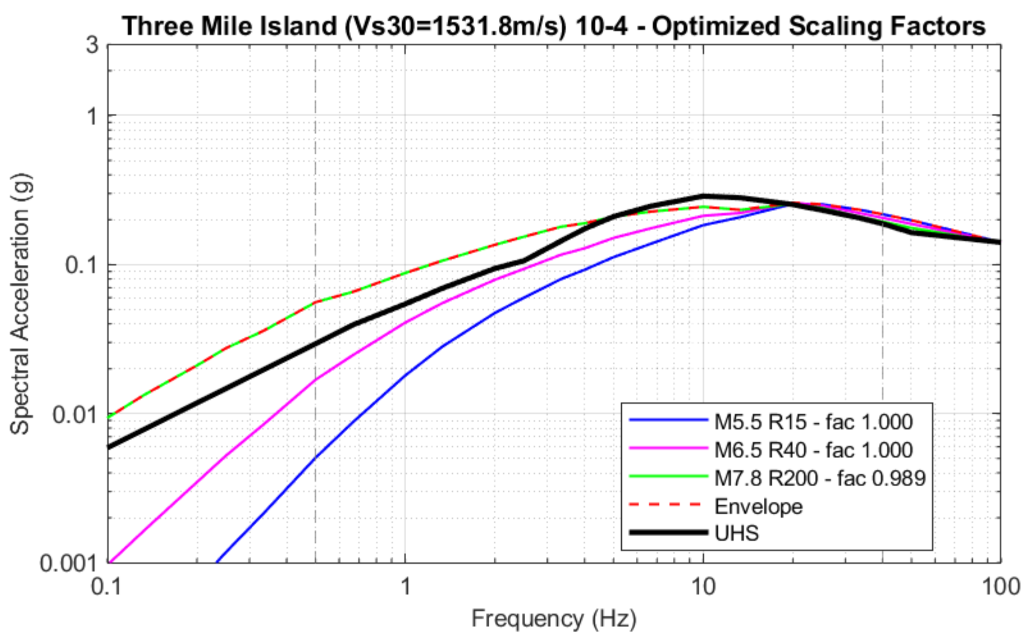
Appendix Figure A-47 Comparison of the scaled scenario spectra to the Summer (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



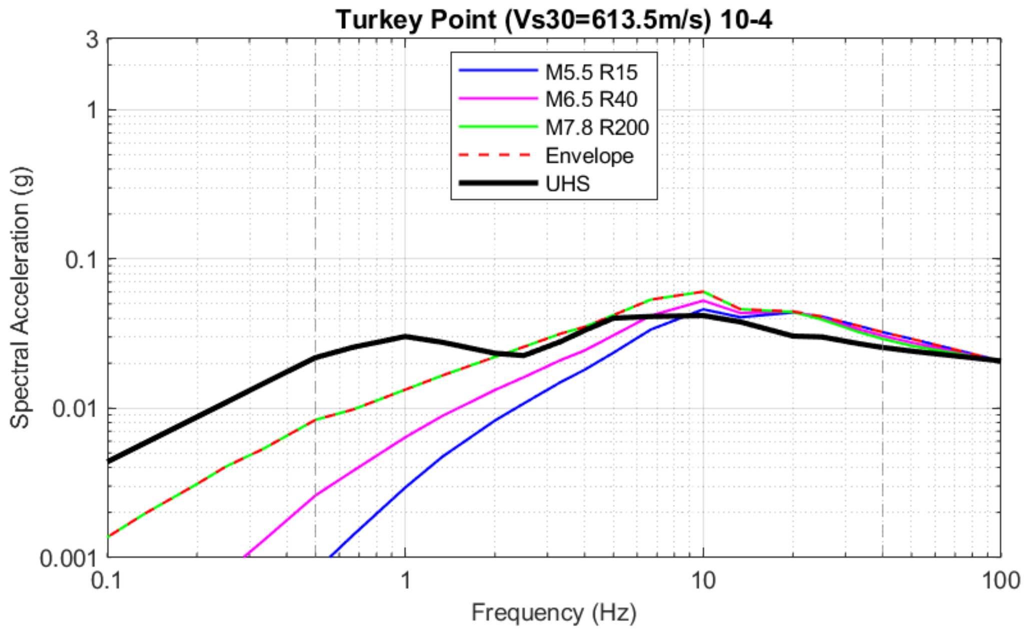


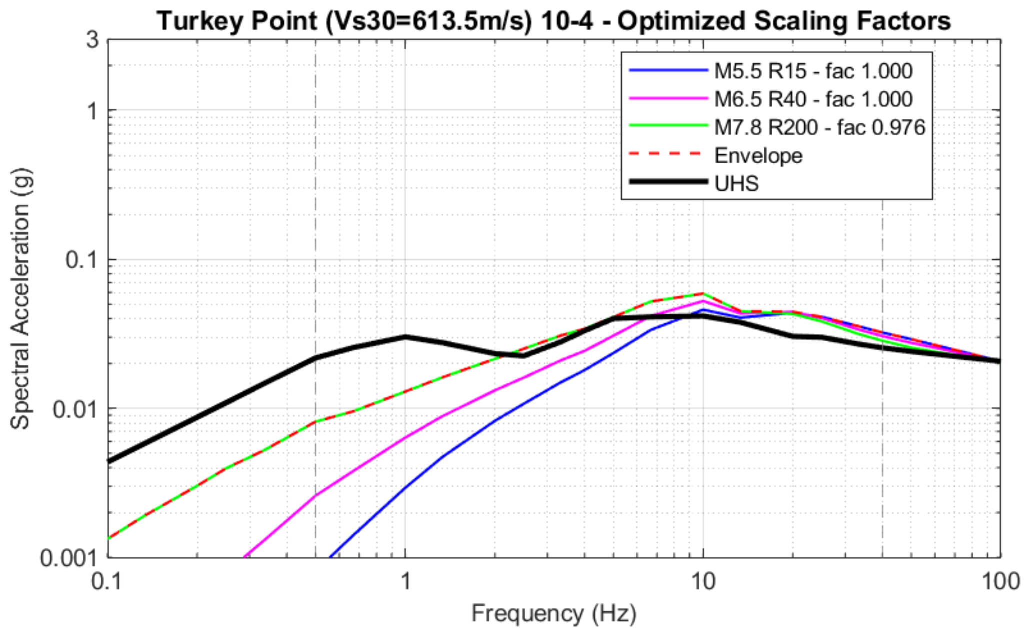
Appendix Figure A-48 Comparison of the scaled scenario spectra to the Susquehana (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



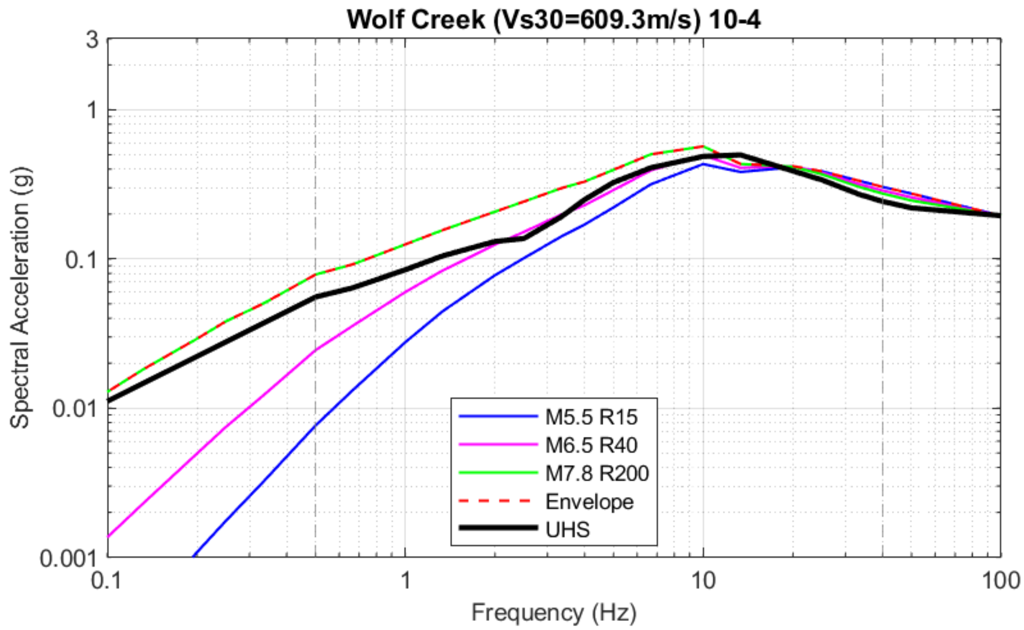


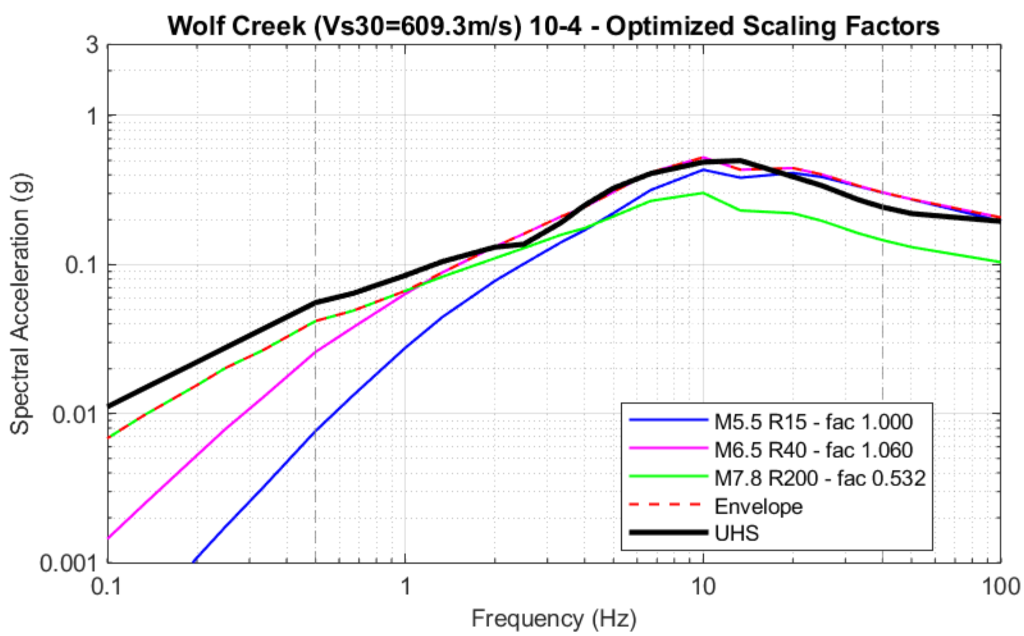
Appendix Figure A-49 Comparison of the scaled scenario spectra to the Three Mile Island (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



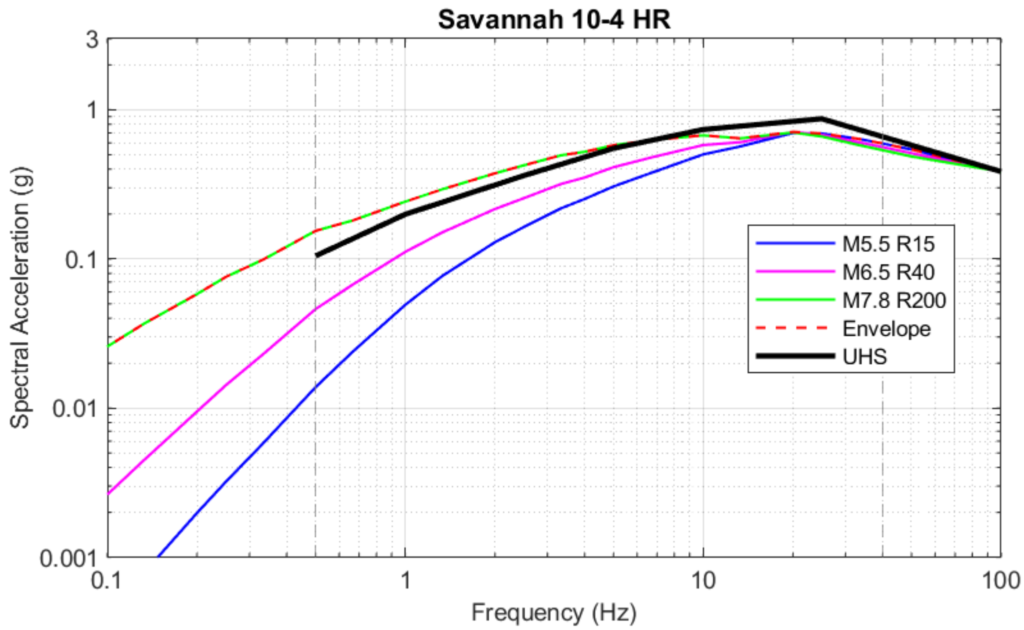


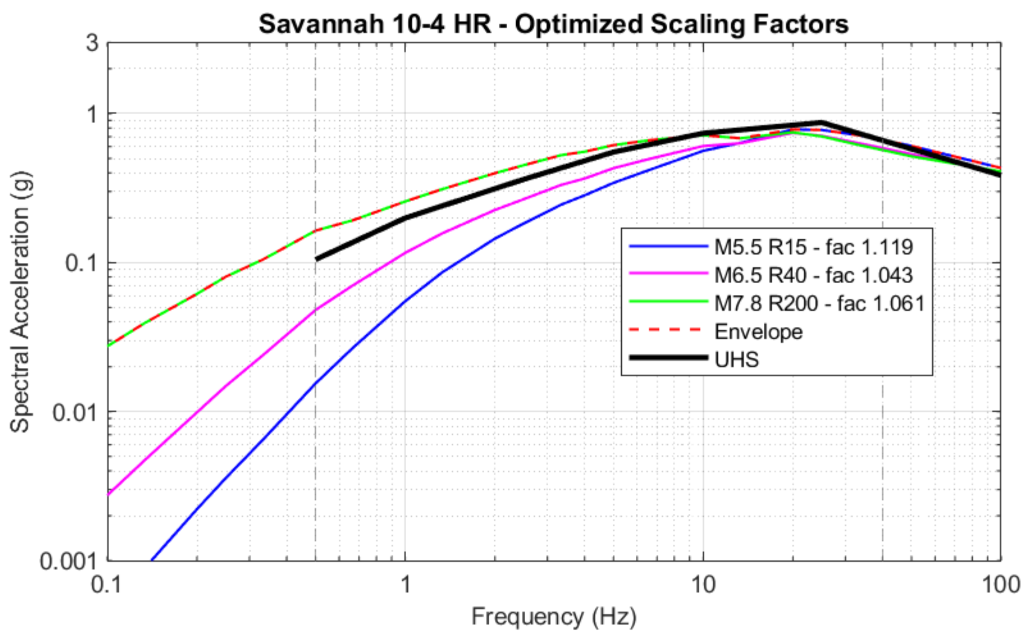
Appendix Figure A-50 Comparison of the scaled scenario spectra to the Turkey Point (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



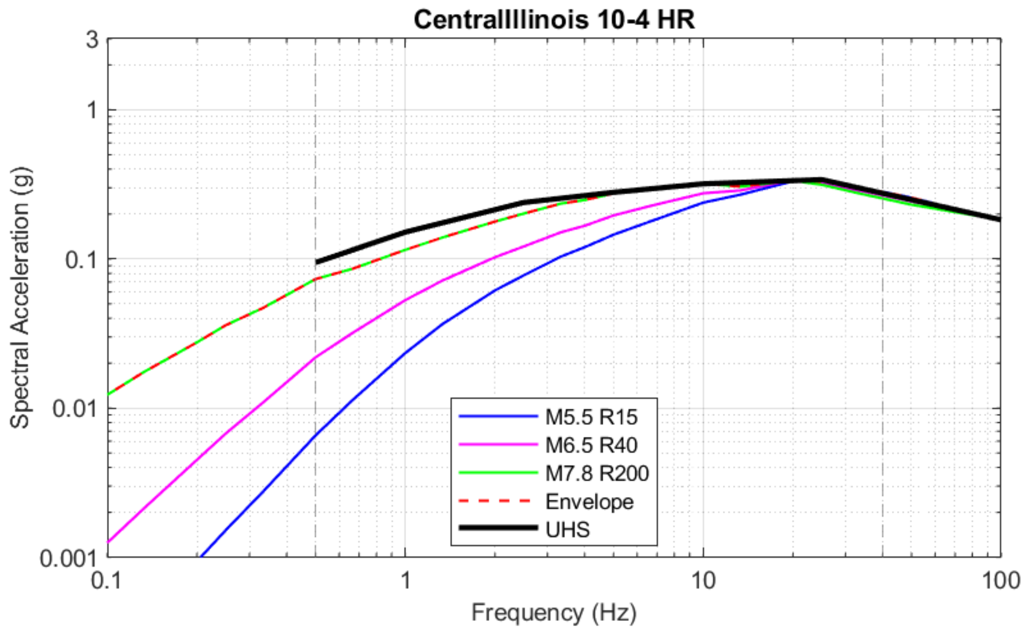


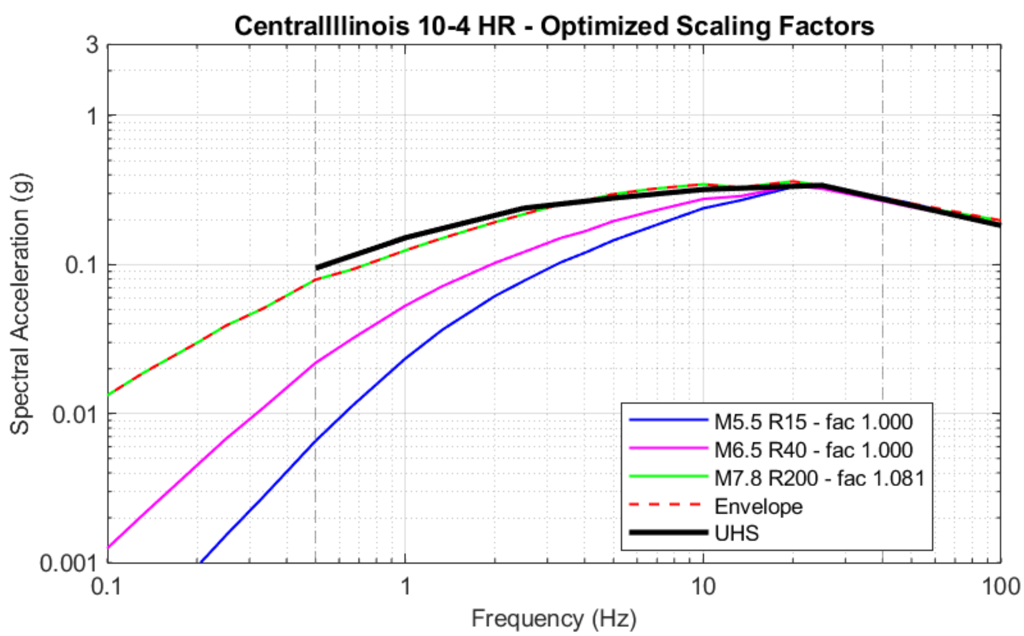
Appendix Figure A-51 Comparison of the scaled scenario spectra to the Wolf Creek (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



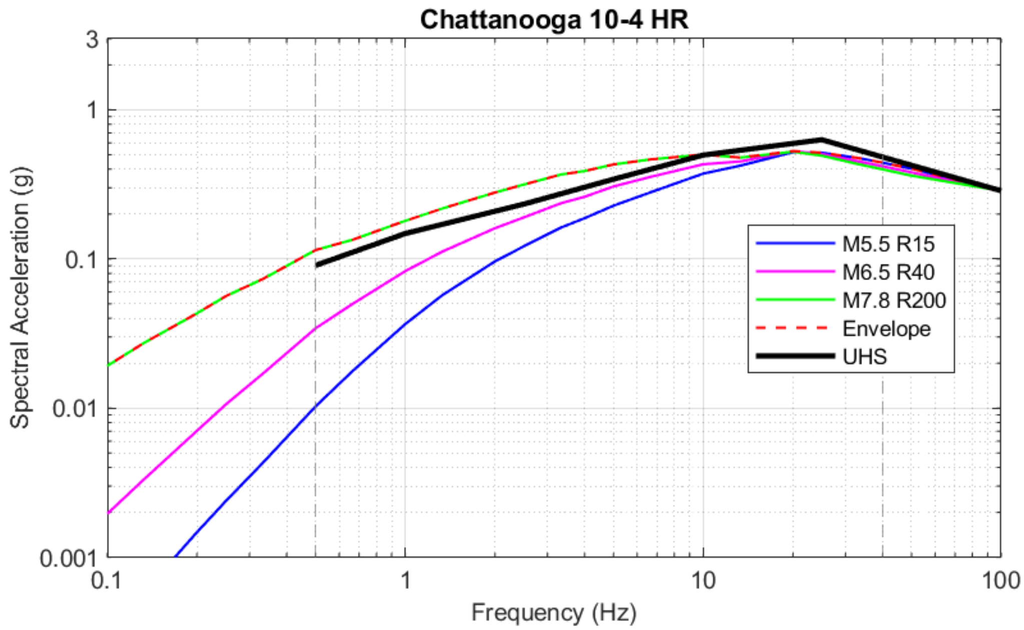


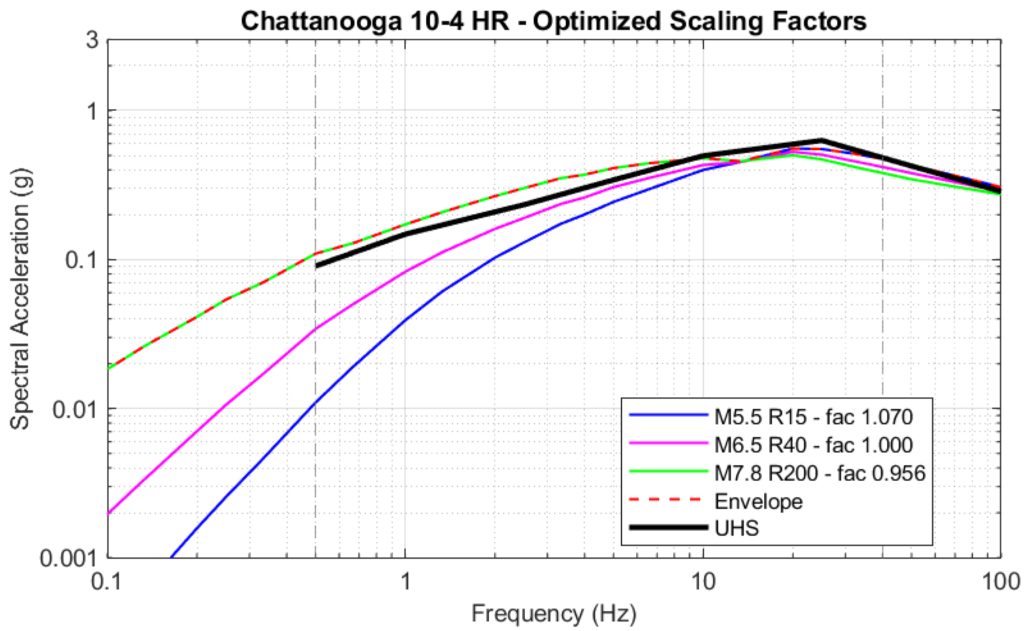
Appendix Figure A-52 Comparison of the scaled scenario spectra to the Savannah (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



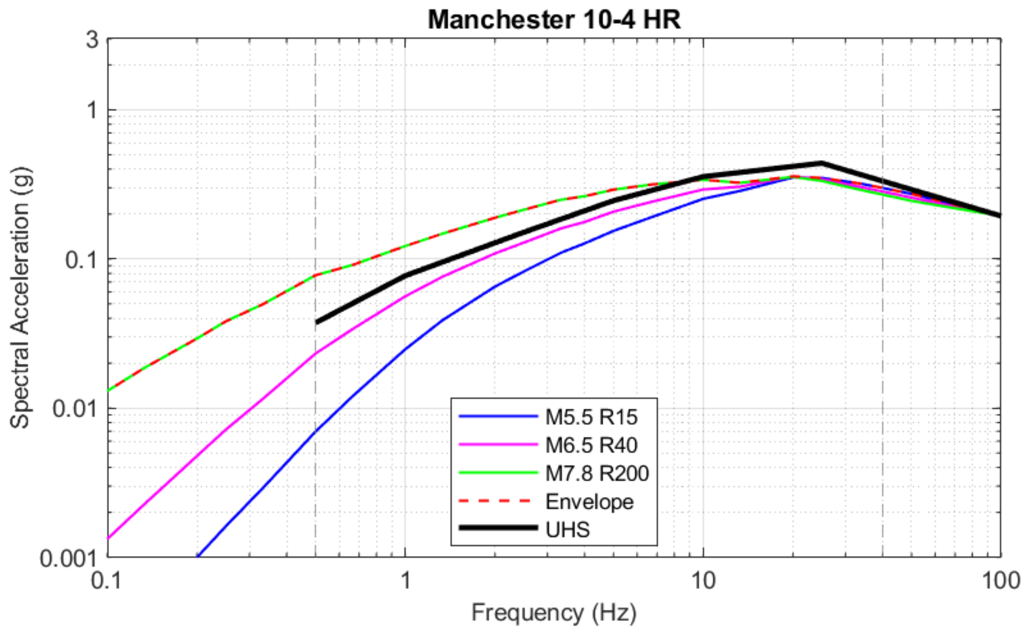


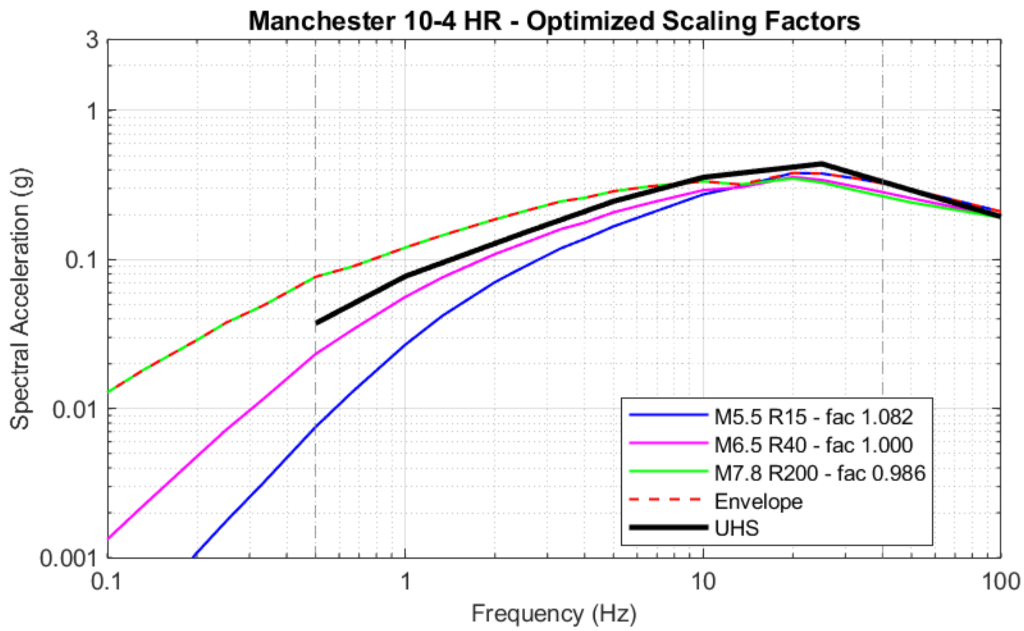
Appendix Figure A-53 Comparison of the scaled scenario spectra to the Central Illinois (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



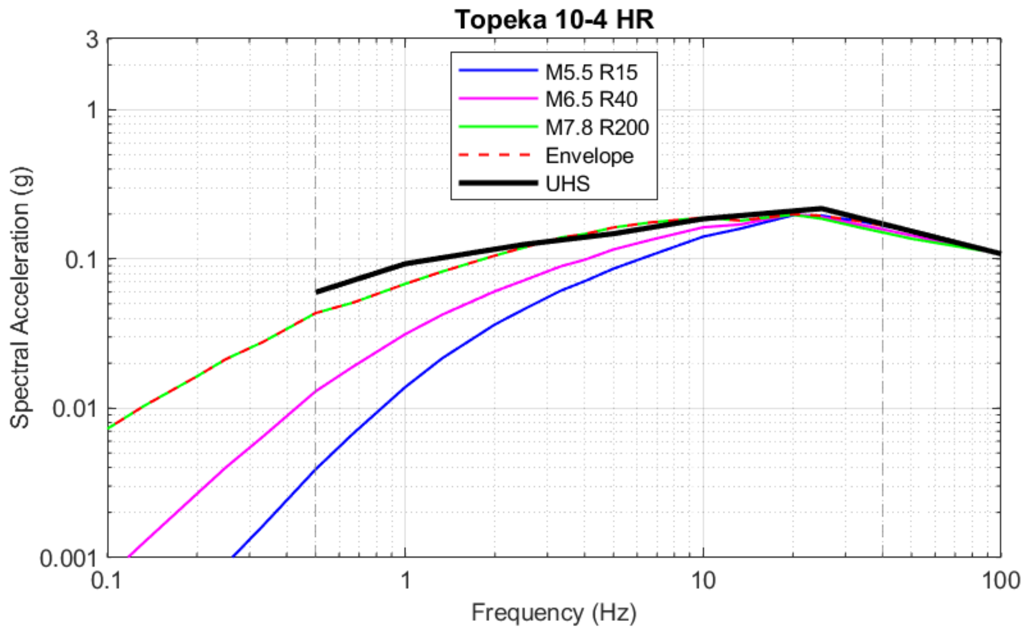


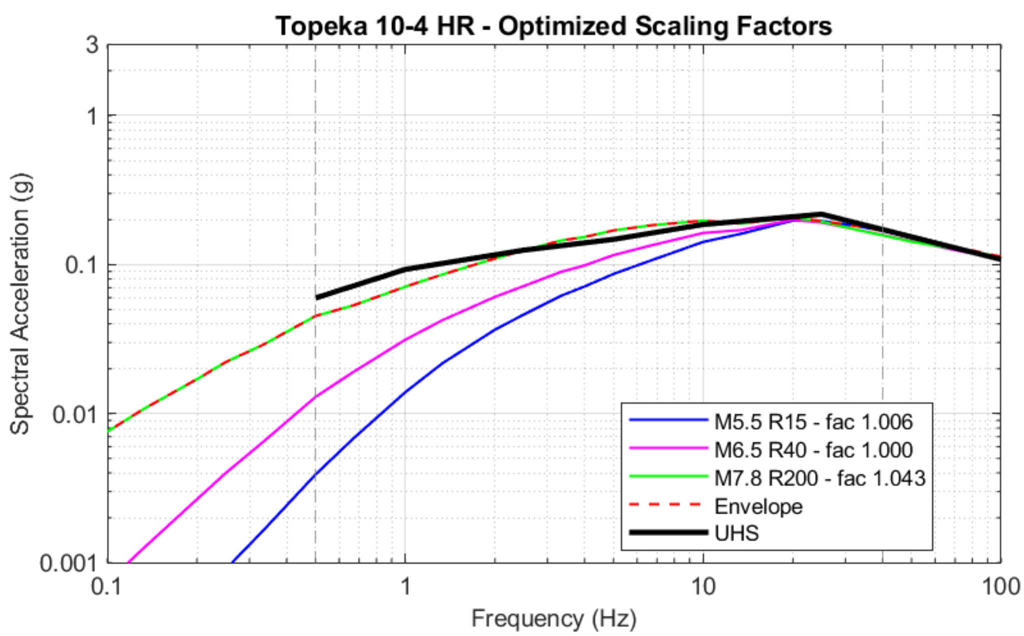
Appendix Figure A-54 Comparison of the scaled scenario spectra to the Chattanooga (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).



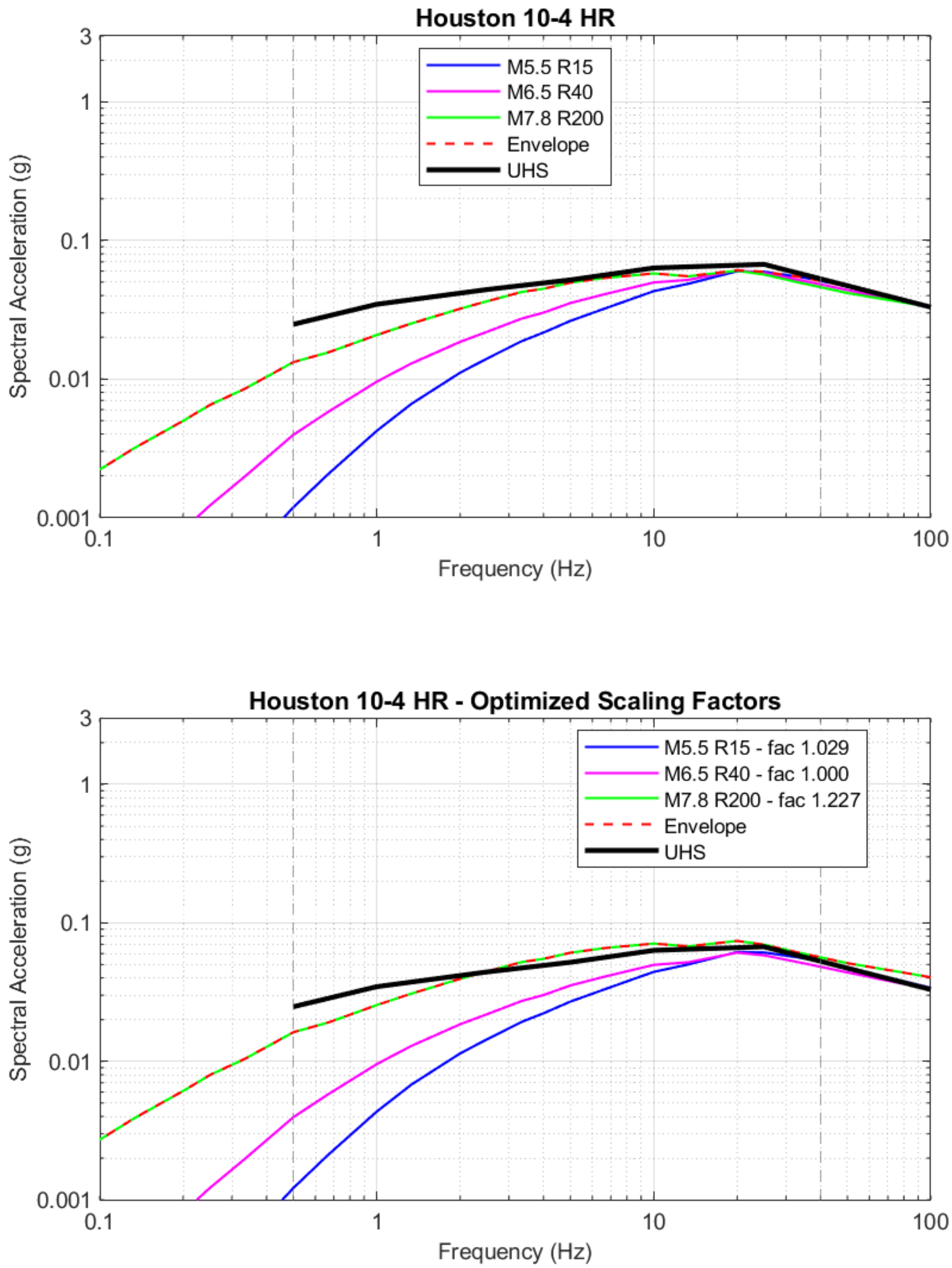


Appendix Figure A-55 Comparison of the scaled scenario spectra to the Manchester (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

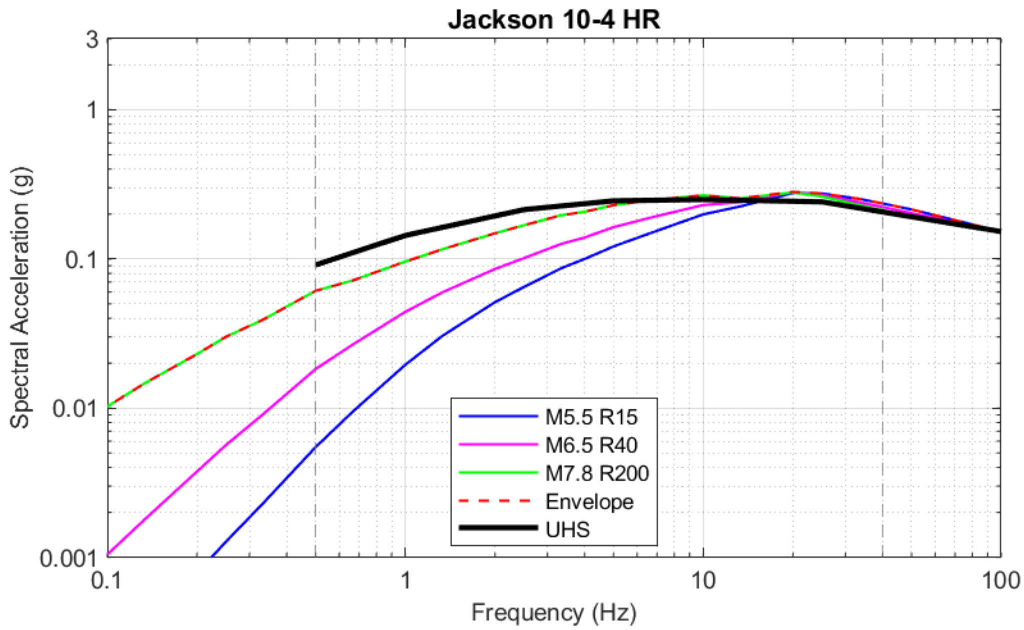


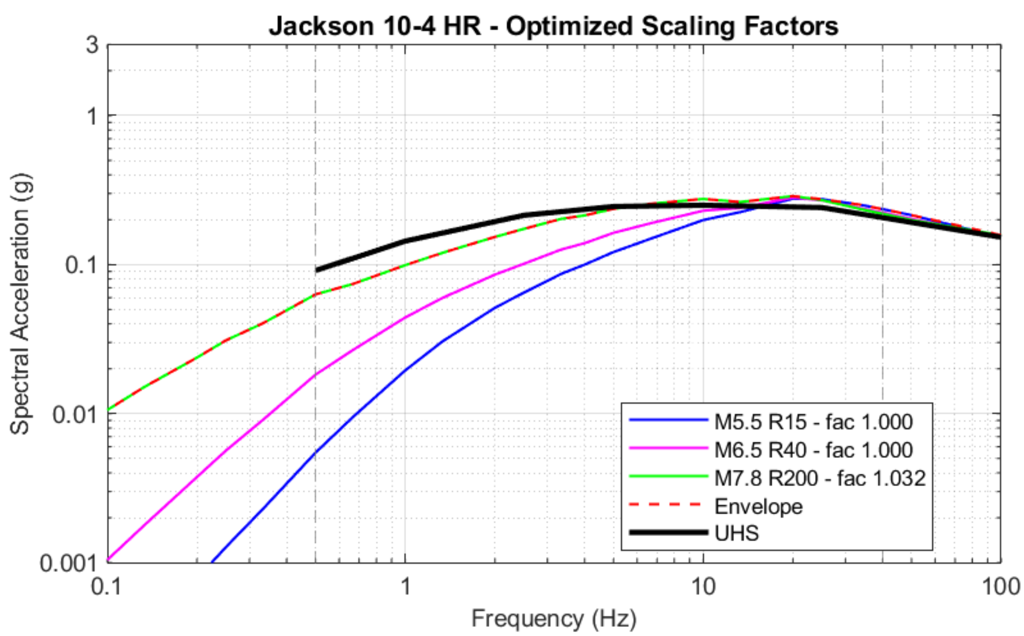


Appendix Figure A-56 Comparison of the scaled scenario spectra to the Topeka (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

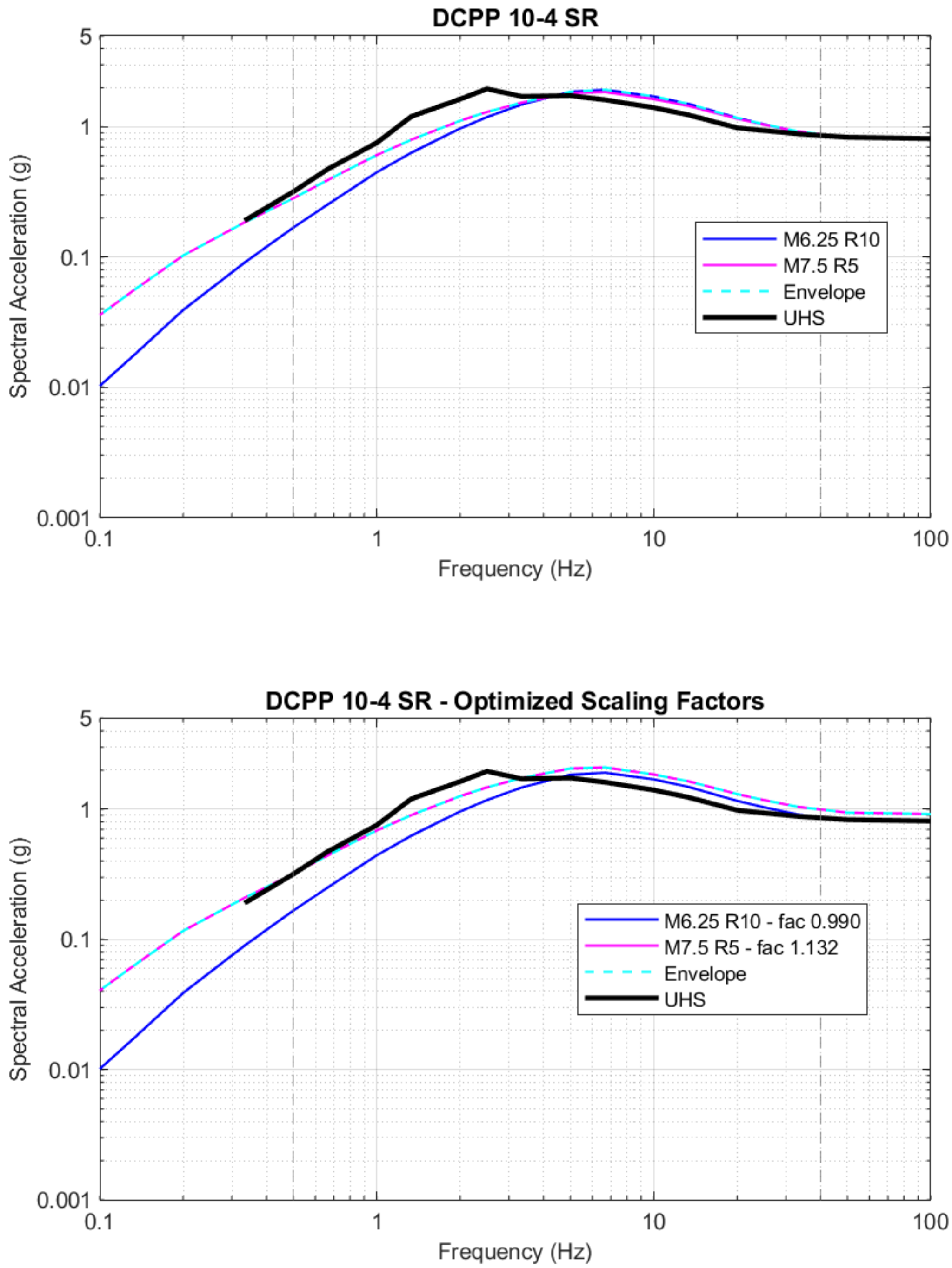


Appendix Figure A-57 Comparison of the scaled scenario spectra to the Houston (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

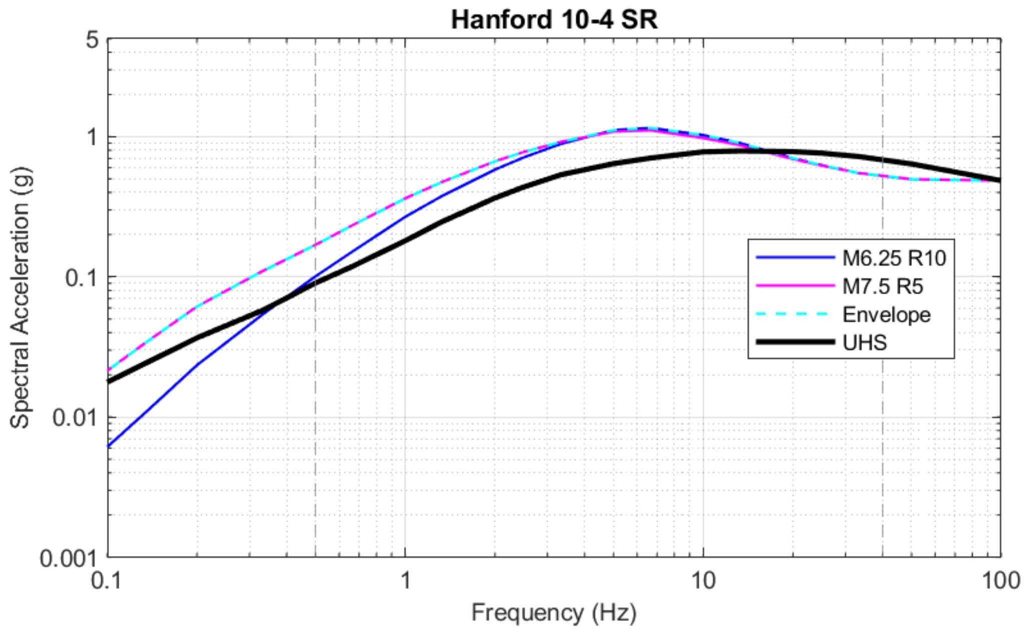


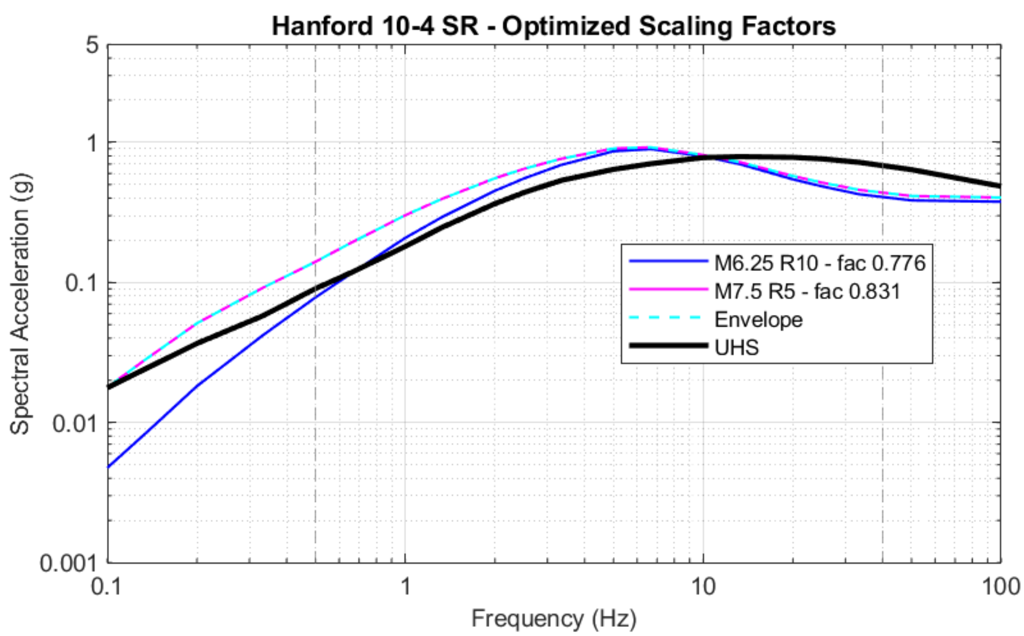


Appendix Figure A-58 Comparison of the scaled scenario spectra to the Jackson (hard rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).

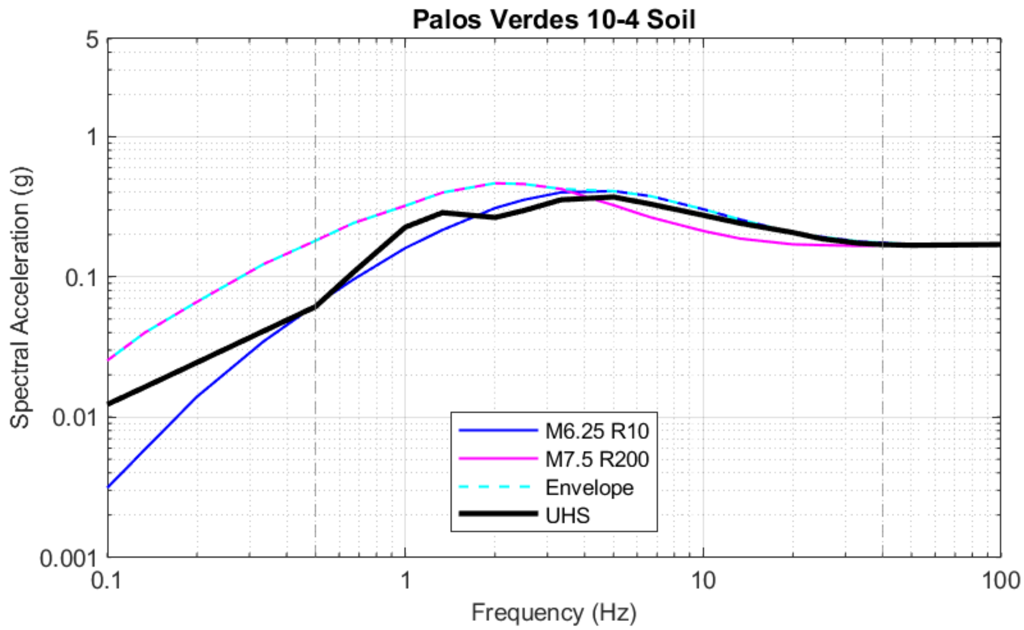


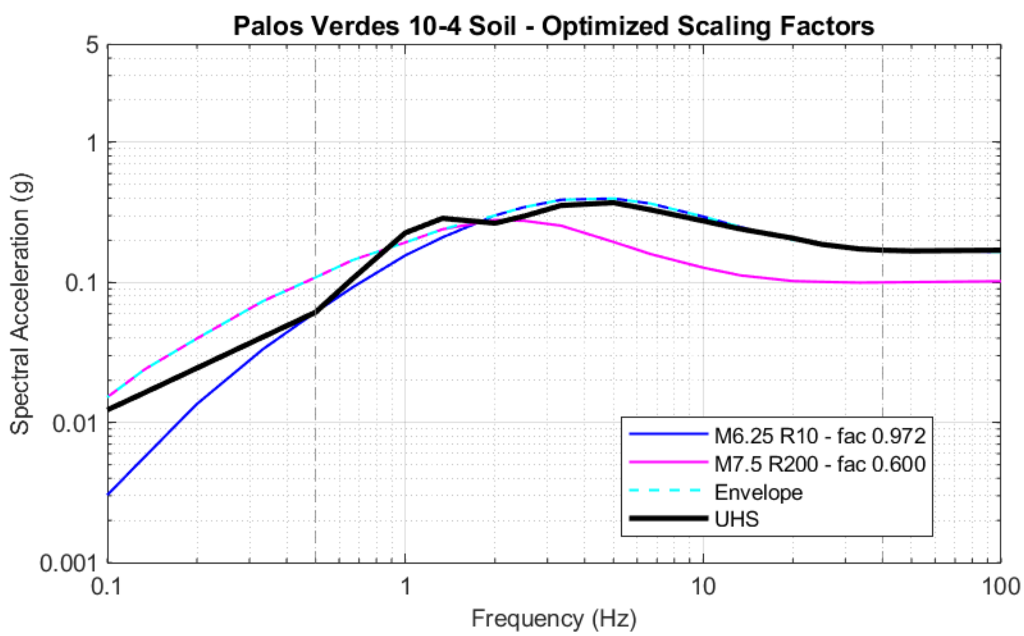
Appendix Figure A-59 Comparison of the scaled scenario spectra to the Diablo Canyon (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).





Appendix Figure A-60 Comparison of the scaled scenario spectra to the Hanford (soft rock) UHS PGA (top plot) and the optimized scaled spectra (lower plot).





Appendix Figure A-61 Comparison of the scaled scenario spectra to the Palo Verde (soil) UHS PGA (top plot) and the optimized scaled spectra (lower plot).