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APPENDIX 3LL

MODEL PROPERTIES AND SEISMIC ANALYSIS RESULTS FOR ESWPT

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ACRONYMS AND ABBREVIATIONS

Acronyms	Definitions
3D	three-dimensional
BE	best estimate
ESW	essential service water
ESWPT	essential service water pipe tunnel
FE	finite element
FIRS	foundation input response spectra
HB	high bound
ISRS	in-structure response spectra
LB	lower bound
OBE	operating-basis earthquake
PCCV	prestressed concrete containment vessel
PSFSV	power source fuel storage vault
R/B	reactor building
SRSS	square root sum of the squares
SSI	soil-structure interaction
UB	upper bound
UHS	ultimate heat sink
UHSRS	ultimate heat sink related structure

3LL MODEL PROPERTIES AND SEISMIC ANALYSIS RESULTS FOR ESWPT

3LL.1 Introduction

This Appendix discusses the seismic analysis of the essential service water pipe tunnel (ESWPT). The computer program SASSI (Reference 3LL-1) serves as the platform for the soil-structure interaction (SSI) analyses. The three-dimensional (3D) finite element (FE) models used in SASSI are condensed from FE models with finer mesh patterns initially developed using the ANSYS computer program (Reference 3LL-2). The dynamic analysis of the SASSI 3D FE model in the frequency domain provides results for the ESWPT seismic response that include SSI effects. The SASSI model results for maximum accelerations, seismic soil pressures and base response spectra are used as input to the ANSYS models for performing the detailed structural design, including loads and load combinations in accordance with the requirements of Section 3.8. Table 3LL-14 summarizes the analyses performed for calculating seismic demands. The SASSI analysis and results presented in this Appendix include site-specific SSI effects such as the layering of the subgrade, flexibility, and embedment of the ESWPT structure, and scattering of the input control design motion. Due to the low seismic response at the Comanche Peak Nuclear Power Plant site and the lack of high-frequency exceedances, the SASSI capability to consider incoherence of the input control motion is not implemented in the analysis of the ESWPT. Wave passage effects are considered small and do not impact the seismic design because the tunnel foundation is supported by a stiff limestone layer, which will experience low strains under the fairly low seismic motion at the site.

3LL.2 Model Description and Analysis Approach

The ESWPT is modeled with three separate models, each model representing a physical portion of the ESWPT, which are separated by expansion joints (see Subsection 3.8.1.6) that prevent any significant interaction of segments at the interface. Tunnel Segment 1 represents a typical straight north-south tunnel segment buried in backfill soil. Tunnel Segment 2 represents east-west segments adjacent to the ultimate heat sink related structures (UHSRS). Two tornado missile shields extend from the top of this segment to protect the essential service water (ESW) piping and openings into the ultimate heat sink (UHS). The FE model for Segment 3 represents east-west segments adjacent to the power source fuel storage vault (PSFSV) and includes elements representing the fuel pipe access tunnels that extend across the top of the ESWPT. The SSI analyses for all tunnel segments considered soil on all sides in which soil is in contact including the top and bottom of the tunnel.

The SSI models for each of the three ESWPT segments are shown in Figures 3LL-1 through 3LL-6 as overall and cutaway views. Tables 3LL-1, 3LL-2, and 3LL-3 present the properties assigned to the structural components of the SASSI FE models for Segments 1, 2, and 3, respectively. Detailed descriptions and figures of the ESWPT including actual dimensions are contained in Section 3.8. Shell elements model the roof, interior, and exterior walls, and basemat. Brick elements model the backfill and fill concrete below the ESWPT basemat. Where the shell elements and brick elements are connected, the shell element is connected to overlap the face of the brick elements. There are no locations in the models where shell elements are connected perpendicularly to the brick elements with the intention of transferring moment through nodal rotational degrees of freedom.

The input motion for the SASSI model analysis is developed using the site-specific foundation input response spectra (FIRS) discussed in Subsection 3.7.1.1 and is applied at the top of the limestone (bottom of the backfill) in the far field. The earthquake input motion for SASSI is developed by converting the outcrop motion of the FIRS to within-layer motion. Site-specific strain-compatible backfill and rock properties are used in determining the within-layer motion. This process is described further in Appendix 3NN.

The ESWPT model is developed and analyzed using methods and approaches consistent with ASCE 4 (Reference 3LL-3) and accounting for the site-specific stratigraphy and subgrade conditions described in Subsection 2.5.4, as well as the backfill conditions around the embedded portions of the ESWPT.

The input within-layer motion and strain-compatible backfill properties for the SASSI analysis are developed from site response analyses described in Section 3NN.2 of Appendix 3NN by using the site-specific foundation input response spectra (FIRS) discussed in Subsection 3.7.1.1. The properties of the supporting media (rock) as well as the site-specific strain-compatible backfill properties used for the SASSI analysis of the ESWPT are the same as those presented in Appendix 3NN for the reactor building (R/B)-prestressed concrete containment vessel (PCCV)-containment internal structure SASSI analyses. The typical properties for a granular engineered backfill are adopted as the best estimate (BE) values for the dynamic properties of the backfill. Four profiles, lower bound (LB), BE, upper bound (UB), and high bound (HB) of input backfill properties are developed for the SASSI analyses considering the different coefficient of variation. The LB and BE backfill profiles are combined with corresponding LB and BE rock subgrade profiles, and the UB and HB backfill profiles are combined with the UB rock subgrade profile. Four sets of SASSI analyses are performed on each segment of the ESWPT embedded in backfill with BE, LB, UB, and HB properties. Table 3LL-16 provides SSI analysis cases for ESWPT Segments 1 and 3.

ESWPT Segment 2 is additionally analyzed considering partial separation for all four soil property cases of the backfill from the exterior shielding walls above the roof slab. Separation is modeled by reducing the shear wave velocity by a factor of 10 for those layers of backfill that are determined to be separated. The potential for separation of the backfill along Segment 2 is determined by comparing peak soil pressure results for the BE condition to the at-rest soil pressure. The analyses also consider unbalanced fill conditions where applicable, such as for Segment 2 of the ESWPT along the interface with the UHSRS. Consideration of these conditions assures that the enveloped results presented herein capture all potential seismic effects of a wide range of backfill properties and conditions in combination with the site-specific supporting media conditions. Table 3LL-17 provides SSI analysis cases for ESWPT Segment 2.

The location of the lower boundary used in the SASSI analysis is greater than 710 feet below grade. The depth is greater than the embedment plus twice the depth of the largest base dimensions (i.e. 192’ x 2 + 31’ = 415’ for Tunnel 1) recommended by SRP 3.7.2 A ten layer half-space is used below the lower boundary in the SASSI analysis. The SASSI half-space simulation consists of additional layers with viscous dashpots added at the base of the half-space. The half-space layer has a thickness of 1.5 Vs/ f where Vs is the shear wave velocity of the half-space and f is the frequency of analysis and it is divided by the selected number of layers in the half-space.

The maximum shear wave passing frequency for all layers below the base slab and concrete fill, based on layer thicknesses of 1/5 wavelength, ranges from 30.6 Hz for LB to 50.4 Hz for HB. The passing frequency for the backfill ranges from 11.6 Hz for LB to 44.9 Hz for HB. The cutoff frequencies for all cases are greater than 29.3Hz and a minimum of 39 frequencies are analyzed for SSI analyses.

For the ESWPT analyses performed, benchmarking is performed to validate the results of the SASSI models. The natural frequencies of Tunnel Segment 1 are calculated for the FE model used for the SSI analysis performed in SASSI (coarse model) and a more refined FE model (ANSYS) used for the analysis of all static load cases (detailed model) and compared. Tunnel 1 is deemed representative of the coarse and fine mesh models of all tunnel segments. For this analysis both models have all nodes at the intersection of mat slab and the walls fixed against translation. Results show close comparison between the calculated frequencies.

The tunnels are simple structures and responses are significantly influenced by the surrounding soil, producing frequencies of peak response in the embedded SASSI model that do not match the eigenvalue analysis of the fixed base structure without soil which limits the ability to compare transfer functions. Therefore, the response of these structures are checked primarily through model and analysis input file checks and reviews of the transfer functions and other output to make sure that adequate frequencies are used for calculation. The SASSI analysis frequencies are selected to cover the range between around 1 Hz and the cutoff frequency. This frequency range includes the SSI frequency and primary structural frequencies. The 1 Hz lower limit is low enough to be outside the range of SSI or structural mode amplification. It was verified that as the transfer functions approached the zero frequency (static input), the co-directional transfer function approached unity while the cross-directional terms approached zero. Initially, the frequencies are selected evenly spaced. Frequencies are added as needed to produce smooth interpolation of the transfer functions and accurately capture peaks. As verification, additional frequencies are added to observe that the results did not change. Transfer functions are examined for each analysis to verify that the interpolation was reasonable and that the expected structural responses were observed. Transfer functions, spectra, accelerations, and soil pressures are compared between the various soil profiles used in analyses to verify that the responses are reasonably similar between these cases except for the expected trends due to soil frequency changes.

Operating-basis earthquake (OBE) structural damping values of Chapter 3 Table 3.7.1-3(b), such as 4 percent damping for reinforced concrete, are used in the site-specific SASSI analysis. This is consistent with the requirements of Section 1.2 of RG 1.61 (Reference 3LL-4) for structures on sites with low seismic responses where the analyses consider a relatively narrow range of site-specific subgrade conditions. The SASSI analyses produce results including peak accelerations, in-structure response spectra, seismic element demands, and seismic soil pressures. All results from SSI analyses represent the envelope of the soil conditions. The SASSI analysis results are used to produce the final response spectra and provide confirmation of the inputs to the ANSYS design model.

ANSYS analyses are used to calculate the structural demands of the ESWPT to seismic soil pressure and seismic inertia which are then added to all other design loads discussed in Section 3.8.

The seismic inertia demand of segment 2 are calculated using ANSYS, response spectra analyses with the site specific 5% damped design response spectra. The design response spectra is based on the standard plant CSDRS anchored to a zero period acceleration of 0.10 g that is shown to envelope the site specific FIRS and the in-structure response spectra calculated at the base slab in SASSI. Modal combination is performed in accordance with RG 1.91 Combination Method B. Analysis of the ESWPT produced 40 modes below 50 Hz. Table 3LL-15 lists five major structural frequencies for each direction of motion organized by mass participation.

The seismic inertia demand of segments 1 and 3 are calculated using an equivalent static lateral load based on the enveloped peak accelerations calculated in SASSI for all soil cases that are shown in Tables 3LL-6 and 3LL-8.

The seismic soil pressure demands are calculated statically in ANSYS. The seismic soil pressure demands are applied on the structural elements as equivalent static pressures. The pressures applied are of larger magnitude compared to the calculated elastic solution used in ASCE 4-98 based on J.H. Wood, 1973 and the enveloped SASSI results. Soil above the tunnel is accounted for in two ways: (1) a shear force was applied at the interface of the tunnel roof and the soil above where the shear value is shown to be higher than that calculated in SASSI SSI analyses and (2) the density of the tunnel roof slab is increased in regions of the tunnel where a balanced soil condition does not exist. This second method accounts for an assumed load path of bringing the entire soil mass into the roof slab through shear.

Demands calculated from the response spectra and soil pressure analyses performed in ANSYS for segment 2 are combined on an absolute basis to produce the maximum demands for each direction of motion and these directions are then combined spatially by 100-40-40 percent combination rule (Eq. 13 of RG 1.92). Calculations of the design forces and moments use the 100-40-40 percent combination rule because the design of concrete elements includes the effects of the interaction of different components, such as interaction of axial forces with the moments or axial forces with shear. Since the direction of input motion that results in the maximum axial force may be different from that producing the maximum moment or shear, the 100-40-40 method produces more accurate design demands.

Demands calculated from the equivalent static accelerations and soil pressure analyses performed in ANSYS for segments 1 and 3 are combined to produce the maximum demands in each direction. The maximum demands for each direction of motion and these directions are then combined spatially by 100-40-40 percent combination rule (Eq. 13 of RG 1.92).

To confirm the design input and results from the ANSYS model of tunnel segment 2 used for response spectra analysis, the enveloped in-structure response spectra at the base slab calculated in the SASSI analysis are compared to the input spectra. The enveloped soil pressures from SASSI are compared to the soil pressures used as input to the ANSYS model, and the plate stresses from SASSI are compared to those calculated in ANSYS. The comparisons show that the seismic loads used for design exceeded those based on results of the SASSI analysis.

3LL.3 Seismic Analysis Results

Table 3LL-4 presents the natural frequencies and descriptions of the associated modal responses obtained from the fixed-base ANSYS analysis of the straight portion of the ESWPT (Segment 1 Model). These frequencies were compared to the frequencies calculated from the transfer functions for the SASSI model to confirm adequacy of the coarser mesh SASSI model to represent dynamic behavior of the tunnels. Table 3LL-5 presents a summary of SSI effects on the seismic response of the ESWPT segments.

The maximum absolute nodal accelerations obtained from the SASSI SSI analyses of the ESWPT models are presented in Tables 3LL-6 to 3LL-8. The results are presented for each of the major ESWPT components and envelope all backfill conditions described above. The maximum accelerations have been obtained by combining cross-directional contributions (i.e. X-response due to X-input, X-response due to Y-input, and X-response due to Z-input) in accordance with RG 1.92 (Reference 3LL-5) using the square root sum of the squares (SRSS) method.

The forces and moments in Tables 3LL-9, 3LL-10, and 3LL-11 represent seismic demands produced from ANSYS seismic analyses. These results include the combined demands from seismic intertia and seismic soil pressure and the combinations of all directions of input motion. For structural design, the accidental torsion load case results in increased shear in the outer walls, which is included in the values reported in Tables 3LL-9, 3LL-10, and 3LL-11. Note that addition of the torsion by scaling the seismic demands results in shear demand in the outer walls that meets or exceeds the accidental torsion requirements for design.

Displacements provided in Table 3LL-12 are the peak displacements of the nodes calculated in the ANSYS seismic analyses representing the deflection calculated using the combined seismic intertia and seismic soil pressure.

Table 3LL-13 presents the maximum pressures below the basemat of the ESWPT calculated from SASSI analyses.

3LL.4 In-Structure Response Spectra (ISRS)

The enveloped broadened ISRS calculated in SASSI are presented in Figures 3LL-7, 3LL-8, and 3LL-9 for ESWPT Segments 1, 2, and 3, respectively. The spectra are presented for the horizontal and vertical directions for the ESWPT base slab and roof for 0.5 percent, 2 percent, 3 percent, 4 percent, 5 percent, 7 percent, 10 percent, and 20 percent damping. The ISRS for the roof of the PSFSV access tunnels are also presented in Figure 3LL-9. The ISRS are resultant spectra, which have been combined using SRSS to account for cross-directional coupling effects in accordance with RG 1.122 (Reference 3LL-6). The ISRS include the envelope of the four site conditions (BE, LB, UB, and HB) with and without backfill separation (if applicable) from the structure. All results have been broadened by 15 percent and all valleys removed. The shape of the spectra presented herein can be simplified by further enveloping of peaks for the design of seismic category I and II subsystems and components housed within or mounted to the ESWPT and PSFSV access tunnels. For the design of seismic category I and II subsystems and components mounted to the ESWPT walls and slabs, it is required to account for the effects of out-of-plane flexibility, including seismic anchor motions.

3LL.5 References

3LL-1 *An Advanced Computational Software for 3D Dynamic Analysis Including Soil Structure Interaction,* ACS SASSI Version 2.2, Ghiocel Predictive Technologies, Inc., July 23, 2007.

3LL-2 ANSYS Release 11.0, SAS IP, Inc. 2007.

3LL-3 *Seismic Analysis of Safety-Related Nuclear Structures,* American Society of Civil Engineers, ASCE 4-98, Reston, Virginia, 2000.

3LL-4 *Damping Values for Seismic Design of Nuclear Power Plants*, Regulatory Guide 1.61, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC, March 2007.

3LL-5 *Combining Responses and Spatial Components in Seismic Response Analysis*, Regulatory Guide 1.92, Rev. 2, U.S. Nuclear Regulatory Commission, Washington, DC, July 2006.

3LL-6 *Development of Floor Design Response Spectra for Seismic Design of Floor-supported Equipment or Components*, Regulatory Guide 1.122, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC, February 1978.

Table 3LL-1

ESWPT Segment 1 FE Model Component Properties

Components	Material	E (ksi)	Poisson's Ratio	Unit Weight (kcf)	Damping Ratio	Width or Height x Thickness[(2)] (ft)	Element type
Roof	5,000 psi concrete	4,030	0.17	0.225[(1)]	0.04	23 x 2	Shell
Base slab	5,000 psi concrete	4,030	0.17	0.200[(1)]	0.04	23 x 2	Shell
Exterior Walls	5,000 psi concrete	4,030	0.17	0.175[(1)]	0.04	16.67 x 2	Shell
Interior Walls	5,000 psi concrete	4,030	0.17	0.250[(1)]	0.04	16.67 x 1	Shell
Fill Concrete	3,000 psi concrete	3,125	0.17	0.15	0.04	23 x 10.08	Brick

Notes:

1) The unit weight includes equivalent dead loads due to piping and other supported components, and 25% of applicable live load for dynamic analysis purposes. A pipe load of 150 psf is considered on the roof slab and 50 psf is considered on all other interior surfaces. The applicable floor live load is 200 psf.
2) The width or height of the component is adjusted from actual dimensions to suit the mesh pattern used for the FE model. The adjustments are minor and do not affect the accuracy of the analysis results. Actual component dimensions are shown in Section 3.8 Figure 3.8-203 and 3.8-205.

Table 3LL-2
ESWPT Segment 2 FE Model Component Properties

Components	Material	E (ksi)	Poisson's Ratio	Unit Weight (kcf)	Damping Ratio	Width or Height x Thickness (ft) (2)	Element type
Roof	5,000 psi concrete	4,030	0.17	0.21(1)	0.04	23 x 2.5	Shell
Base slab	5,000 psi concrete	4,030	0.17	0.19(1)	0.04	34 x 2.5	Shell
Exterior Walls	5,000 psi concrete	4,030	0.17	0.175(1)	0.04	17.17 x 2	Shell
Interior Walls	5,000 psi concrete	4,030	0.17	0.250(1)	0.04	17.17 x 1	Shell
Basin Missile Shield Walls	5,000 psi concrete	4,030	0.17	0.15	0.04	32 x 2	Shell
Basin Missile Shield Roof Slab	5,000 psi concrete	4,030	0.17	0.15	0.04	11.5 x 2 x 95	Shell
Pump House Missile Shield Walls	5,000 psi concrete	4,030	0.17	0.1875(1)	0.04	26 x 2	Brick
Pump House Missile Shield Roof Slab	5,000 psi concrete	4,030	0.17	0.1875(1)	0.04	10 x 2 x 23	Brick
Fill Concrete	3,000 psi concrete	3,125	0.17	0.15	0.04	34 x 9.83	Brick

Notes:

1) The unit weight includes equivalent dead loads due to piping and other supported components, and 25% of applicable live load for dynamic analysis purposes. A pipe load of 150 psf is considered on the tunnel roof slab, 75 psf on the pump house missile shield surfaces, and 50 psf is considered on all other interior surfaces. The applicable floor live load is 200 psf.
2) The width or height of the component is adjusted from actual dimensions to suit the mesh pattern used for the FE model. The adjustments are minor and do not affect the accuracy of the analysis results. Actual component dimensions are shown in Section 3.8 Figure 3.8-202.

Table 3LL-3

ESWPT Segment 3 FE Model Component Properties

Components	Material	E (ksi)	Poisson's Ratio	Unit Weight (kcf)	Damping Ratio	Width or Height x Thickness (ft) (2)	Element type
Roof	5,000 psi concrete	4,030	0.17	0.225(1)	0.04	23 x 2	Shell
Base slab	5,000 psi concrete	4,030	0.17	0.200(1)	0.04	23 x 2	Shell
Exterior Walls	5,000 psi concrete	4,030	0.17	0.175(1)	0.04	16.67 x 2	Shell
Interior Walls	5,000 psi concrete	4,030	0.17	0.250(1)	0.04	16.67 x 1	Shell
Service Tunnel Roof	5,000 psi concrete	4,030	0.17	0.344(1)	0.04	Width varies x 2	Shell
Service Tunnel Outer Walls	5,000 psi concrete	4,030	0.17	0.175(1)	0.04	13.25 x 2	Shell
Service Tunnel Inner Walls	5,000 psi concrete	4,030	0.17	0.217(1)	0.04	13.25 x 1.5	Shell
Fill Concrete	3,000 psi concrete	3,125	0.17	0.15	0.04	23 x 10.08	Brick

Notes:

1) The unit weight includes equivalent dead loads due to piping and other supported components, and 25% of applicable live load for dynamic analysis purposes. A pipe load of 150 psf is considered on the roof slab and service tunnel roof, and 50 psf is considered on all other interior surfaces. The applicable floor live load is 200 psf for the base slab and service tunnel roof. Also, additional backfill dead load of 187.5 psf due to fill above elevation 822 is considered on the service tunnel roof.
2) The width of the component is adjusted from actual dimensions to suit the mesh pattern used for the FE model. The adjustments are minor and do not affect the accuracy of the analysis results. Actual component dimensions are shown in Section 3.8 Figures 3.8-203 and 3.8-204.

Table 3LL-4

ESWPT Structural Frequencies

Frequency (Hz)	Comments
7.3	Tunnel racking (due to shear deformation) in transverse direction
31.3	Local out of plane response of interior wall

Notes:

1) Natural frequencies and effective masses were calculated in ANSYS using the same mesh as used for SASSI analyses.

Table 3LL-5

SASSI Results for ESWPT Seismic Response

SSI Effect	Observed Response
Rock Subgrade	The rock subgrade has insignificant SSI effect on the ESWPT seismic response.
Backfill	The properties of the backfill determine the overall response of the buried ESWPT structure. The analyses of ESWPT Segment 1 show that the aboveground part of the structure has small effect on the response of the underground tunnel. The backfill soil frequencies that are in the range from 3 Hz for lower bound to 9 Hz for high bound, characterize the ESWPT horizontal response for all three segments. Frequencies of 7 Hz for lower bound, to 17 Hz for high bound characterize the vertical response of the ESWPT.
Backfill soil separation	The potential for backfill separation of ESWPT Segment 2 results in a small increase in the structural peak amplification.
Motion Scattering Effects	Motion scattering effects are inherent in the SASSI analysis results. The dynamic properties mismatch between the backfill and the rock results in reflection of the seismic waves within the backfill stratum. Consequentially, multiple modes characterize the backfill soil column and affect the ESWPT response when their frequencies are close to the structural frequencies.

Table 3LL-6

ESWPT Segment 1 SASSI FE Model Component Peak Accelerations(1) (g)

Component	Transverse Direction	Longitudinal Direction	Vertical Direction
Base Slab	0.12	0.12	0.15
Roof Slab	0.24	0.14	0.19
Interior Walls	0.26	0.13	0.17
Exterior Walls	0.24	0.14	0.16

Notes:

1) For structural design using the loads and load combinations in Section 3.8, the seismic demands are calculated in ANSYS by applying these peak accelerations as statically equivalent loads across the entire component and combining with the demands calculated in ANSYS by applying an equivalent static seismic soil pressure.

Table 3LL-7

ESWPT Segment 2 SASSI FE Model Component Peak Accelerations[3] (g)

Component	Transverse Direction	Longitudinal Direction	Vertical Direction
Base Slab	0.13	0.12	0.13
Roof Slab	0.36	0.16	0.21
Interior Walls	0.35	0.14	0.16
Exterior Walls	0.35	0.14	0.15
Pump House Pipe Missile Shield	0.95[1]	0.46[1]	0.19
Air Intake Missile Shield	0.83[2]	0.21[2]	1.09

Notes:

1) The transverse direction for the pipe missile shield is the east-west direction; the longitudinal direction is the north-south direction.
2) The transverse direction for the duct missile shield is the north-south direction; the longitudinal direction is the vertical direction.
3) For structural design using the loads and load combinations in Section 3.8, the seismic demands are calculated in ANSYS by response spectra analysis of the Segment 2 model using the site-specific design response spectra as input, and by combining the resulting demands with the demands calculated in ANSYS by applying an equivalent static seismic soil pressure.

Table 3LL-8

ESWPT Segment 3 SASSI FE Model Component Peak Accelerations[4] (g)

Component	Transverse Direction	Longitudinal Direction	Vertical Direction
Base Slab	0.12[1]	0.12[1]	0.13[1]
Roof Slab	0.50[1]	0.16[1]	0.21[1]
Interior Walls	0.50[3]	0.19	0.20
Exterior Walls	0.50[3]	0.16	0.15
PSFSV Service Tunnel Walls	0.32[2]	0.38[2]	0.15
PSFSV Service Tunnel Roof	0.32[2]	0.38[2]	0.16

Notes:

1) The transverse direction for the base slab and roof is the north-south direction; the longitudinal direction is the east-west direction.
2) The transverse direction for the PSFSV service tunnel walls and roof is the east-west direction; the longitudinal direction is the north south direction.
3) For interior and exterior walls, the transverse direction is the out-of-plane direction.
4) For structural design using the loads and load combinations in Section 3.8, the seismic demands are calculated in ANSYS using the peak accelerations as statically equivalent loads and combining them with the demands calculated in ANSYS by applying an equivalent static seismic soil pressure.

Table 3LL-9

ESWPT Segment 1 FE Model Maximum Component Seismic Forces and Moments

Component		Maximum component forces and moments							
		N_V (k/ft)	N_L (k/ft)	Q_V (k/ft)	Q_L (k/ft)	In-plane Shear (k/ft)	M_V (k-ft/ft)	M_L (k-ft/ft)	M_{VL} (k-ft/ft)
Base Slab	+	4.75	2.38	8.83	1.77	1.07	32.60	5.56	1.00
	-	7.86	2.87	8.83	1.77	1.07	39.40	6.70	1.00
Roof Slab	+	0.33	1.06	4.22	2.15	0.83	22.60	0.72	0.72
	-	4.19	1.42	4.22	2.15	0.83	29.00	4.90	0.72
Interior Walls	+	5.57	0.79	1.91	1.08	0.58	9.55	1.62	0.29
	-	4.89	0.66	1.91	1.08	0.63	9.55	1.62	0.29
Exterior Walls	+	7.91	1.28	7.68	2.09	2.14	36.61	6.19	1.01
	-	8.57	1.17	7.68	2.09	2.14	36.61	6.19	1.01

Notes:

1) The forces and moments shown above include forces and moments due to seismic soil pressure that envelope all four subgrade shear wave velocity conditions (LB, BE, UB, and HB). The forces and moments are used for structural design as described in Section 3.8.
2) The forces and moments are obtained by combination of the three orthogonal directions used in the model by the Newmark 100%-40%-40% method.
3) In the table above the vertical and longitudinal directions define the plane of the walls. N stands for axial force, Q for out-of-plane shear and M for moment. The M_V results in normal stresses in the vertical direction of the wall and similarly, M_L results in normal stresses in the longitudinal (horizontal) direction of the wall, and M_{VL} is the torsional moment on the wall. The Q_V is out-of-plane shear force acting on horizontal cross section of the wall, and Q_L is out-of-plane shear force acting on a vertical cross section of the wall. For the roof slab and base slab the vertical axis is oriented along the east-west direction and the longitudinal along the north-south direction.

Table 3LL-10

ESWPT Segment 2 FE Model Maximum Component Seismic Forces and Moments

Component		Maximum component forces and moments							
		N_V (k/ft)	N_L (k/ft)	Q_V (k/ft)	Q_L (k/ft)	In-plane Shear (k/ft)	M_V (k-ft/ft)	M_L (k-ft/ft)	M_{VL} (k-ft/ft)
Base Slab	+/-	44.99	29.32	93.44	25.14	31.03	128.74	31.82	21.56
Roof Slab	+/-	85.48	31.38	39.62	22.41	62.82	88.21	51.33	14.78
Interior Walls	+/-	58.08	141.34	12.03	4.23	62.54	22.46	7.20	2.00
Exterior Walls	+/-	76.65	216.05	47.54	24.29	76.22	142.71	30.27	17.35
Pump House Pipe Missile Shield Walls	+/-	69.99	34.46	22.68	9.29	42.20	40.75	10.93	4.64
Pump House Pipe Missile Shield Roof	+/-	1.77	24.75	1.93	3.82	7.56	7.63	10.63	4.35
Air Intake Missile Shield	+/-	46.51	18.70	18.10	9.81	23.18	31.91	14.45	6.49

Notes:

1) The forces and moments shown above include forces and moments due to seismic soil pressure that envelope all four subgrade shear wave velocity conditions (LB, BE, UB, and HB). The forces and moments are used for structural design as described in Section 3.8.
2) The forces and moments are obtained by combination of the three orthogonal directions used in the model by the Newmark 100%-40%-40% method. For Segment 2 a response spectra analysis was performed and combined with the absolute value of dynamic soil pressure. The demands obtained from this combination were found to envelope the SASSI demands.
3) In the table above the vertical and longitudinal directions define the plane of the walls. N stands for axial force, Q for out-of-plane shear and M for moment. The M_V results in normal stresses in the vertical direction of the wall and similarly, M_L results in normal stresses in the longitudinal (horizontal) direction of the wall, and M_{VL} is the torsional moment on the wall. The Q_V is out-of-plane shear force acting on horizontal cross section of the wall, and Q_L is out-of-plane shear force acting on a vertical cross section of the wall. For the roof slab and base slab the vertical axis is oriented along the north-south direction and the longitudinal in the east-west direction.

Table 3LL-11

ESWPT Segment 3 FE Model Maximum Component Seismic Forces and Moments

Component		Maximum component forces and moments							
		N_V (k/ft)	N_L (k/ft)	Q_V (k/ft)	Q_L (k/ft)	In-plane Shear (k/ft)	M_V (k-ft/ft)	M_L (k-ft/ft)	M_{VL} (k-ft/ft)
Base Slab	+ -	29.25 31.50	26.53 29.59	58.48 56.36	21.90 24.43	25.42 25.52	54.31 53.70	23.73 21.08	15.30 15.78
Roof Slab	+ -	32.24 37.42	59.80 61.68	22.30 22.42	19.00 19.00	35.79 36.54	46.43 46.57	25.12 28.26	7.47 7.19
Interior Walls	+ -	59.24 53.12	93.26 98.64	12.02 11.12	4.27 3.92	36.67 38.67	18.08 18.21	5.62 5.76	1.94 1.88
Exterior Walls	+ -	30.48 31.06	95.00 98.80	20.16 19.29	15.99 16.49	45.89 46.23	66.74 65.90	69.98 67.39	11.48 11.48
PSFSV Service Tunnel Walls	+ -	32.95 32.62	10.05 10.21	12.16 13.76	5.94 5.70	19.81 19.47	40.35 39.74	8.50 7.82	3.64 3.78
PSFSV Service Tunnel Roof	+ -	10.79 11.80	6.21 6.56	8.69 8.63	20.78 20.69	4.28 4.44	12.17 16.00	21.25 20.98	2.21 2.17

Notes:

1) The forces and moments shown above include forces and moments due to seismic soil pressure that envelope all four subgrade shear wave velocity conditions (LB, BE, UB, and HB). The forces and moments are used for structural design as described in Section 3.8.
2) The forces and moments are obtained by combination of the three orthogonal directions used in the model by the Newmark 100%-40%-40% method.
3) In the table above the vertical and longitudinal directions define the plane of the walls. N stands for axial force, Q for out-of-plane shear and M for moment. The M_V results in normal stresses in the vertical direction of the wall and similarly, M_L results in normal stresses in the longitudinal (horizontal) direction of the wall, and M_{VL} is the torsional moment on the wall. The Q_V is out-of-plane shear force acting on horizontal cross section of the wall, and Q_L is out-of-plane shear force acting on a vertical cross section of the wall. For the roof slab and base slab the vertical axis is oriented along the north-south direction and the longitudinal in the east-west direction.

Table 3LL-12

ESWPT Maximum Seismic Displacements for All Enveloped Conditions

ESWPT Segment	Longitudinal Direction (in)	Transverse (in)	Vertical (in)
1	0.002	0.11	0.003
2	0.09[(1)]	0.18	0.05[(2)]
3	0.10[(1)]	0.19	0.01

Notes:

1) The reported displacement are the north-south displacement at edge of separation joints that is about 10 ft south or north of north or south tunnels respectively. The maximum longitudinal (east-west) displacement of the east-west part of Segment 2 or 3 tunnel is less than 0.002 inches.
2) The maximum vertical occurs at the edge of separation joint edge 10 ft south of the east-west part of the tunnel, which is due to rocking behavior of the tunnel with tall shielding walls.

Table 3LL-13

Bearing Pressures Below ESWPT (ksf)

	Peak Single Element(1)	Peak Design(2)	Average Dynamic(3)	Allowable Bearing Capacity(4)	
				Static Case	Dynamic Case
Segment 1	4.4	4.4	2.1	48.7	73.0
Segment 2	16.6	8.8	2.2	48.7	73.0
Segment 3	17.5	5.7	2.5	48.7	73.0

Notes:

1) Peak single element pressure represents corner pressures on elements representing less than 1% of the slab area.
2) Peak design pressure is the edge envelope pressure excluding the corner peaks, to be used for design.
3) Average dynamic pressure is the average of peak values for every element below the base slab.
4) Allowable bearing capacities are taken from Table 3.8-202.

Table 3LL-14

Summary of Analyses Performed

Model	Loading Case	Analysis Method	Program	Input	Output	Three Components Combination	Modal Combination (for Dynamic Analyses)
Three-dimensional ESWPT FE Model	Seismic soil pressure	Static	ANSYS	Peak soil pressures based on ASCE 4-98, separate analysis for each direction of pressure.	Element and section demands for design	Added to seismic demands in same direction and combined by Newmark 100-40-40 percent combination rule	N/A
Three-dimensional ESWPT FE Model	Seismic intertia Segment 1 and 3	Static	ANSYS	Peak accelerations that envelope results of SASSI.	Element and section demands for design	Combined by Newmark 100-40-40 percent combination rule	N/A
Three-dimensional ESWPT FE Model	Seismic intertia segment 2	Response Spectra Analysis	ANSYS	Site specific design response spectra 5% damped.	Element and section demands for design	Combined by Newmark 100-40-40 percent combination rule	RG 1.92 Combination Method B
Three-dimensional ESWPT FE Model	Seismic motion	Time history soil-structure interaction analysis in frequency domain using sub-structuring technique	SASSI	Time history input matching site-specific design response spectra from site-response analysis, site-specific soil profiles.	Peak accelerations, in-structure response spectra, element forces, soil pressure.	SRSS	N/A

Table 3LL-15

Major Structural Modes of Tunnel Segment 2 - Adjacent to UHS Structures

Major North-South (X) Direction Modes				
Mode	Frequency (Hz)	Period (sec)	Participation Factor	Effective Mass (kip sec^2/ft)
1	5.478	0.1825484	12.78	163.455
5	15.02	0.0665779	-3.381	11.432
4	13.33	0.0750188	-3.147	9.901
13	26.24	0.0381098	1.397	1.953
40	49.03	0.0203957	-1.381	1.908
Major East-West (Y) Direction Modes				
Mode	Frequency (Hz)	Period (sec)	Participation Factor	Effective Mass (kip sec^2/ft)
6	17.52	0.057078	9.757	95.205
21	31.98	0.03127	-6.261	39.201
10	22.86	0.043745	4.599	21.148
2	7.968	0.125502	3.84	14.746
15	29.7	0.03367	3.495	12.215
Major Vertical Modes				
Mode	Frequency (Hz)	Period (sec)	Participation Factor	Effective Mass (kip sec^2/ft)
13	26.24	0.03811	-11.08	122.688
8	20.9	0.047847	5.715	32.662
9	21.36	0.046816	4.76	22.653
10	22.86	0.043745	3.611	13.042
38	47.69	0.020969	3.353	11.244

Table 3LL-16

SSI Analysis Cases for ESWPT Segments 1 and 3

Ana;ysis	Description	Backfill Soil	Rock Subgrade	Soil Separation
1	Best Estimate	Best estimate	Best estimate	No
2	Lower Bound	Lower bound	Lower bound	No
3	Upper Bound	Upper bound	Upper bound	No
4	High Bound	High bound	Upper bound	No

Table 3LL-17

SSI Analysis Cases for ESWPT Segments 2

Ana;ysis	Description	Backfill Soil	Rock Subgrade	Soil Separation
1	Best Estimate	Best estimate	Best estimate	No
2	Lower Bound	Lower bound	Lower bound	No
3	Upper Bound	Upper bound	Upper bound	No
4	High Bound	High bound	Upper bound	No
5	Best Estimate Separated	Best estimate	Best estimate	Yes
6	Lower Bound Separated	Lower bound	Lower bound	Yes
7	Upper Bound Separated	Upper bound	Upper bound	Yes
8	High Bound Separated	High bound	Upper bound	Yes

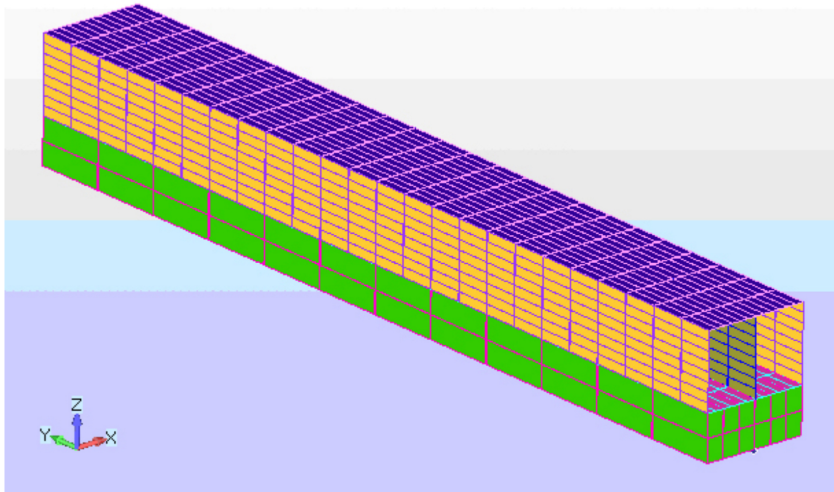

Figure 3LL-1 Overall SASSI Model of ESWPT Segment 1 (Excluding elements representing backfill)

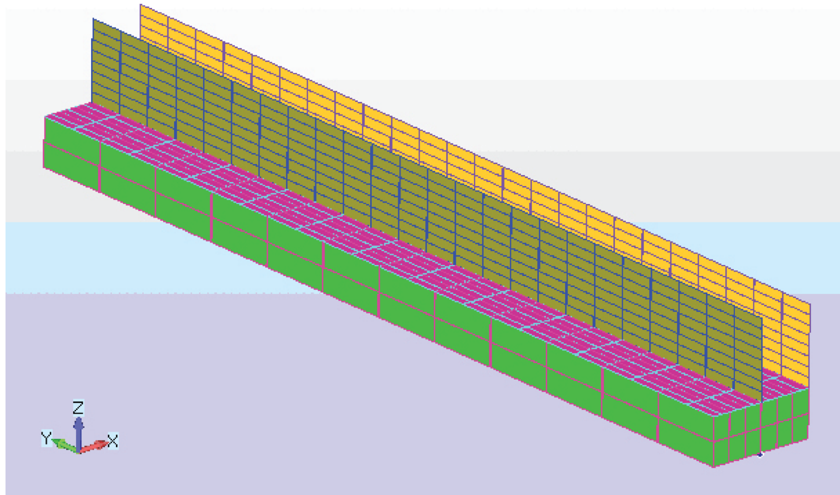

Figure 3LL-2 Cutaway View of SASSI Model of ESWPT Segment 1 (Excluding backfill, roof, and one side wall elements)

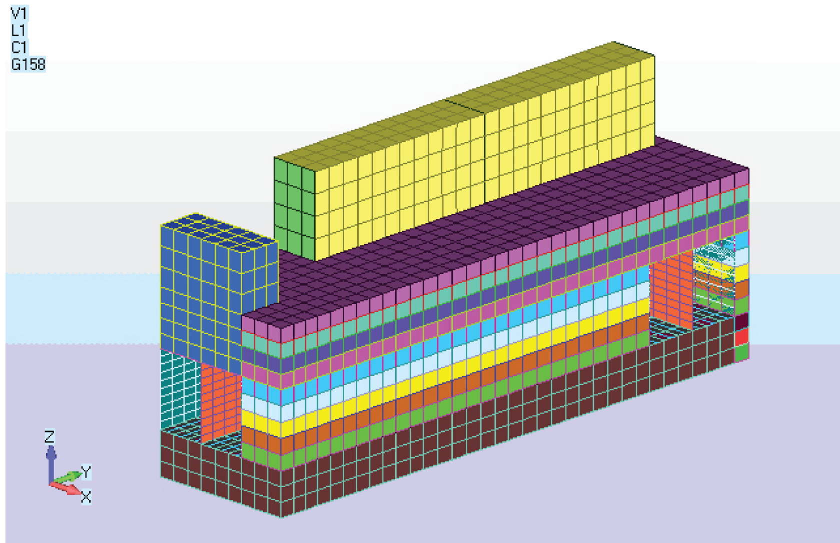

Figure 3LL-3 Overall View of SASSI Model of ESWPT Segment 2 (Including backfill elements)

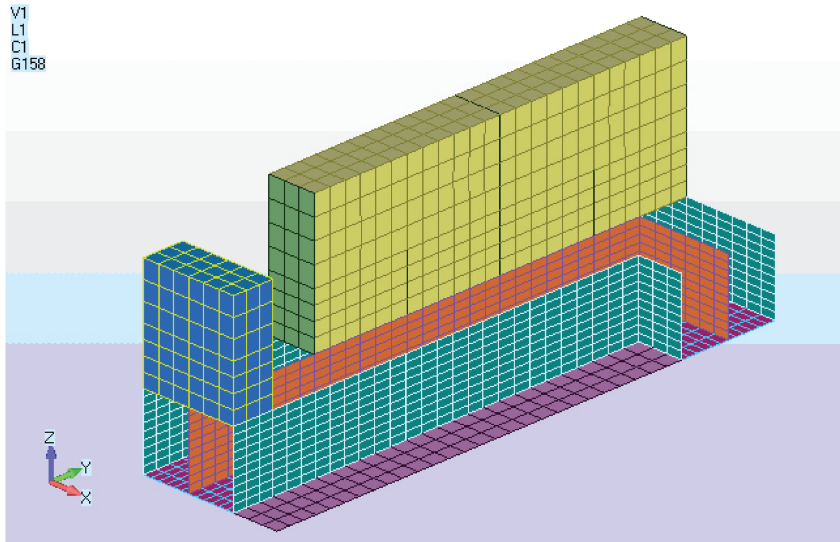

Figure 3LL-4 Cutaway View of SASSI Model of ESWPT Segment 2
(Excluding backfill, concrete fill, and roof slab)

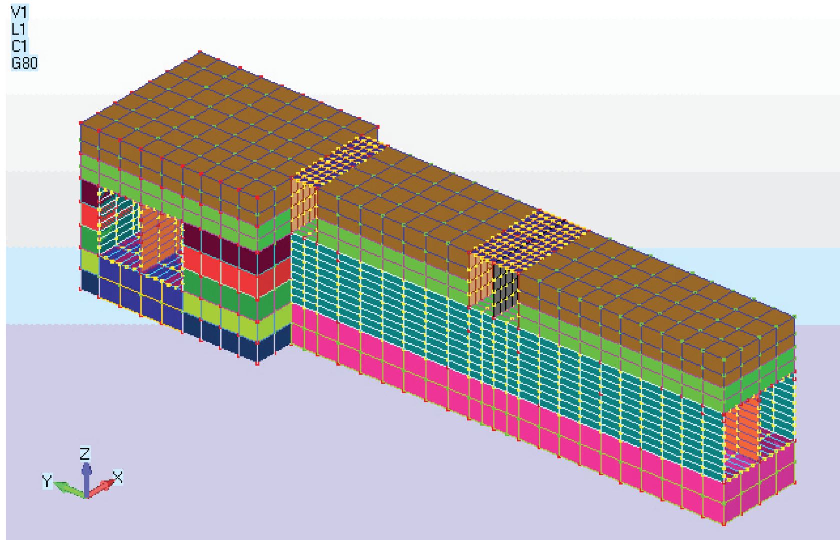

Figure 3LL-5 Overall View of SASSI Model of ESWPT Segment 3 (Including PSFSV tunnel elements)

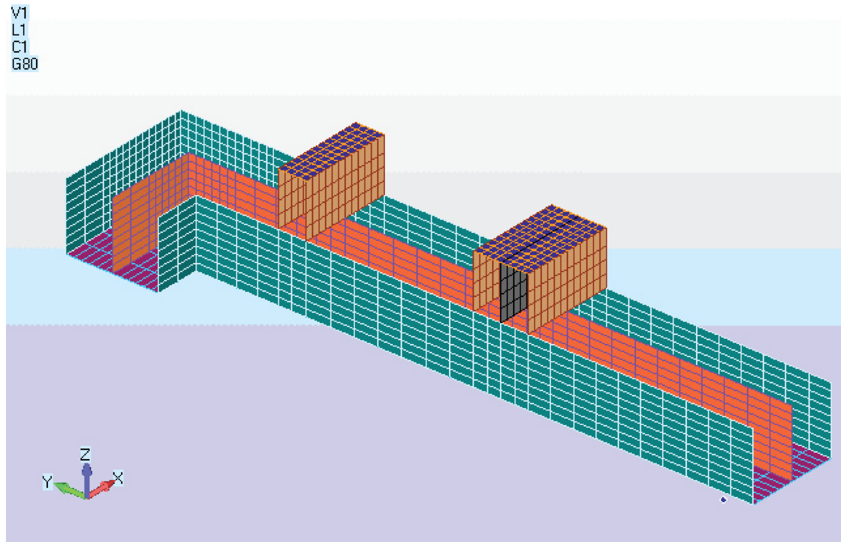

Figure 3LL-6 Cutaway View of SASSI Model of ESWPT Segment 3 (Excluding backfill, concrete fill, and roof elements)

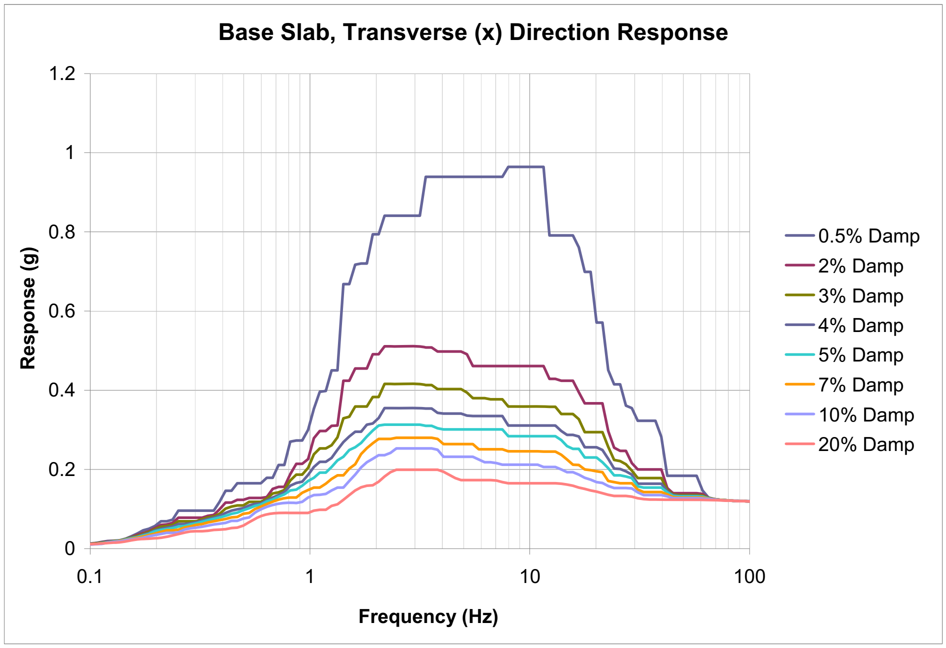

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 1 of 6)

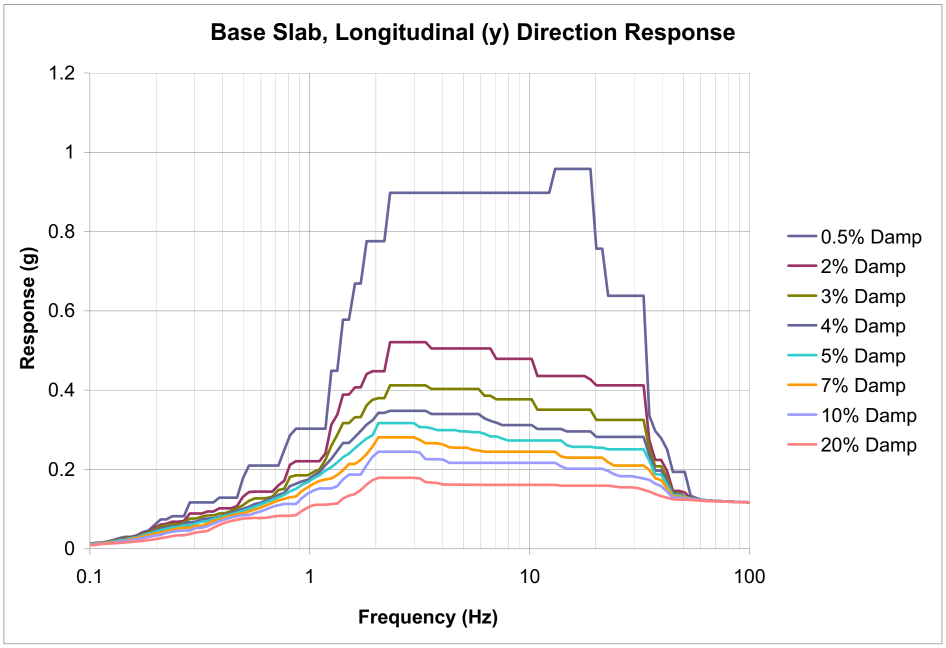

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 2 of 6)

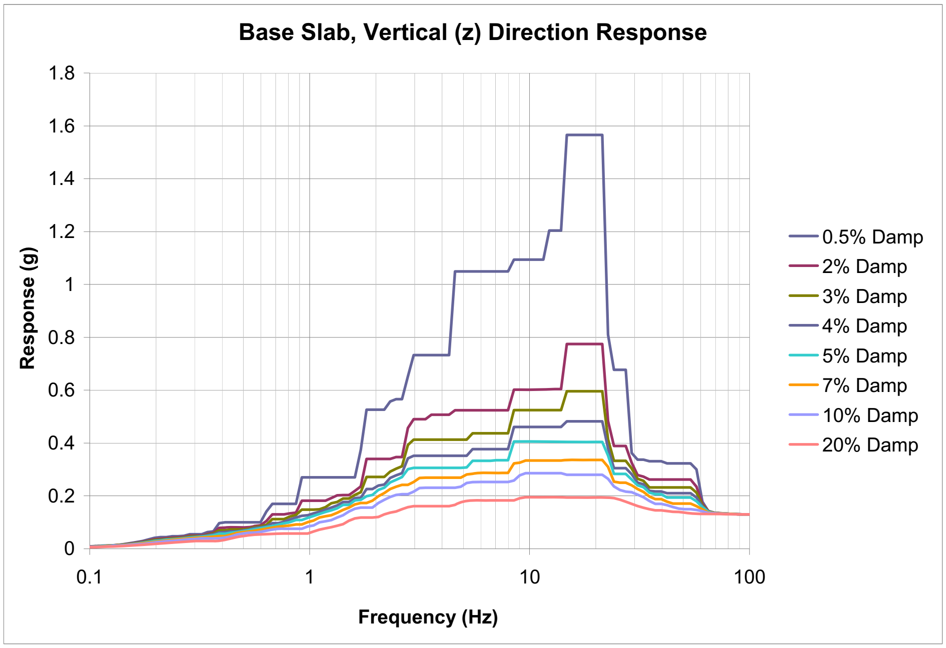

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 3 of 6)

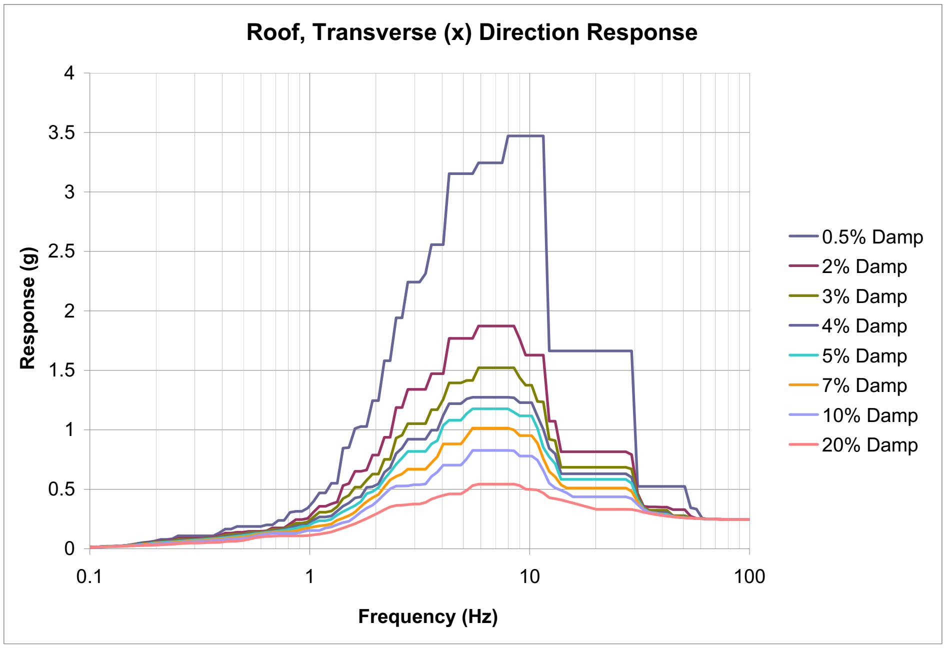

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 4 of 6)

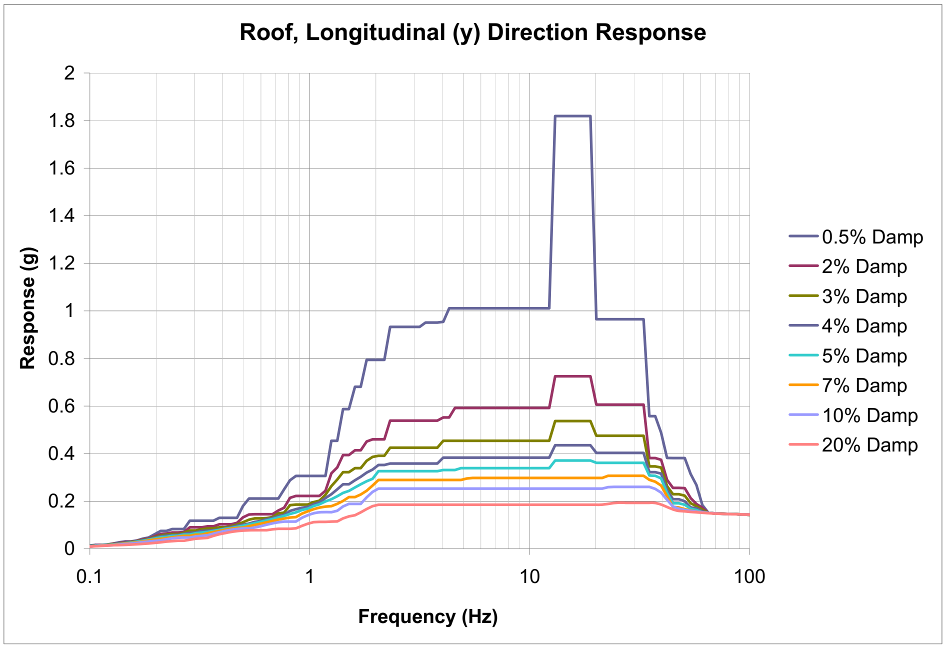

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 5 of 6)

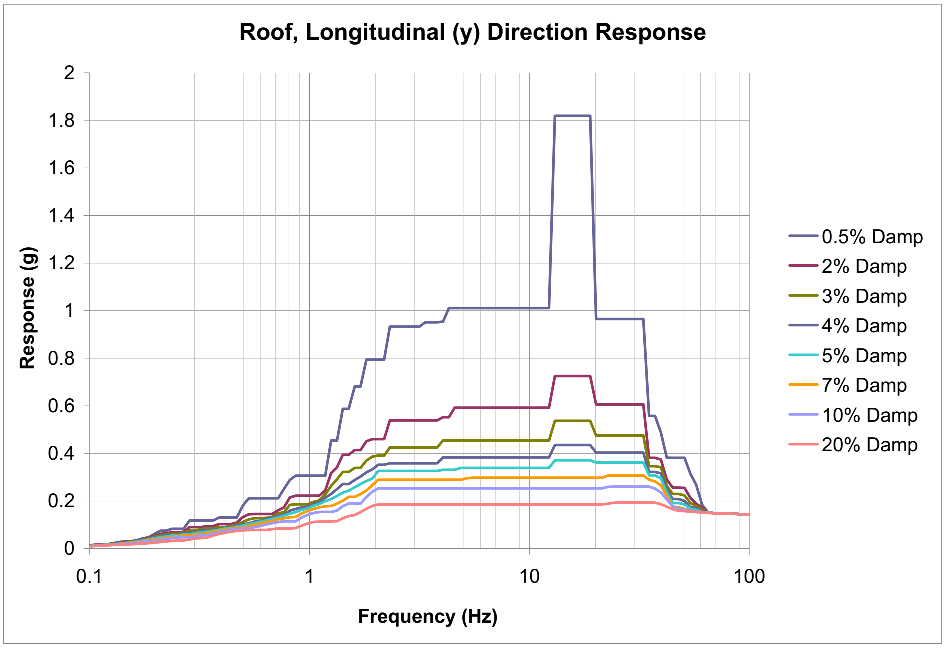

Figure 3LL-7 ISRS for ESWPT Segment 1 (Sheet 6 of 6)

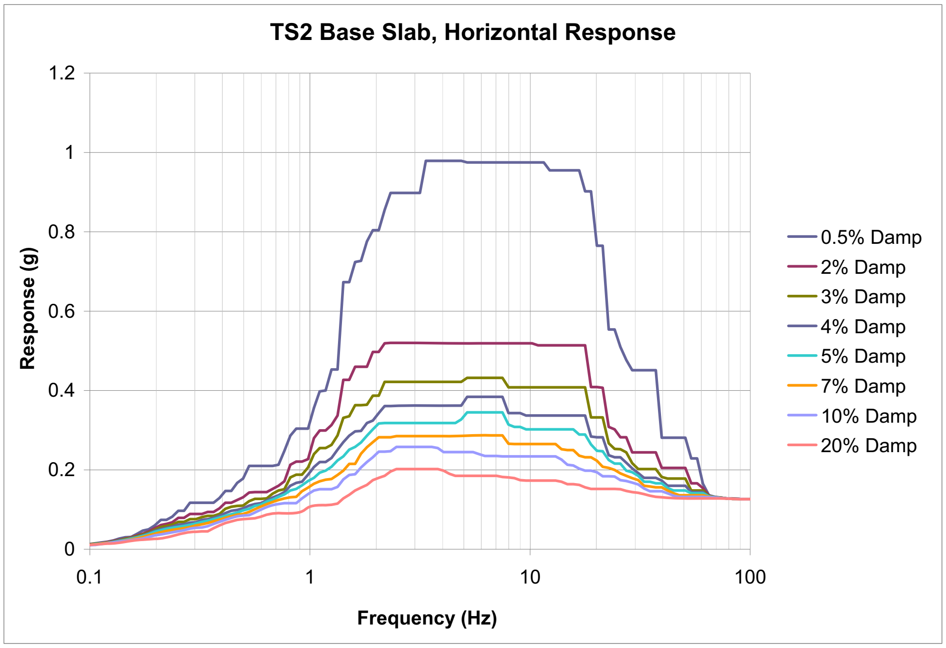

Figure 3LL-8 ISRS for ESWPT Segment 2 (Sheet 1 of 4) (enveloped response for east-west and north-south directions)

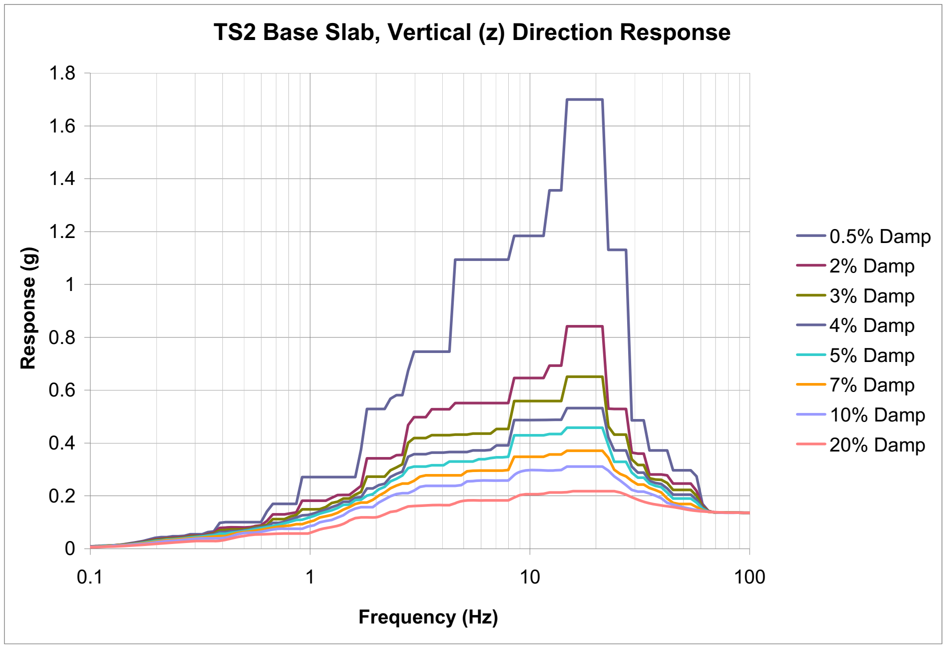

Figure 3LL-8 ISRS for ESWPT Segment 2 (Sheet 2 of 4)

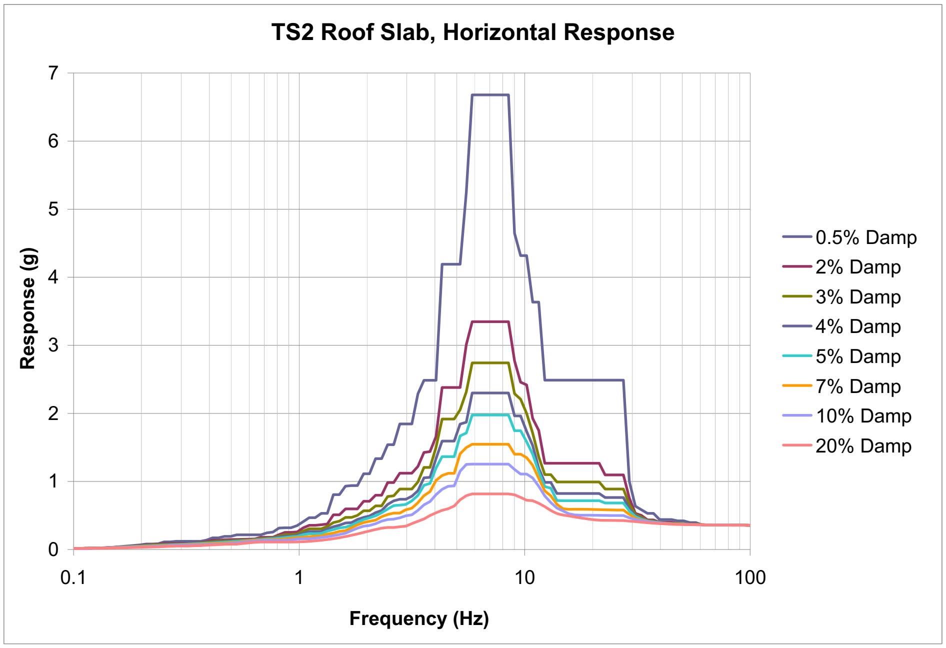

Figure 3LL-8 ISRS for ESWPT Segment 2 (Sheet 3 of 4) (enveloped response for the east-west and north-south directions)

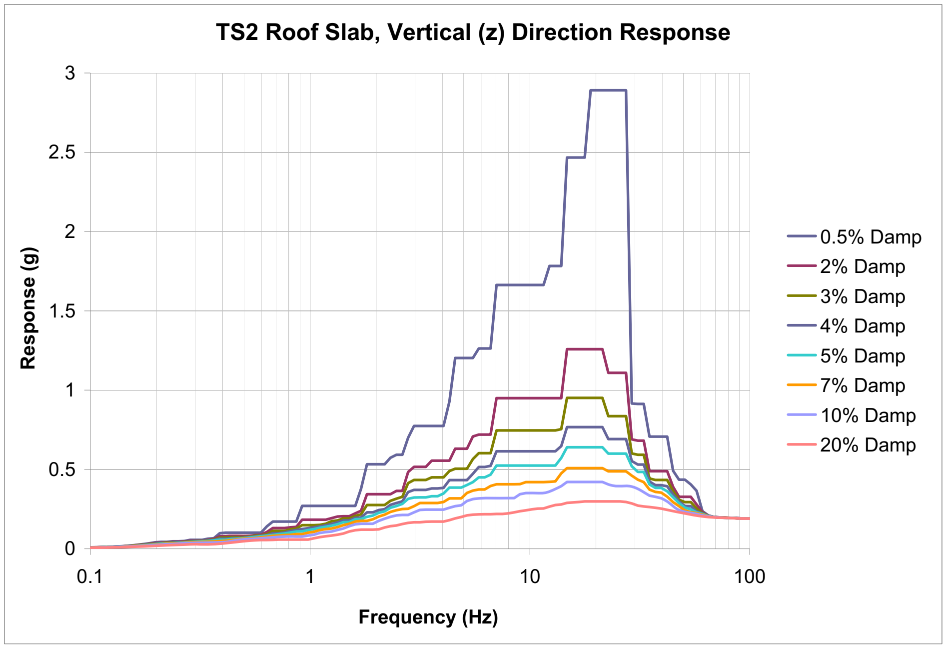

Figure 3LL-8 ISRS for ESWPT Segment 2 (Sheet 4 of 4)

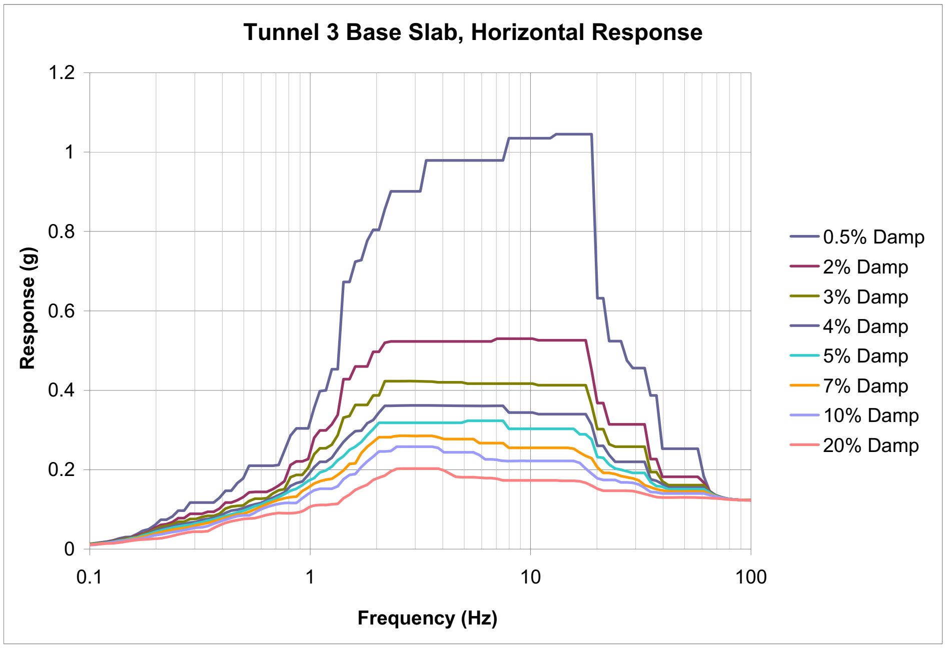

Figure 3LL-9 ISRS for ESWPT Segment 3 (Sheet 1 of 6) (enveloped north-south and east-west response)

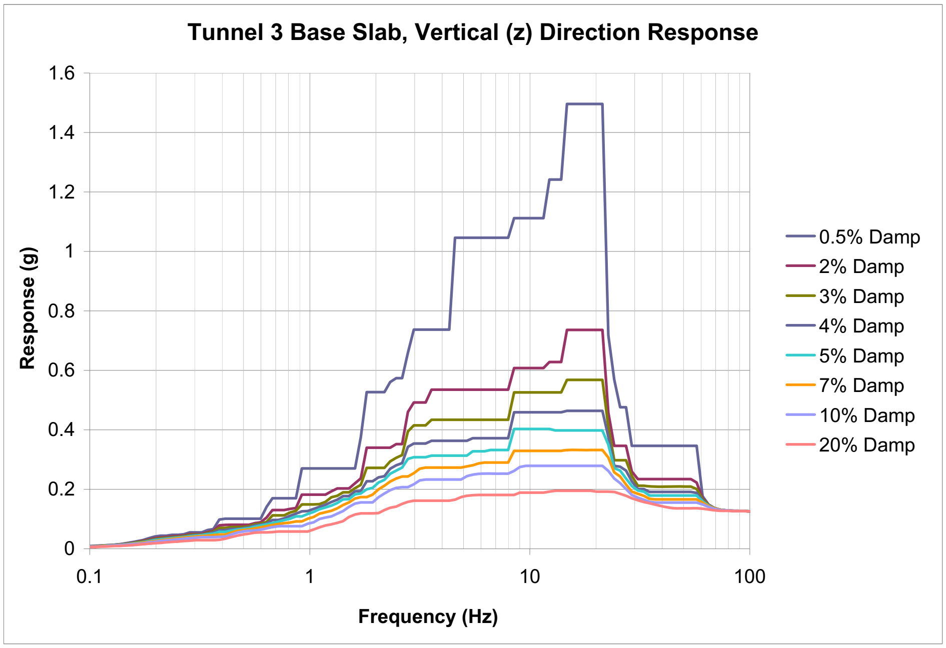

Figure 3LL-9 ISRS for ESWPT Segment 3 (Sheet 2 of 6)

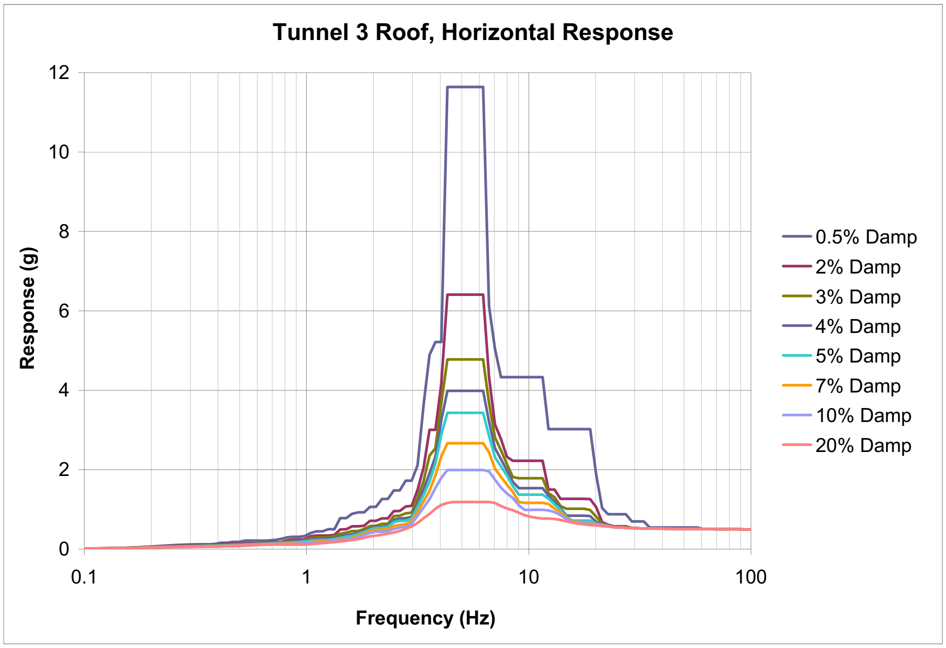

Figure 3LL-9 ISRS for ESWPT Segment 3 (Sheet 3 of 6) (enveloped north-south and east-west response)

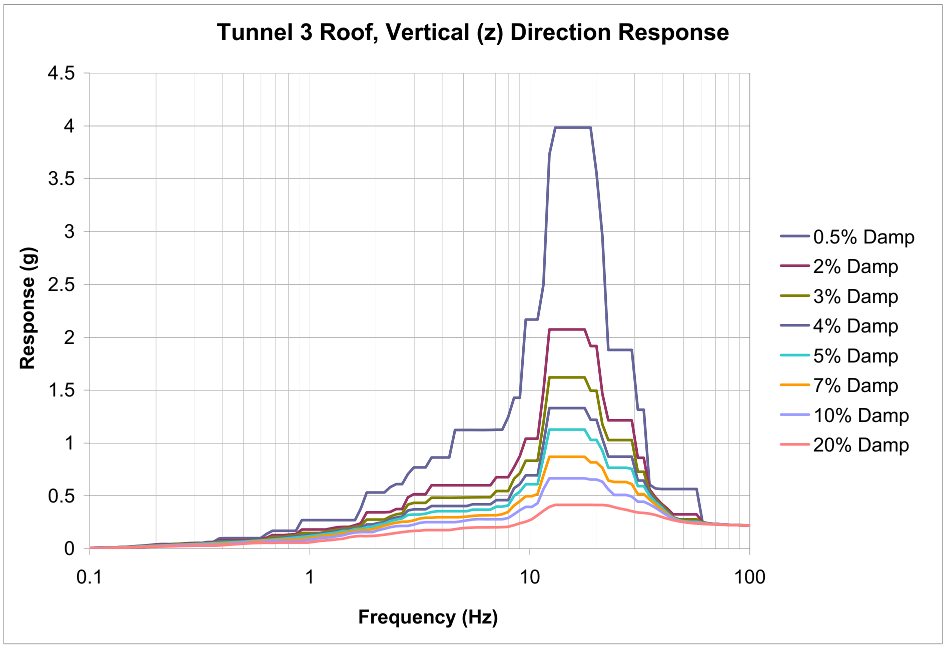

Figure 3LL-9 ISRS for ESWPT Segment 3 (Sheet 4 of 6)

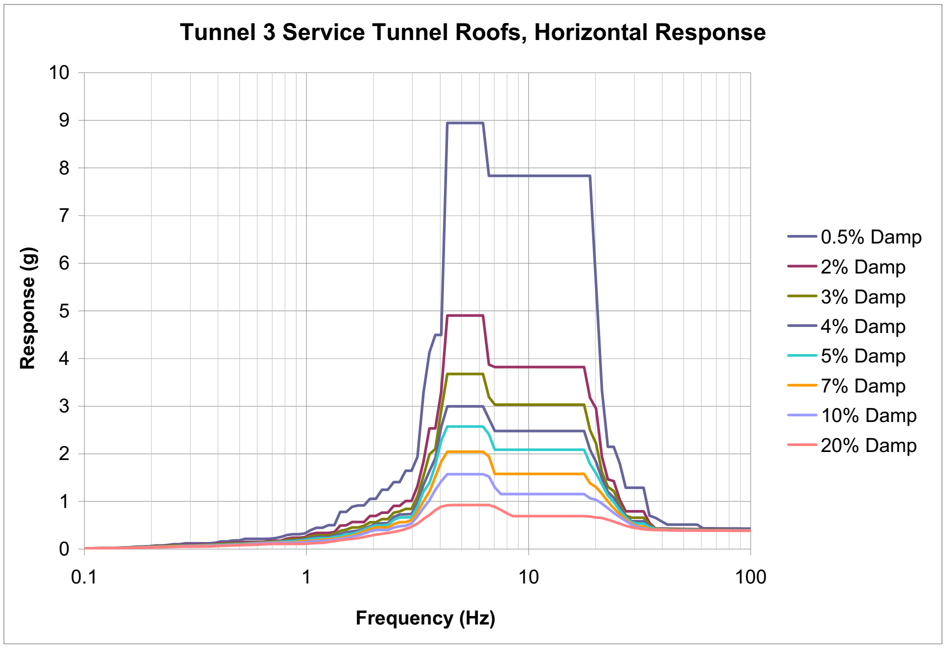

Figure 3LL-9 ISRS for Roofs of Service Tunnels Crossing ESWPT Segment 3 (Sheet 5 of 6) (enveloped response for north-south and east-west directions)

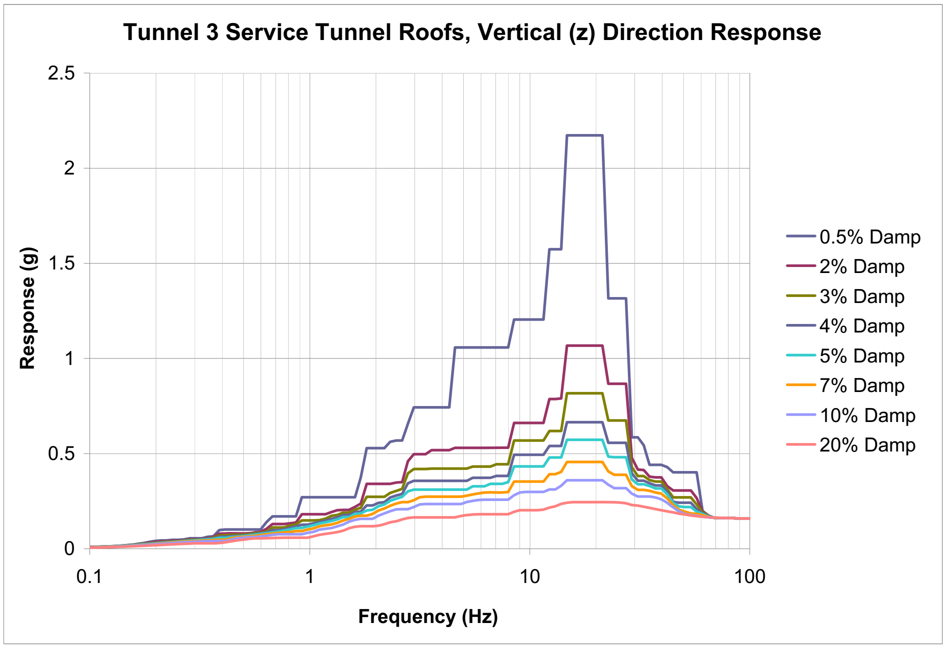

Figure 3LL-9 ISRS for Roofs of Service Tunnels Crossing ESWPT Segment 3 (Sheet 6 of 6)

CP COL 3.7(3)
CP COL 3.7(12)
CP COL 3.7(26)
CP COL 3.8(29)

APPENDIX 3MM

MODEL PROPERTIES AND SEISMIC ANALYSIS RESULTS FOR PSFSVs

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ACRONYMS AND ABBREVIATIONS

Acronyms	Definitions
3D	three-dimensional
BE	best estimate
FE	finite element
FIRS	foundation input response spectra
HB	high bound
ISRS	in-structure response spectra
LB	lower bound
OBE	operating-basis earthquake
PSFSV	power source fuel storage vault
SRSS	square root sum of the squares
SSI	soil-structure interaction
UB	upper bound

3MM MODEL PROPERTIES AND SEISMIC ANALYSIS RESULTS FOR PSFSVs

3MM.1 Introduction

This Appendix discusses the seismic analysis of the power source fuel storage vaults (PSFSVs). The computer program SASSI (Reference 3MM-1) serves as the platform for the soil-structure interaction (SSI) analyses. The three-dimensional (3D) finite element (FE) models used in the SASSI are condensed from FE models with finer mesh patterns initially developed using the ANSYS computer program (Reference 3MM-2). Further, the translation of the model from ANSYS to SASSI is confirmed by comparing the results from the modal analysis of the fixed base structure in ANSYS and the SASSI analysis of the model resting on a half-space with high stiffness. The close correlation between the SASSI transfer function results with the ANSYS eigenvalues results ensures the accuracy of the translation.

The SASSI 3D FE model is dynamically analyzed to obtain seismic results including SSI effects. The SASSI model results including seismic soil pressures are used as input to the ANSYS models for performing the detailed structural design including loads and load combinations in accordance with the requirements of Section 3.8. The Table 3MM-8 summarizes the analyses performed for calculating seismic demands. The SASSI analysis and results presented in this Appendix include site-specific effects such as the layering of the subgrade, embedment of the PSFSVs, flexibility of the basemat and subgrade, and scattering of the input control design motion. Due to the low seismic response at the Comanche Peak Nuclear Power Plant site and lack of high-frequency exceedances, the spatial variation of the input ground motion is deemed not significant for the design of the PSFSVs. Therefore, the SASSI capability to consider incoherence of the input control motion is not implemented in the analysis of the PSFSVs.

3MM.2 Model Description and Analysis Approach

The SASSI FE model for the PSFSV is shown in Figure 3MM-1. Table 3MM-1 presents the properties assigned to the structural components of the SASSI FE model. Table 3MM-2 summarizes the SASSI FE model structural component dimensions and weights. Detailed descriptions and figures of the PSFSV are contained in Section 3.8.

The PSVSV is a simple shear wall structure with four exterior walls plus two interior shear walls. The walls must resist the out of plane flexure and shear due to transverse accelerations, soil pressures (for exterior walls) and flexure imparted on the wall from flexure in the roof slab. The roof slab resists vertical seismic demands as a continuous three span plate although there is some two-way response. Critical locations are therefore centers and edges of roof slabs and walls for flexure and bottom of walls for in-plane shear.

Shell elements are used for the roof, interior and exterior walls, brick elements are used for the base mat, and stiff beam elements are used to represent the emergency power fuel oil tanks and their supports, which are connected to the basemat. The three tanks are considered to be rigid, and full with a total weight of 1155 kips each, which corresponds to the normal operating fuel level. The steel tank mass and stiffness properties, and seismic behavior including hydrodynamic effects, will be accounted for in the design of tank supports, tank support attachments to the slab, and local reinforcement in the tank slab. Walls are modeled using gross section properties at the centerline. The tapered east wall of the vault is modeled at the centerline of the top portion of the wall. The change in thickness is modeled using the average thickness of the wall at each element layer.

The materials and properties of the roof slab are changed to reflect the cracked concrete properties for out of plane bending. The cracked concrete properties are modeled for one-half of the uncracked flexural stiffness of the roof. Un-cracked properties are considered for the in-plane stiffness (Reference 3MM-3). Therefore, to achieve 1/2 flexural out-of-plane stiffness of the slab without reducing its in-plane stiffness or mass, the following element properties are assigned:

$$t_{cracked} = (C_F)^{0.5} \cdot t$$

$$E_{cracked} = [1/(C_F)^{0.5}] \cdot E_{concrete}$$

$$\gamma_{cracked} = [1/(C_F)^{0.5}] \cdot \gamma_{concrete}$$

where:

C_F = the factor for the reduction of flexural stiffness, taken as 1/2,

$t_{cracked}$ = the effective slab thickness to account for cracking

t = the gross section thickness

$\gamma_{cracked}$ = the effective unit weight to offset the reduced stiffness and provide the same total mass

$\gamma_{concrete}$ = unit weight of concrete

$E_{cracked}$ = effective modulus to account for the reduction in thickness that keeps the same axial stiffness while reducing the flexural stiffness by C_F

$E_{concrete}$ = modulus of elasticity of concrete.

The above approach is conservative because slab flexural cracking results in a lower frequency which is closer to the input spectra peak and produces higher design demands. Also, flexural cracking of the slabs does not change the primary load paths for the overall structure and has negligible effect on dynamic load distribution and response.

The analysis of the PSFSV produces 50 modes below 45 Hz. The natural frequencies and descriptions of the associated modal responses of the fixed-base model are presented in Table 3MM-3 for the PSFSV and these frequencies are compared to structural frequencies calculated from the transfer functions of the SASSI model.

The PSFSV model is developed and analyzed using methods and approaches consistent with ASCE 4 (Reference 3MM-3) and accounting for the site-specific stratigraphy and subgrade conditions described in Subsection 2.5.4, as well as the backfill conditions around the embedded PSFSVs. The PSFSV structure is modeled using three orthogonal axes: a y-axis pointing south, an x-axis pointing west, and a z-axis pointing up. The east and west PSFSVs are nearly symmetric; backfill is present on the south and east sides of the east vault and on the south and west sides of the west vault. Due to symmetry, SSI analysis is performed only on the east vault, and the responses are deemed applicable to the west vault.

The input within-layer motion and strain-compatible backfill properties for the SASSI analysis are developed from site response analyses described in Section 3NN.2 of Appendix 3NN by using the site-specific foundation input response spectra (FIRS) discussed in Subsection 3.7.1.1. The properties of the supporting media (rock) as well as the site-specific strain-compatible backfill properties used for the SASSI analysis of the PSFSVs are the same as those presented in Appendix 3NN for the R/B-PCCV-containment internal structure SASSI analyses. To account for uncertainty in the site-specific properties, several sets of dynamic properties of the rock and the backfill are considered, including best estimate (BE), lower bound (LB), and upper bound (UB) properties. For backfill, an additional high bound (HB) set of properties is also used to account for expected uncertainty in the backfill properties.

The above four sets of soil dynamic properties are applied for analysis of the PSFSV structure considering full embedment within the backfill and partial separation of the backfill. An additional case representing a surface foundation condition using lower bound in-situ soil properties beneath the base slab without presence of any backfill is included. The backfill separation is modeled by reducing the shear wave velocity by a factor of 10 for all soil elements adjacent to the structure within the separation depth. The factor of 10 on shear wave velocity represents a factor of 100 on soil shear modulus and Young's modulus. This value is considered adequate to reduce soil pressures sufficiently to represent soil separation. Soil pressures calculated in these layers show that very little pressure is transferred in these layers and the response is not significantly influenced by the small pressures. The potential for separation of backfill is determined by comparing the peak envelope soil pressure results to the at-rest soil pressure for the BE soil case. Consideration of all these conditions assures that the enveloped results presented herein capture all potential seismic effects of a wide range of backfill properties and conditions in combination with the site-specific supporting media conditions. Table 3MM-10 provides SSI analysis cases for the PSFSV.

The shear wave passing frequency for all layers below the base slab and concrete fill, based on layer thickness of 1/5 wavelength, ranges from 30.6Hz for LB to 50.4Hz for HB. The shear wave passing frequency for the backfill ranges from 11.4Hz for LB to 31.1Hz for HB.

A ten-layer half-space is used in the SASSI analysis in accordance with the SASSI Manual recommendations. The SASSI half-space simulation consists of additional layers with viscous dashpots added at the base of the half-space. The half-space layer has a thickness of 1.5 Vs/ f where Vs is the shear wave velocity of the half-space and f is the frequency of analysis. The half-space is sub-divided by the selected number of layers in the half-space.

The lower boundary used in the SASSI analysis is 809 feet below grade. The depth is more than the embedment depth plus twice the depth of the largest base dimension (88’ x 2 + 40’ = 216’) recommended by SRP 3.7.2.

The cutoff frequencies for all cases are greater than 29.9Hz and a minimum of 48 frequencies are analyzed for SSI analyses. The SASSI analysis frequencies were selected to cover the range between around 1 Hz and the cutoff frequency. This frequency range includes the SSI frequency and primary structural frequencies. The 1 Hz lower limit is shown to be low enough to be outside the range of SSI or structural mode amplification. It was verified that as the transfer functions approached the zero frequency (static input), the co-directional transfer function approached unity while the cross-directional terms approached zero. Initially, the frequencies are selected evenly spaced. Frequencies are added as needed to produce smooth interpolation of the transfer functions and accurately capture peaks. As verification, additional frequencies were added to observe that the results did not change.

For the PSFSV analyses, benchmarking is performed to validate the results of the SASSI models for verification of both the mesh and the dynamic response. The mesh used for SASSI analyses is justified with respect to with the more refined design model by calculating eigenvalues and mode shapes for the models with each mesh using ANSYS and comparing the results. The comparisons show that the two models provide similar dynamic responses.

To verify the dynamic response, fixed base eigenvalue analysis is performed in ANSYS, and a corresponding fixed base analysis is performed in SASSI by placing the structure at the soil surface and setting the stiffness of the soil layers to high values to represent the fixed base condition. The fixed base ANSYS eigenvalues are compared to the transfer functions of the SASSI “fixed base” case to verify that the SASSI model exhibits the same dynamic response as the ANSYS model.

Transfer functions are examined for each analysis to verify that the interpolation was reasonable and that the expected structural responses are observed. Transfer functions, spectra, accelerations, and soil pressures are compared between the various soil profiles used in analyses to verify that the responses were reasonably similar between these cases except for the expected trends due to soil frequency changes.

Operating-basis earthquake (OBE) structural damping values of Chapter 3 Table 3.7.1-3(b), such as 4 percent damping for reinforced concrete, are used in the site-specific SASSI analysis. This is consistent with the requirements of Section 1.2 of RG 1.61 (Reference 3MM-4) for structures on sites with low seismic responses where the analyses consider a relatively narrow range of site-specific subgrade conditions.

The SASSI analyses produce results including peak accelerations, in-structure response spectra, and seismic soil pressures. All results from SSI analyses represent the envelope of the nine soil conditions. The SASSI analysis results are used to produce the final response spectra and provide confirmation of the ANSYS design input and output demands.

ANSYS analyses are used to calculate the structural demands of the PSFSV to seismic soil pressure and seismic inertia which are then added to the effects of all other design loads discussed in Section 3.8.4.3. Seismic inertia is analyzed in ANSYS by applying equivalent static lateral loads. The equivalent static lateral loads applied are based on the enveloped peak accelerations calculated in SASSI (provided in Table 3MM-5 and discussed in the following section). For reference, the modal properties of the ANSYS design model are provided in Table 3MM-9.

The seismic soil pressure is analyzed statically in ANSYS. The seismic soil pressure demands are applied on the structural elements as equivalent static pressures. The pressures applied are shown to be conservative when compared to the calculated elastic solution used in ASCE 4-98 based on J.H. Wood, 1973 and the enveloped SASSI results.

Demands from the equivalent static accelerations and soil pressure analyses performed in ANSYS are combined on an absolute basis to produce the maximum demand in each direction.

The effects of fuel tank flexibility are accounted for in the design of the base slab and global stability criteria. The fuel tank flexibility is accounted for by applying an acceleration on the tanks equal to 1.5 times the peak of the 2% damped base spectra from the SASSI analysis.

3MM.3 Seismic Analysis Results

Table 3MM-4 presents a summary of SSI effects on the seismic response of the PSFSV. The maximum absolute nodal accelerations obtained from the SASSI analyses of the PSFSV models are presented in Table 3MM-5. The results are presented for each of the major PSFSV components and envelope all site conditions described above. The maximum accelerations have been obtained by combining cross-directional contributions in accordance with RG 1.92 (Reference 3MM-5) using the square root sum of the squares (SRSS) method.

The seismic design forces and moments based on the ANSYS analysis are presented in Table 3MM-6. The force and moment values represent the enveloped seismic results for all site conditions considered in the analysis. These results are calculated from ANSYS design model subjected to the enveloped of accelerations and dynamic lateral soil pressure from all calculated SASSI analyses. Accidental torsion is accounted by increasing the wall shears given in Table 3MM-6. The walls seismic base shear was increased to account for accidental torsion and total seismic base shear to be resisted by in plane shear of walls. The total adjusted wall shear forces used for design are presented in Figure 3MM-2. The forces presented in the figure are not symmetrical due to model non-symmetry including the sizes of the exterior walls and openings in the north wall. For structural design of members and components, the design seismic forces due to three different components of the earthquake are combined using the Newmark 100% - 40% – 40% method.

The PSFSV displacements due to seismic loading are less than 0.07 inch. Table 3MM-7 summarizes the resulting maximum displacements for enveloped seismic loading conditions.

3MM.4 In-Structure Response Spectra (ISRS)

The enveloped broadened ISRS calculated in SASSI are presented in Figure 3MM-3 for the PSFSV base slab and roof for each of the three orthogonal directions (east-west, north-south, vertical) for 0.5 percent, 2 percent, 3 percent, 4 percent, 5 percent, 7 percent, 10 percent and 20 percent damping. The ISRS for each orthogonal direction are resultant spectra which have been combined using SRSS to account for cross-directional coupling effects in accordance with RG 1.122 (Reference 3MM-6). The ISRS include the envelope of the 11 site conditions (BE, LB, UB, and HB with and without backfill separation from the structure, and the no-fill surface foundation condition with BE, LB, and UB subgrade conditions). All results have been broadened by 15 percent and all valleys removed. The spectra are used for the design of seismic category I and II subsystems and components housed within or mounted to the PSFSV. For the design of seismic category I and II subsystems and components mounted to the PSFSV walls and slabs, it is required to account for the effects of out-of-plane wall flexibility, including seismic anchor motions.

3MM.5 References

3MM-1 *An Advanced Computational Software for 3D Dynamic Analysis Including Soil Structure Interaction,* ACS SASSI Version 2.2, Ghiocel Predictive Technologies, Inc., July 23, 2007.

3MM-2 ANSYS Release 11.0, SAS IP, Inc. 2007.

3MM-3 *Seismic Analysis of Safety-Related Nuclear Structures*. American Society of Civil Engineers, ASCE 4-98, Reston, Virginia, 2000.

3MM-4 *Damping Values for Seismic Design of Nuclear Power Plants*, Regulatory Guide 1.61, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC, March 2007.

3MM-5 *Combining Responses and Spatial Components in Seismic Response Analysis,* Regulatory Guide 1.92, Rev. 2, U.S. Nuclear Regulatory Commission, Washington, DC, July 2006.

3MM-6 *Development of Floor Design Response Spectra for Seismic Design of Floor-supported Equipment or Components*, Regulatory Guide 1.122, Rev. 1, U.S. Nuclear Regulatory Commission, Washington, DC, February 1978.

Table 3MM-1

FE Model Component Properties

Components	Material	E (ksi)	Poisson's Ratio	Unit Weight (kcf)	Damping Ratio	FE Thickness (ft)	Element type
Exterior Walls	5,000 psi concrete	4,030	0.17	0.170(1)	0.04	2.5	Shell
Exterior Tapered Wall	5,000 psi concrete	4,030	0.17	0.170(1)	0.04	3.14 to 4.38	Shell
Interior Walls	5,000 psi concrete	4,030	0.17	0.2167(1)	0.04	1.5	Shell
Roof (2)	5,000 psi concrete	5,696	0.17	0.2475(2)	0.04	1.414	Shell
Base slab	5,000 psi concrete	4,030	0.17	0.1577(1)	0.04	6.5	Brick
Emergency Fuel Oil Tanks	Steel	29,000	0.3	5.28(3)	0.04	N/A	Beam

Notes:

1) The unit weight includes uniform equivalent dead loads of 50 psf on all interior surfaces.
2) The values of E, thickness and unit weight are adjusted to consider cracked concrete properties of the roof slab for out-of-plane bending as discussed in Appendix Subsection 3MM.2. Roof unit weight includes 50 psf (for either 50 psf pipe load or 25 percent of a 200 psf live load on the roof slab).
3) The unit weight includes the weight of the emergency fuel oil tanks and the oil stored within. Tank supports are modeled as massless beams.

Table 3MM-2

SASSI FE Model Component Dimensions and Weights[1]

FE Component	Slab Width or Wall Height (ft)	Slab or Wall Length (ft)	Slab or Wall Thickness (ft)	Weight (kips)
North Exterior Wall	40	83.5	2.5	1,330
South Exterior Wall	40	83.5	2.5	1,420
West Exterior Wall	40	75.5	2.5	1,284
East Exterior Wall	40	75.5	Varies from 4.5 at bottom to 2.5 at top	1,926
West Interior Wall	40	75.5	1.5	982
East Interior Wall	40	75.5	1.5	982
Roof Slab	83.5 (east-west)	75.5 (north-south)	2[2]	2,206
Base mat	83.5 (east-west)	75.5 (north – south)	6.5	6,462
Tanks including full fuel oil content	N/A	N/A	N/A	1,155 x 3 = 3,465
Total Weight	40	83.5	2.5	20,057
Equivalent Weight (ksf) on Slab Area (78'x88')				2.9
Peak Dynamic Pressure[3] (ksf)				2.2

Notes:

1) The width and length dimensions in the table have been adjusted from actual dimensions to suit the mesh pattern used for the FE model. The adjustments are minor and do not affect the accuracy of the analysis results. Actual component dimensions are shown in Section 3.8 Figures 3.8-212, 3.8-213, and 3.8-214.
2) The actual roof slab thickness of 2 ft is adjusted to 1.414 ft in the FE model to account for its cracked properties, as discussed in Appendix Subsection 3MM.2.
3) Peak dynamic pressure at corner elements, each representing less than 1 percent of the slab area, are as high as 4.1 ksf. Average peak pressure over total slab area is 0.7 ksf.

Table 3MM-3

SASSI FE Model Natural Frequencies[(1)]

Frequency (Hz)	Comments
12.7	East-west response, interior walls out-of plane
15.5	East-west response, exterior walls out-of plane
18.3	East-west response, walls in plane
18.9	Vertical response, roof slab
23.7	North-south response, overall structure

Notes:

1) Natural frequencies and effective masses were calculated in ANSYS using the same mesh as used for SASSI analyses.

Table 3MM-4

SASSI Results for PSFSV Seismic Response

SSI Effect	Observed Response
Rock Subgrade	The rock subgrade has insignificant SSI effect on the PSFSV seismic response. Instead, the structural natural frequencies obtained from SASSI analyses of the surface foundation characterize the response, due to the high stiffness of the rock and the small weight of the foundation.
Backfill Embedment	The properties of the backfill embedment affect the overall response of PSFSV structure. Backfill soil frequencies, in the range of 4 Hz for lower bound to 8 Hz for high bound, characterize the PSFSV horizontal response. Frequencies of 7 Hz for lower bound, 11 Hz for best estimate, 14 Hz for upper bound, and 17 Hz for high bound, characterize the vertical response of the backfill. The peaks increase in magnitude as the frequency of the backfill approaches that of the PSFSV structure.
Backfill soil separation	The effects of backfill soil separation on the PSFSV response are small.
Scattering Effects	The dynamic properties mismatch between the backfill and the rock results in reflection of the seismic waves within the backfill stratum. Multiple modes characterize the backfill soil column that can have some effect on the PSFSV response when their frequencies are close to the structural frequencies.

Table 3MM-5

SASSI FE Model Component Peak Accelerations

Component	N-S Acceleration (g) (+/- Y Direction)	E-W Acceleration (g) (+/- X Direction)	Vertical (g) (+/- Z Direction)
North Exterior Wall	0.18	0.18	0.13
South Exterior Wall	0.21	0.17	0.13
West Exterior Wall	0.16	0.42	0.13
East Exterior Wall	0.15	0.26	0.13
West Interior Wall	0.17	0.67	0.13
East Interior Wall	0.17	0.67	0.13
Roof Slab	0.17	0.21	0.63
Basemat	0.11	0.12	0.12

Notes:

1) The peak accelerations presented above envelope all of the considered site conditions, i.e. PSFSV embedded in BE, LB, UB, and HB backfill with and without soil separation, as well as the PSFSV supported by a surface foundation.

2) For structural design using the loads and load combinations in Section 3.8, the seismic loads are obtained by applying uniform accelerations to the PSFSV structure. This approach captured effects due to localized peak accelerations presented above. The uniform accelerations are applied as follows: For the horizontal direction a uniform acceleration of 0.25g was applied. For the vertical direction a uniform acceleration of 0.15g was applied. These accelerations were applied to all elements in the vault, except that the horizontal acceleration applied to the tanks for purposes of basemat design was 0.87g. This value represents 1.5 times the peak horizontal acceleration of 0.58g obtained from the 2% damping ISRS for the base slab given in Figure 3MM-3 (Sheet 1 of 6). An additional distributed load corresponding to 0.40g was applied to the two interior walls and the east wall to account for increased local out-of-plane accelerations obtained from the SASSI analysis. An additional distributed load corresponding to 0.50g was applied to all the roof slabs to account for increased local accelerations obtained from the SASSI analysis. Seismic load also includes seismic backfill pressures on the sides of the PSFSV walls.

Table 3MM-6

Maximum Component Seismic Forces and Moments

Component		Maximum component forces and moments N_V (k/ft)	N_L (k/ft)	Q_V (k/ft)	Q_L (k/ft)	S_W (k/ft)	M_V (k-ft/ft)	M_L (k-ft/ft)	M_{VL} (k-ft/ft)
South Exterior Wall	+	65.07	54.87	14.32	23.61	41.24	25.70	28.28	13.42
	-	87.05	63.09	10.58	24.39	24.18	39.11	68.79	14.45
North Exterior Wall	+	22.62	6.88	4.06	2.02	29.98	9.37	27.50	3.60
	-	19.94	15.12	19.53	3.54	19.54	12.38	15.04	4.68
West Exterior Wall	+	20.07	17.25	19.82	5.27	19.90	76.89	26.73	29.56
	-	15.06	27.82	14.26	13.00	14.06	119.32	48.10	30.14
East Exterior Wall	+	13.82	24.29	6.40	4.71	16.40	34.89	32.23	7.53
	-	16.42	17.29	6.28	5.52	14.10	37.00	14.21	8.06
West Interior Wall	+	25.13	4.29	9.18	5.27	18.51	18.97	11.95	3.38
	-	17.33	31.42	5.31	4.95	13.27	19.53	12.14	3.28
East Interior Wall	+	12.04	4.14	5.20	9.63	17.96	18.75	14.01	3.92
	-	12.87	32.65	6.50	7.75	8.89	19.75	16.26	3.56
Roof Slab	+	25.64	20.19	9.78	6.72	21.22	19.77	8.82	6.74
	-	43.10	20.47	10.99	7.73	17.65	21.19	20.59	7.06
Basemat	+	30.98	29.30	33.41	40.91	35.66	229.94	238.11	103.25
	-	38.83	29.15	24.73	37.91	34.94	137.87	240.56	102.25

Notes:

1) The forces and moments shown above include forces and moments due to seismic soil pressure that envelope the all four subgrade shear wave velocity conditions (LB, BE, UB, and HB). The forces and moments are used for structural design as described in Section 3.8.
2) The forces and moments are obtained by combination of the three orthogonal directions used in the model by the Newmark 100%-40%-40% method.
3) In the table above the vertical and longitudinal directions define the plane of the walls. N stands for axial force, Q for out-of-plane shear, S_W for in-plane shear and M for moment. The M_V results in normal stresses in the vertical direction of the wall and similarly, M_L results in normal stresses in the longitudinal (horizontal) direction of the wall, and M_{VL} is the torsional moment on the wall. The Q_V is out-of-plane shear force acting on horizontal cross section of the wall, and Q_L is out-of-plane shear force acting on a vertical cross section of the wall. For the roof slab and base slab the vertical axis is oriented along the east-west direction and the longitudinal in the north-south direction

Table 3MM-7

PSFSV Maximum Displacements for All Enveloped Conditions

Component	Maximum Displacement (inches)	Description
Roof slab	0.05	Horizontal displacement equivalent to story drift; occurs at edge of slab near center of wall
East exterior wall	0.07	Horizontal (out-of-plane) displacement near center of wall
West exterior wall	0.05	Horizontal (out-of-plane) displacement near center of wall

Table 3MM-8

Summary of Analyses Performed

Model	Loading Case	Analysis Method	Program	Input	Output	Three Components Combination
Three-dimensional PSFSVs FE Model	Seismic motion	Time history soil-structure interaction analysis in frequency domain using sub-structuring technique	SASSI	Time history input matching site-specific design response spectra from site-response analysis, site-specific soil profiles.	Peak accelerations, in-structure response spectra	SRSS
Three-dimensional PSFSVs FE Model	Seismic soil pressure	Static	ANSYS	Peak soil pressures based on ASCE 4-98, separate analysis for each direction of pressure.	Element and section demands	Added to seismic demands in same direction and combined by Newmark 100-40-40 percent combination rule
Three-dimensional PSFSVs FE Model	Seismic inertia	Static	ANSYS	Peak accelerations that envelope results of SASSI.	Element and section demands	Combined by Newmark 100-40-40 percent combination rule

Table 3MM-9

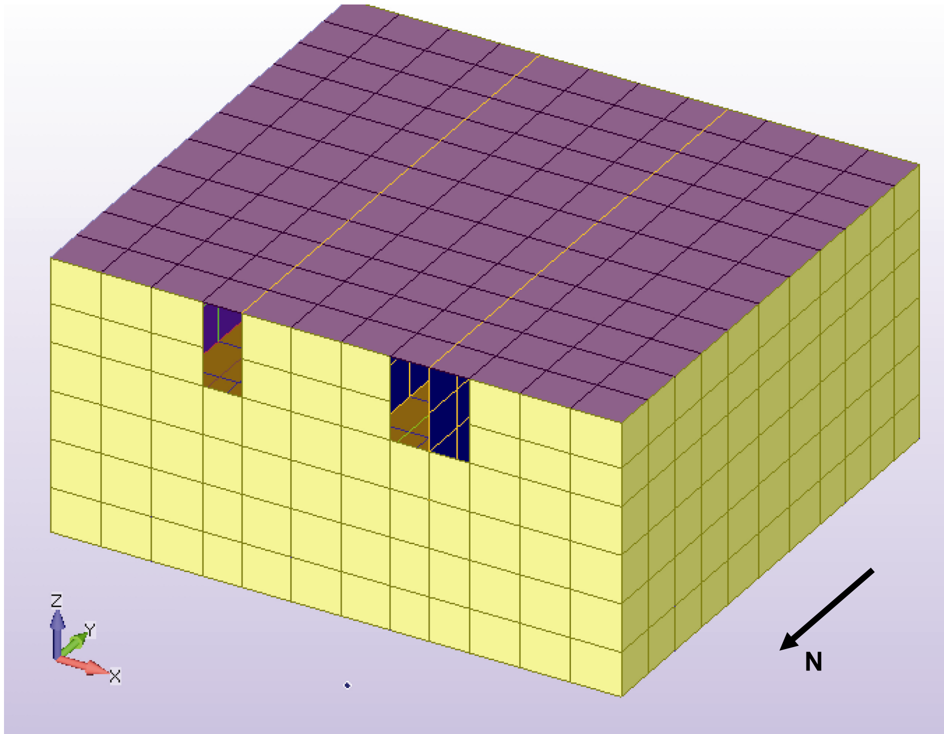
Major Structural Modes of PSFSV

Major East-West Direction Modes			
Mode	Frequency (Hz)	Period (sec)	Effective Mass (kip sec^2/ft)
8	17.688	0.0566	87.744
2	11.861	0.08431	46.6474
6	15.459	0.064687	26.7655
4	14.71	0.067981	26.1976
7	17.237	0.058015	7.20513
Major North-South Direction Modes			
Mode	Frequency (Hz)	Period (sec)	Effective Mass (kip sec^2/ft)
17	24.056	0.04157	160.91
18	24.929	0.040114	32.7644
19	24.994	0.04001	4.96764
16	23.799	0.042019	3.74051
27	31.991	0.031259	2.01327
Major Vertical Modes			
Mode	Frequency (Hz)	Period (sec)	Effective Mass (kip sec^2/ft)
7	17.237	0.058015	30.7952
8	17.668	0.0566	10.7574
19	24.994	0.04001	7.17713
4	14.71	0.067981	3.83556
14	21.549	0.046406	3.75472

Table 3MM-10

SSI Analysis Cases for the PSFSV

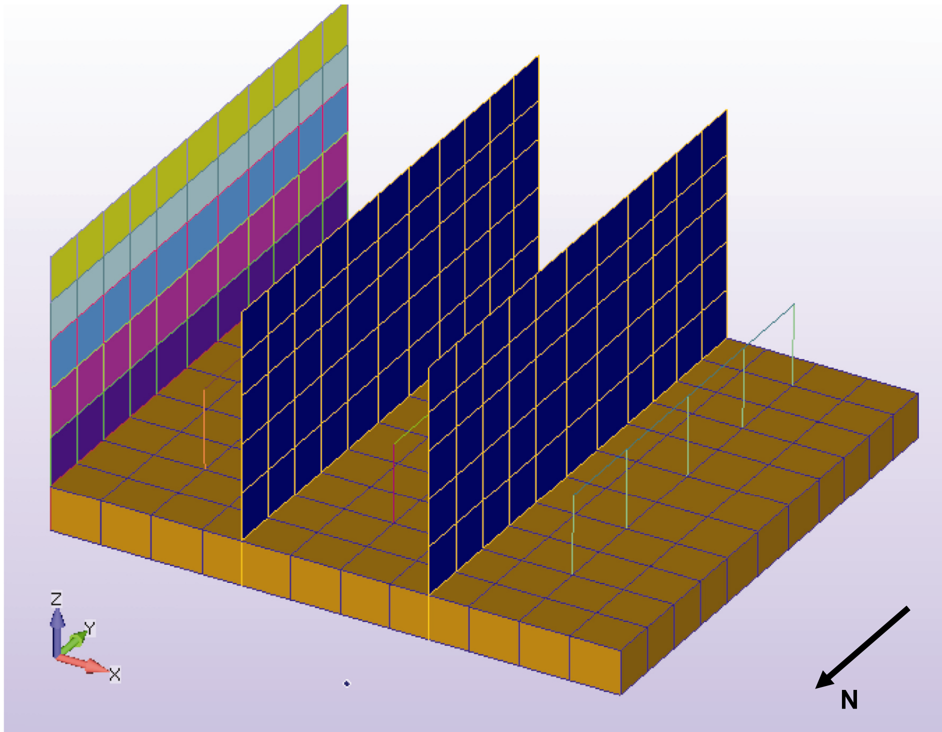
Ana;ysis	Description	Backfill Soil	Rock Subgrade	Soil Separation
1	Best Estimate	Best estimate	Best estimate	No
2	Lower Bound	Lower bound	Lower bound	No
3	Upper Bound	Upper bound	Upper bound	No
4	High Bound	High bound	Upper bound	No
5	Best Estimate Separated	Best estimate	Best estimate	Yes
6	Lower Bound Separated	Lower bound	Lower bound	Yes
7	Upper Bound Separated	Upper bound	Upper bound	Yes
8	High Bound Separated	High bound	Upper bound	Yes
9	Lower Bound No Fill	-	Lower bound	N/A



Notes:

1) The vault pipe/access tunnel openings are on the north exterior wall as shown in the model above.

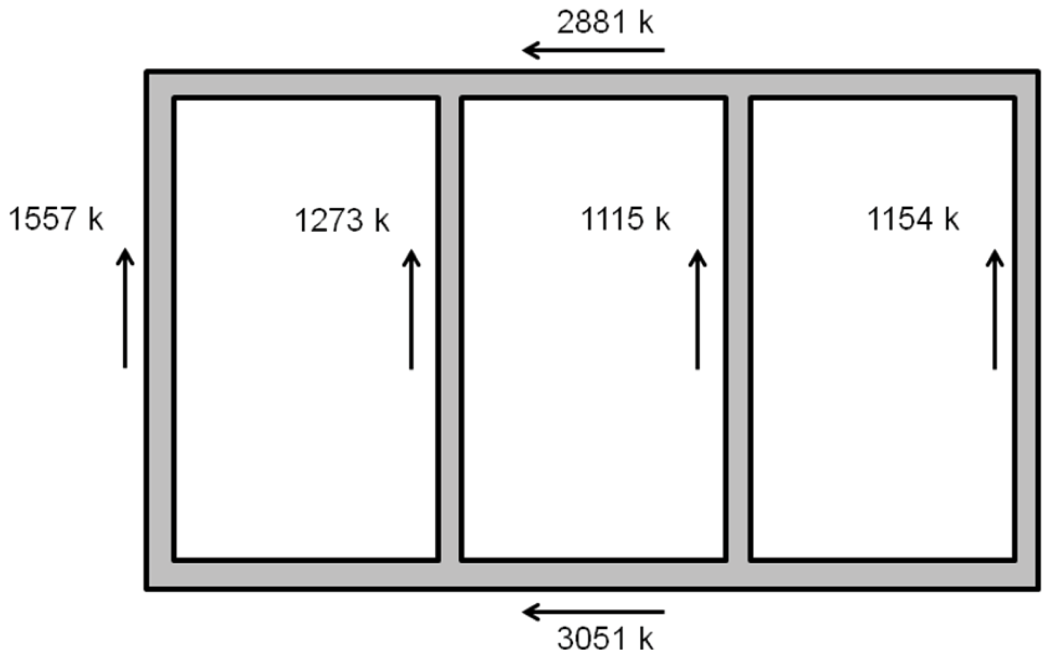
Figure 3MM-1 Overall SASSI Model of PSFSV (Sheet 1 of 2)



Notes:

1) The steel elements representing the tank are shown above as column and beams. The tank supports are modeled as beam elements oriented in the east-west direction and located at the base of each tank column element.

Figure 3MM-1 Overall SASSI Model of PSFSV (Sheet 2 of 2, Cutaway View of SASSI Model of PSFSV)



Notes:

1) The seismic shear forces shown above are computed for the west vaulltat the bottom of each wall at the interface with the foundation mat and account for accidental eccentricity and total seismic base shear to be resisted by in plane shear of walls. East vault shear forces are symmetrical about the north-south axis.

Figure 3MM-2 Maximum Seismic Base Shear Forces in Wall

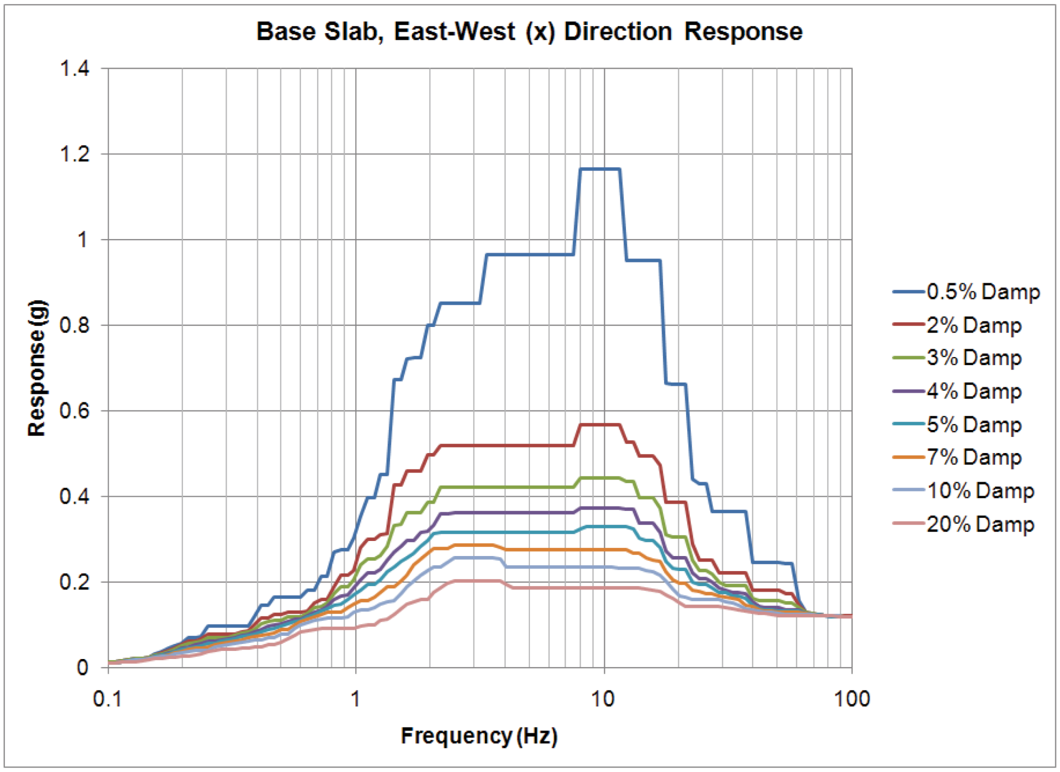


Figure 3MM-3 ISRS for PSFSV (Sheet 1 of 6)

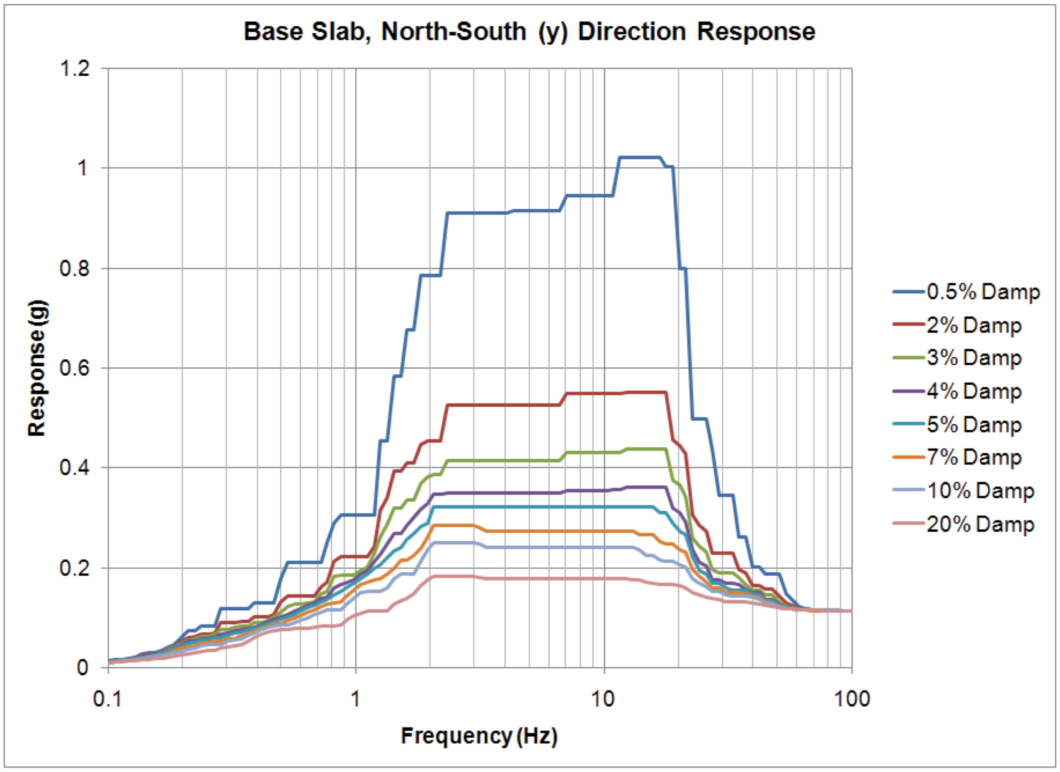


Figure 3MM-3 ISRS for PSFSV (Sheet 2 of 6)

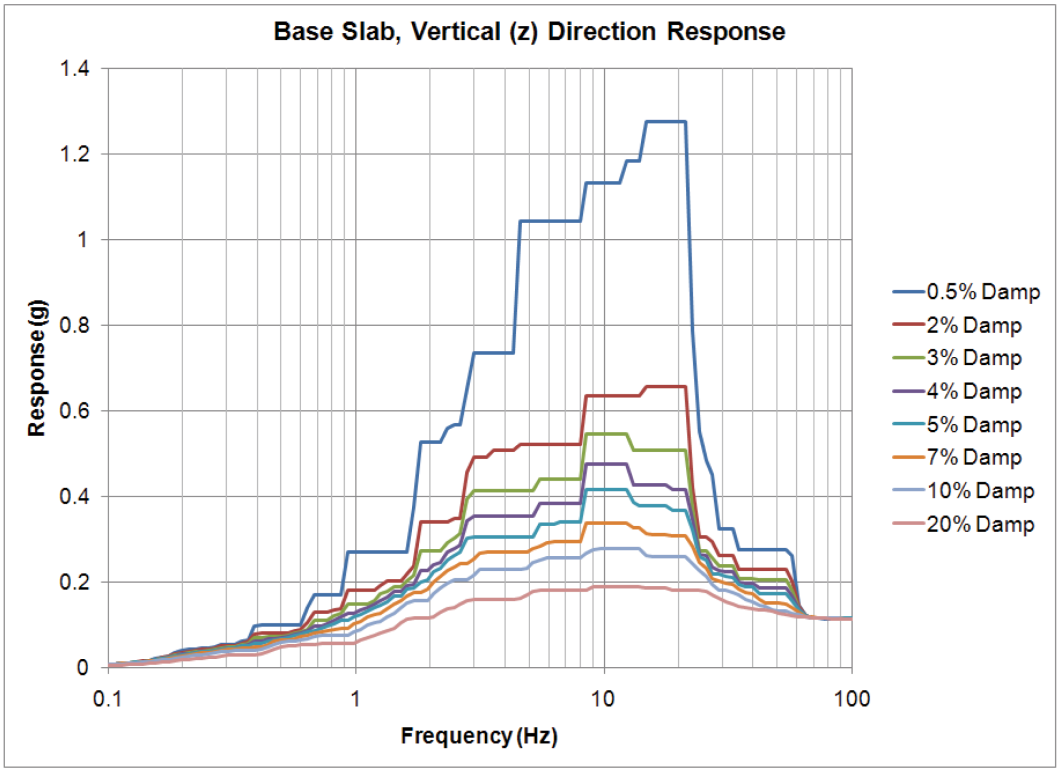


Figure 3MM-3 ISRS for PSFSV (Sheet 3 of 6)

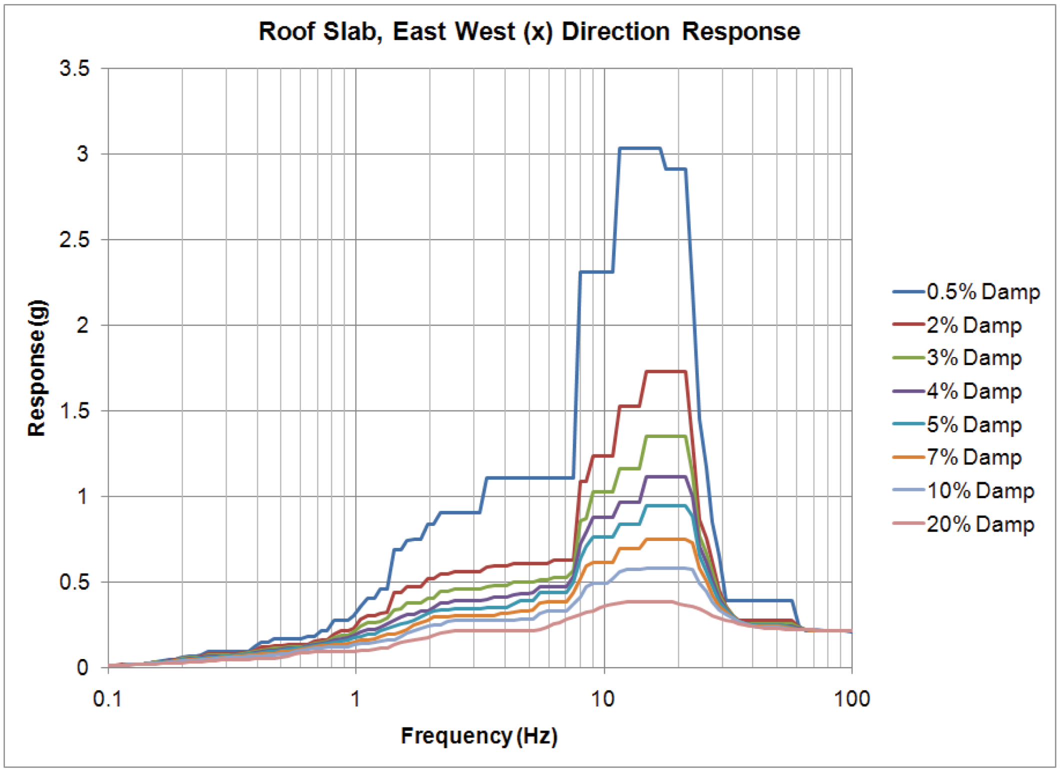


Figure 3MM-3 ISRS for PSFSV (Sheet 4 of 6)

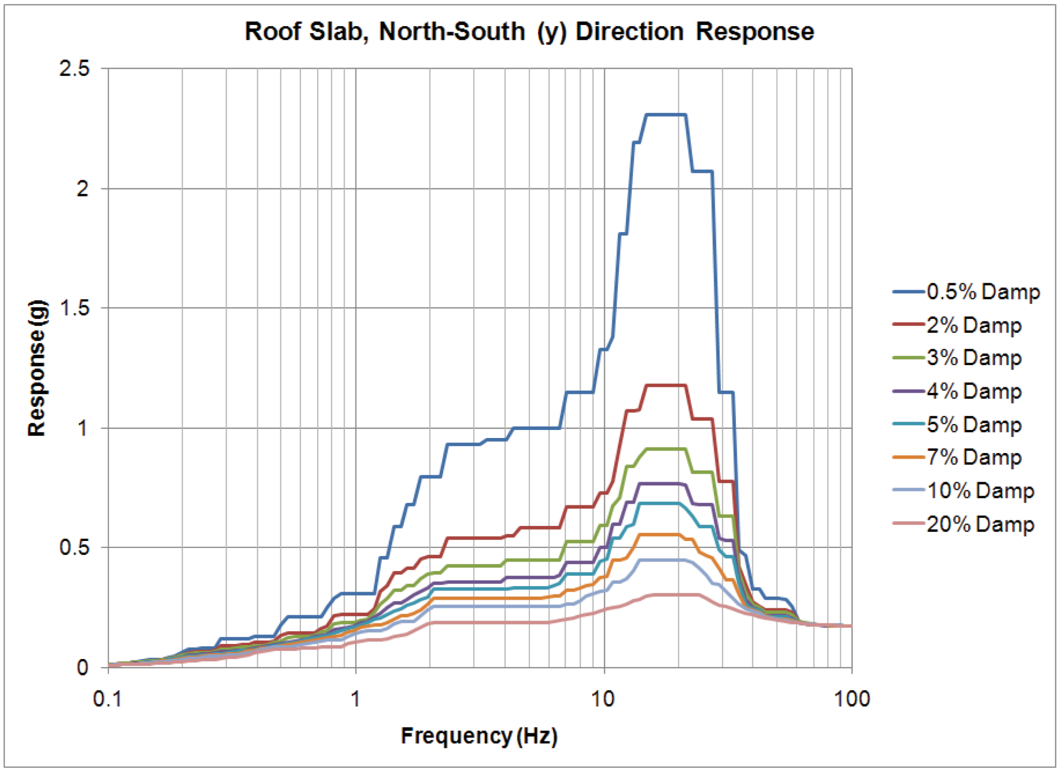


Figure 3MM-3 ISRS for PSFSV (Sheet 5 of 6)

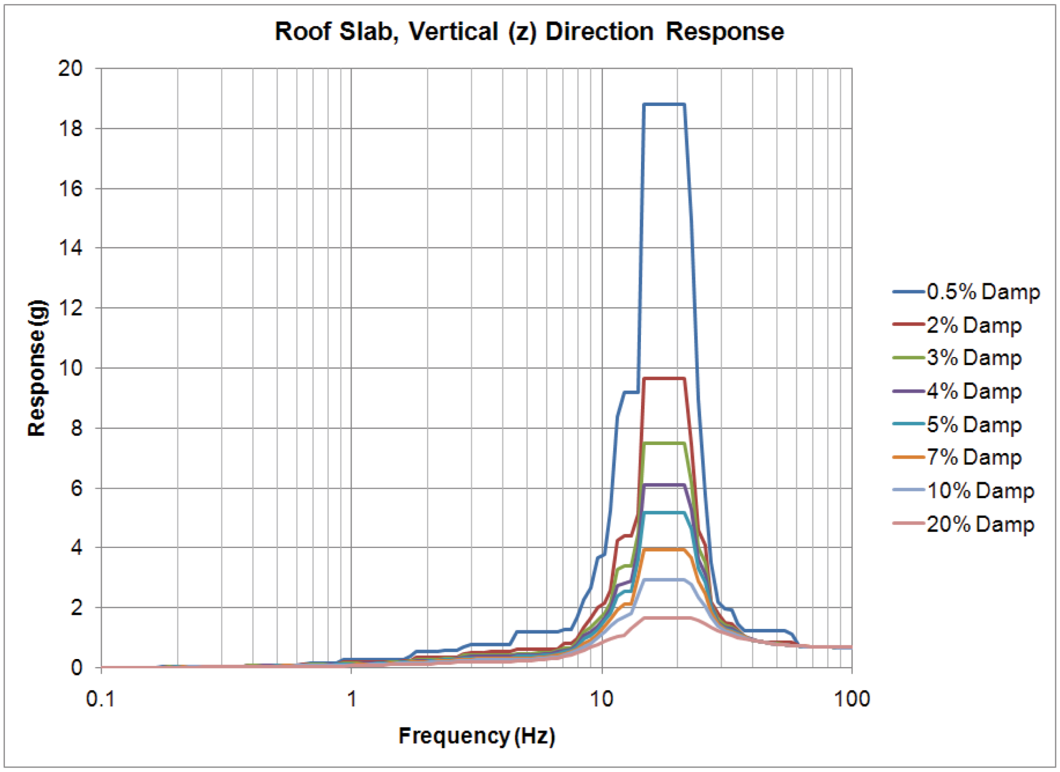


Figure 3MM-3 ISRS for PSFSV (Sheet 6 of 6)