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Site-Specific Site Response Analysis and Cascadia Subduction Zone Ground Motions Evaluation for a Site Near Portland

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Site-Specific Site Response Analysis and Cascadia Subduction Zone Ground Motions Evaluation for a Site Near Portland

BY

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A research project report submitted in partial fulfillment
of the requirement for the degree of

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Second, I would like to thank my supervisor at work, Ryan White, for his mentorship throughout the past several years of my engineering career. Ryan helped provide me with advice, technical assistance, and some of the software necessary to complete this project.

Lastly, I'd like to thank all of the excellent instructors I've had throughout my academic career, at Portland State University, as well as while earning my bachelor's degree at the University of Pittsburgh. These instructors have been essential to starting my engineering career and helped facilitate my interest in geotechnical engineering.

ABSTRACT

Site-specific ground motions, site-specific site response analysis, and development of site-specific acceleration ground spectra at the ground surface was developed per ASCE 7-10 for the Kirkland Renaissance Boardwalk, a site in Vancouver, Washington.

Synthetic broadband ground motions developed specifically for Cascadia Subduction Zone (CSZ) megathrust earthquake were used for site-response analysis. The results of site-specific site response analyses using the strong motions were compared with the results from the 5 motions considered for the ASCE 7-10 procedure. The effect of motion duration and other ground motion intensity measures on the results of the site-specific site response analysis was investigated.

Similar trends of resulting amplification factors were observed when considering long duration CSZ motions and the 5 historical motions utilized for the ASCE 7-10 site-specific site response analysis procedure. Maximum amplification from the CSZ motions was consistent with the 5 historical motions, although maximum amplification occurred at shorter periods. In addition, the amplification factors at PGA from the CSZ motions were generally higher.

It was found that amplification factors developed using 5 historic motions or CSZ-specific synthetic motions did not show a strong correlation with strong motion duration and other ground motion intensity measures. For the CSZ motions, amplification at PGA tended to decrease as intensity parameters increased, but increased as significant duration increased. The trends between maximum amplification and intensity measures were not as apparent for the 5 historical motions.

The results of this study highlighted the advantages of performing site-specific site response analysis in reducing uncertainty in design accelerations. This study also indicated the applicability of broadband synthetic CSZ ground motions for the purpose of performing site response analysis.

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1.0 INTRODUCTION

The Kirkland Renaissance Boardwalk site is located in Vancouver, Washington. The coordinates of the site are 45.62109, -122.67134.

Plans for the project include developing a 2.2-acre site currently occupied by the former Joe's Crab Shack, and Who Song and Larry's restaurants, and associated parking and landscaping. The new development will include a combination of both retail and residential space. Three, 3-story commercial structures are planned along the Columbia River frontage, on the south side of the property, with a seven- to eight-story tower on the north side of the property that includes residential units over ground-floor commercial development. Current plans include below-grade parking that may extend up to 30 feet below the existing ground surface to accommodate car parking and stackers.

Subsurface conditions at the site consist of dense to very dense gravel. Any potentially liquefiable soils will be removed to accommodate below-grade parking. Based on subsurface conditions encountered in explorations completed by PBS Engineering and Environmental, combined with shear wave velocity testing of the dense to very dense gravel layer at the nearby I-5 Columbia River Crossing by Shannon and Wilson in 2010, Site Class C is appropriate for use in design.

2.0 DEVELOPMENT OF MCE_R SPECTRA FOR BEDROCK PER ASCE 7-10

2.1 Development of probabilistic MCER spectra for bedrock

Table 1, below, presents the Uniform Hazard Spectra (UHS) at a 2475-year return period for the Kirkland Renaissance Boardwalk. This UHS was developed using the 2014 USGS maps. However, the 2014 USGS maps do not provide the full range of spectral response. The UHS for a nearby site in Portland, Oregon, developed by an outside consultant using the software EZ-FRISK, was utilized to obtain missing response spectra that could not be obtained from the 2014 USGS maps.

Table 1. Uniform hazard spectra (UHS) at 2475-year return period for the Kirkland Renaissance Boardwalk, Site Class B/C (Vs=760 m/s), based on USGS 2014

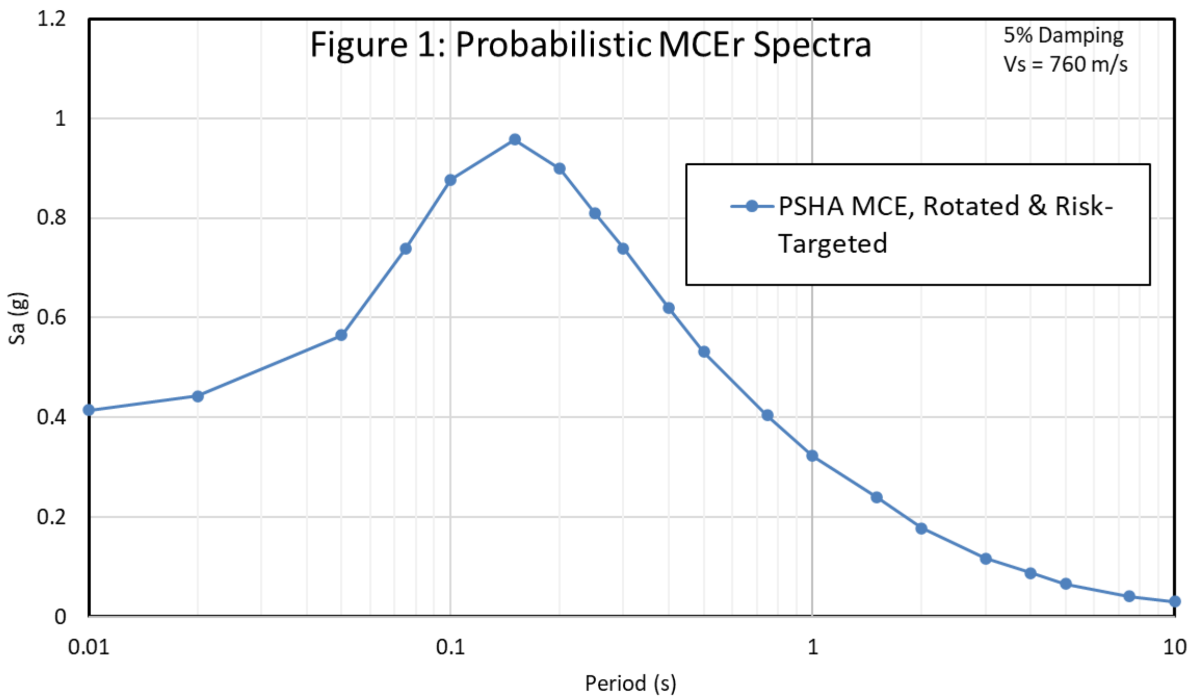
Period (sec)	Spectral Acceleration, Sa (g)
0.01	0.4149
0.02	0.4433
0.03	0.4819
0.05	0.5651
0.075	0.7382
0.1	0.8771
0.15	0.9573
0.2	0.8992
0.25	0.8100
0.3	0.7390
0.4	0.6200
0.5	0.5317
0.75	0.4040
1	0.3224
1.5	0.2400
2	0.1776
3	0.1169
4	0.0875
5	0.0657
7.5	0.0404
10	0.03017

Table 2, below, summarizes the risk and maximum rotation coefficients used to develop the probabilistic MCE_R spectra per ASCE 7-10.

Table 2. Risk and Maximum Rotation Coefficients, per ASCE 7-10

Period (sec)	Cr	ASCE 7-10 Max. Rot. Factor
0.01	0.886	1.1
0.02	0.886	1.1
0.05	0.886	1.1
0.075	0.886	1.1
0.1	0.886	1.1
0.15	0.886	1.1
0.2	0.886	1.1
0.25	0.885	1.11
0.3	0.883	1.13
0.4	0.881	1.15
0.5	0.878	1.18
0.75	0.872	1.24
1	0.865	1.3
1.5	0.865	1.33
2	0.865	1.35
3	0.865	1.4
4	0.865	1.45
5	0.865	1.5
7.5	0.865	1.5
10	0.865	1.5

Figure 1 below provides a plot of the probabilistic MCE_R spectra for bedrock (Site Class B/C) per ASCE 7-10 Section 21.2.1.



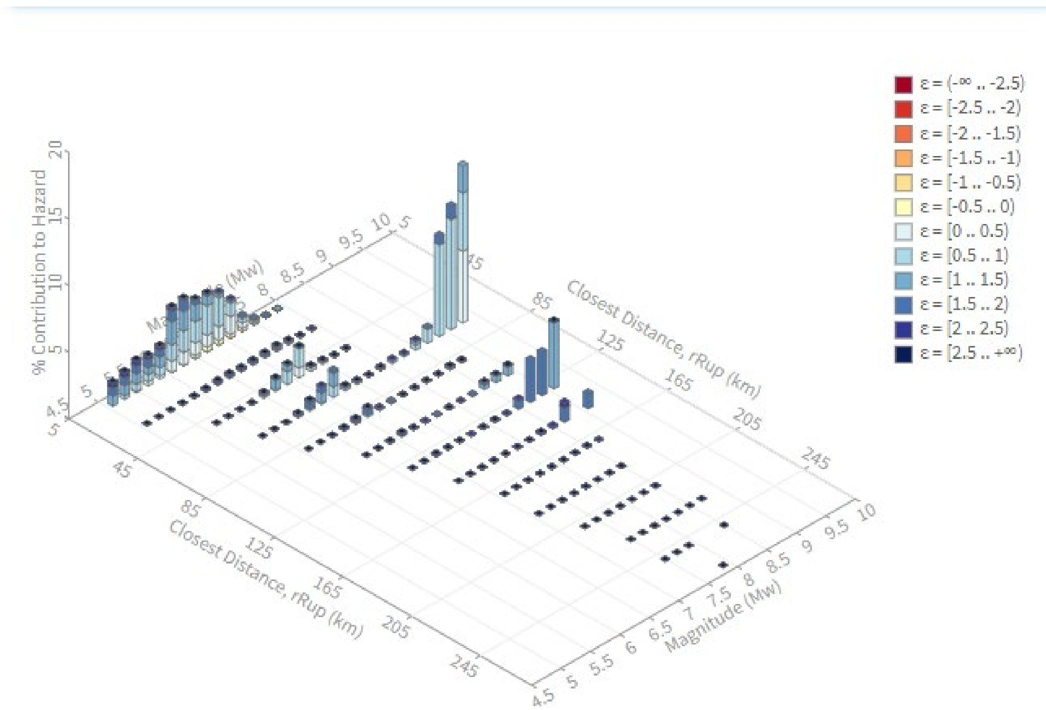
2.2 Development of deterministic MCE_R spectra for bedrock

Results of deaggregation analyses using the USGS 2014 maps for the Kirkland Renaissance Boardwalk are summarized below in Table 3 and Figure 2. Results were obtained using USGS Dynamic: Conterminous U.S. 2014 v 4.2.0. Site Class B/C (760 m/s) was considered, and a 2475 year return period.

Table 3. Summary of deaggregation results for Kirkland Renaissance Boardwalk based on USGS 2014 (2475 year, PGA)

Seismic Source	Contribution
CSZ interface (interface)	38%
CSZ intraslab (stab)	7%
Portland Hills Fault (PHF)	7%
Grant Butte	5%
Grid	8%
Others	35%

Figure 2. Deaggregation results at the site



Deterministic seismic hazard analysis (DSHA) was then performed per ASCE 7-10 Section 21.2.2 on the highest contributing subduction zone (CSZ Interface) and largest contributor shallow crustal source (PHF).

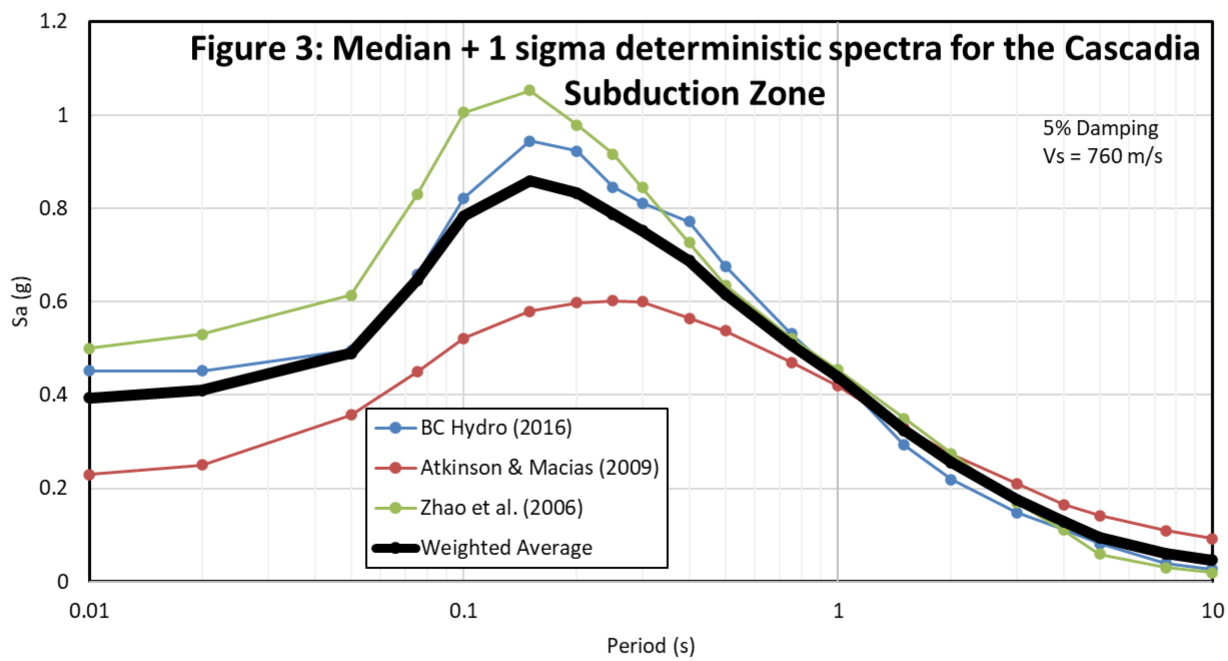
For the CSZ Interface, the following ground motion prediction equations (GMPEs), presented in Table 4, were used with weighting per USGS.

Table 4. GMPEs and weightings used to model the Cascadia Subduction Zone in the DSHA

GMPE	Weight
BC Hydro (2012)	0.33
Atkinson and Macias (2009)	0.33
Zhao et al. (2006)	0.33

A moment magnitude of 9, closest distance to rupture of 80 kilometers, and Vs of 760 m/s was considered for calculating the DSHA for CSZ Interface using the GMPEs.

Figure 3, below, shows the completed DSHA for the CSZ Interface.



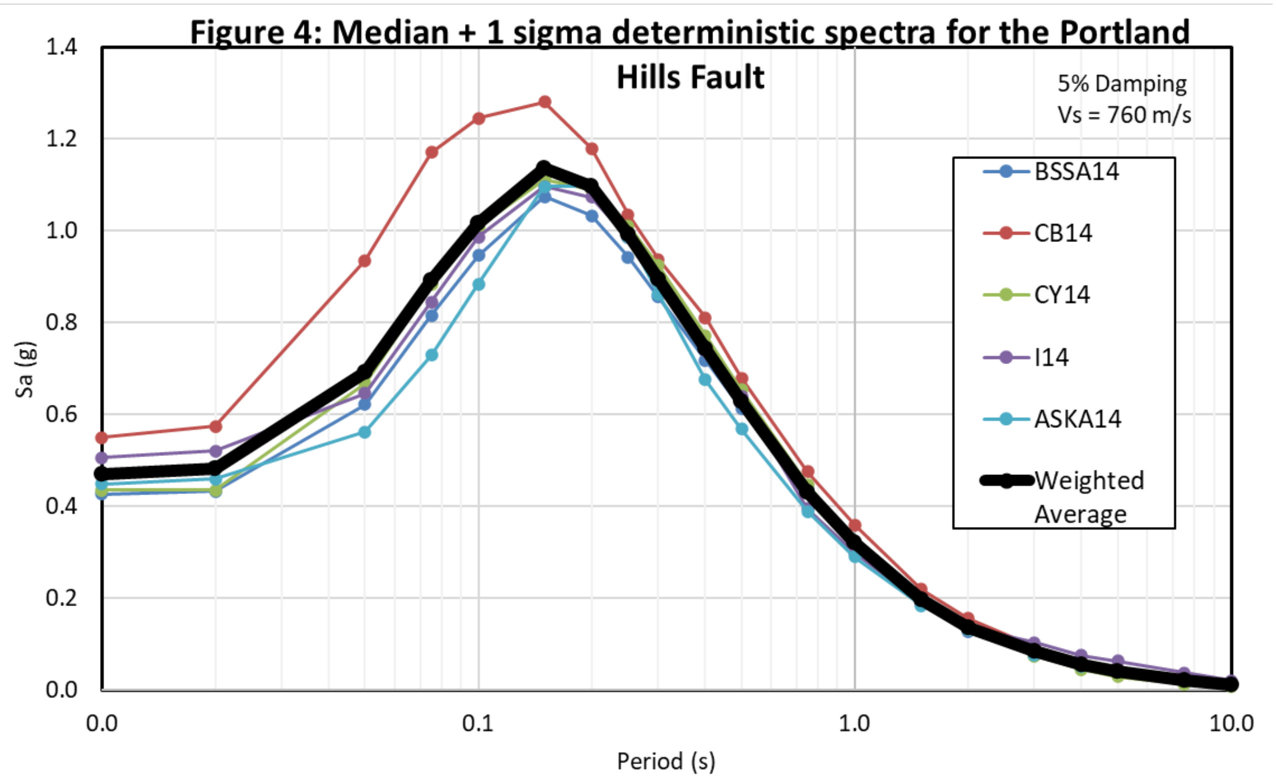
For the PHF, the following GMPEs, presented in Table 5, were used with weighting per USGS.

Table 5. GMPEs and weightings used to model the Portland Hills Fault in the DSHA

GMPE	Abbreviation	Weight
Abrahamson et al. (2014)	ASK14	0.22
Boore et al. (2014)	BSSA14	0.22
Campbell and Bozorginia (2014)	CB14	0.22
Chiou and Youngs (2014)	CY14	0.22
Idriss (2014)	I14	0.12

A moment magnitude of 7, closest distance to rupture of 10 kilometers, and Vs of 760 m/s was considered for calculating the DSHA for PHF using the GMPEs.

Figure 4, below, shows the completed DSHA for PHF.



A comparison of the deterministic spectra for Portland Hills Fault and CSZ is presented below in Figure 5. For a 2475-year return period the response spectra is controlled by the Portland Hills Fault until a period of approximately 0.5 seconds. After a period of approximately 0.5 seconds, the CSZ controls the response spectra.

Figure 5: Comparison of the deterministic spectra for Portland Hills Fault and Cascadia Subduction Zone

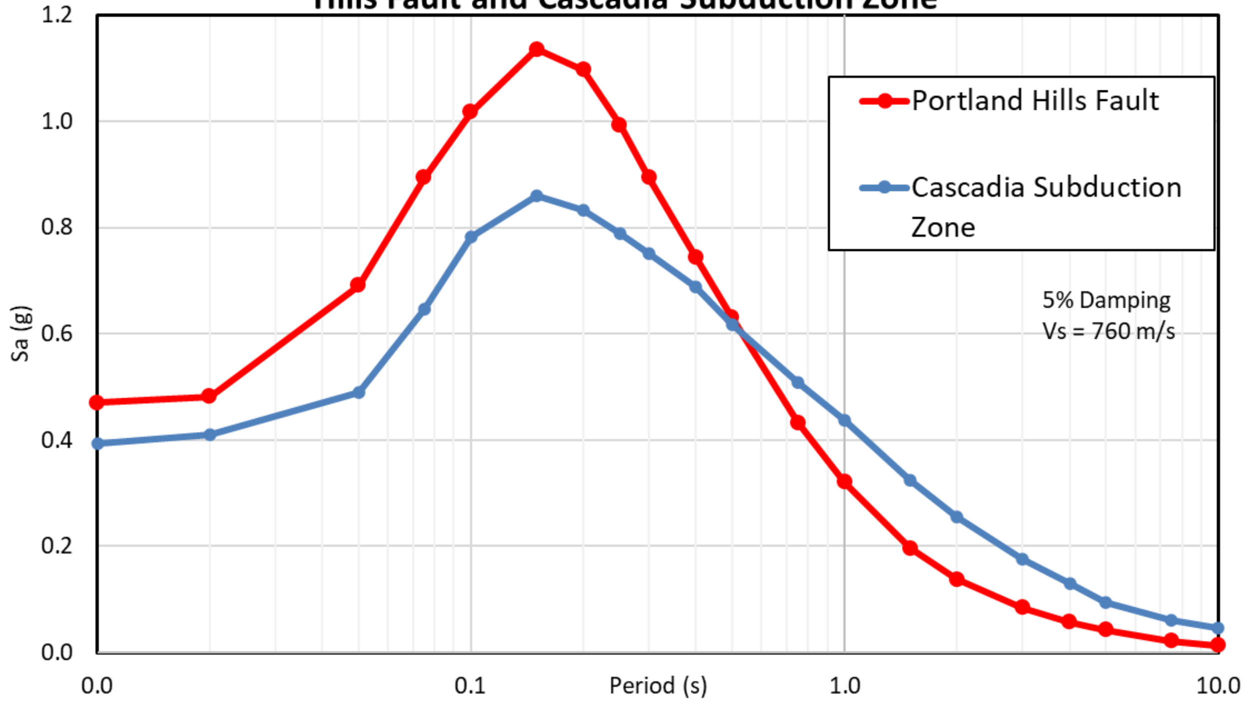
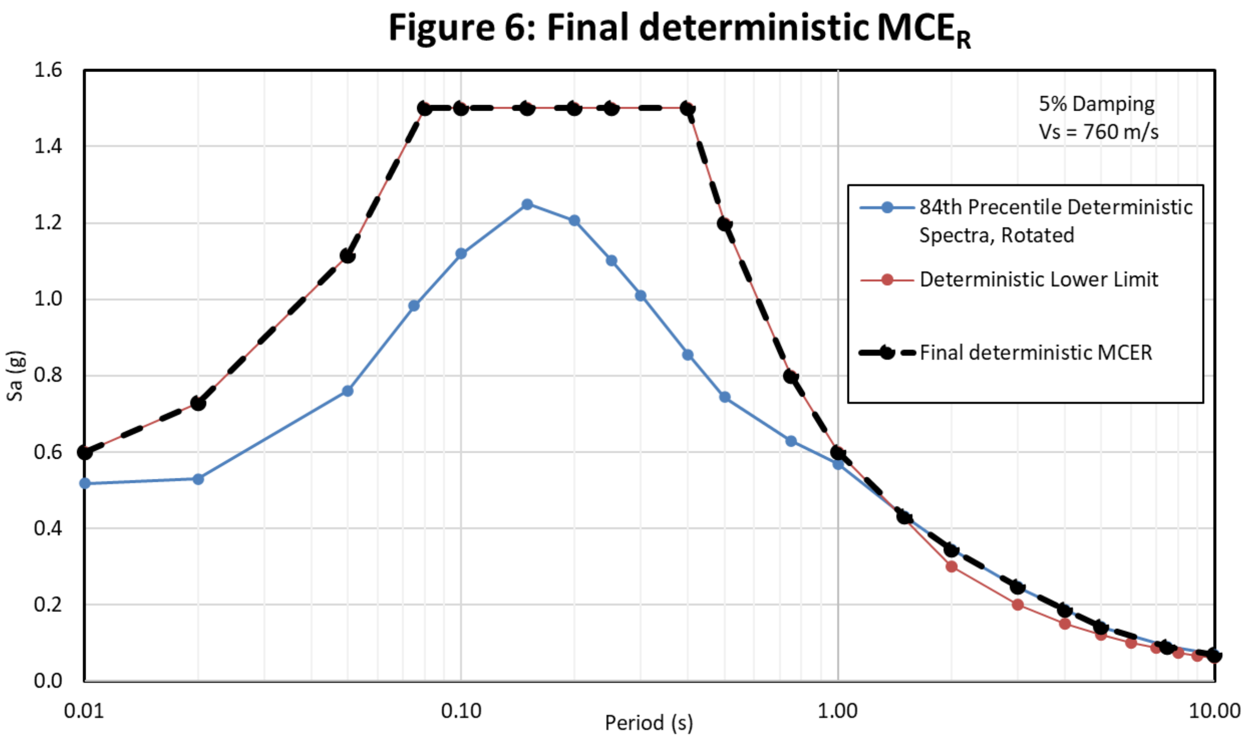


Figure 6 below provides the final deterministic MCE_R per ASCE 7-10 21.2.2.



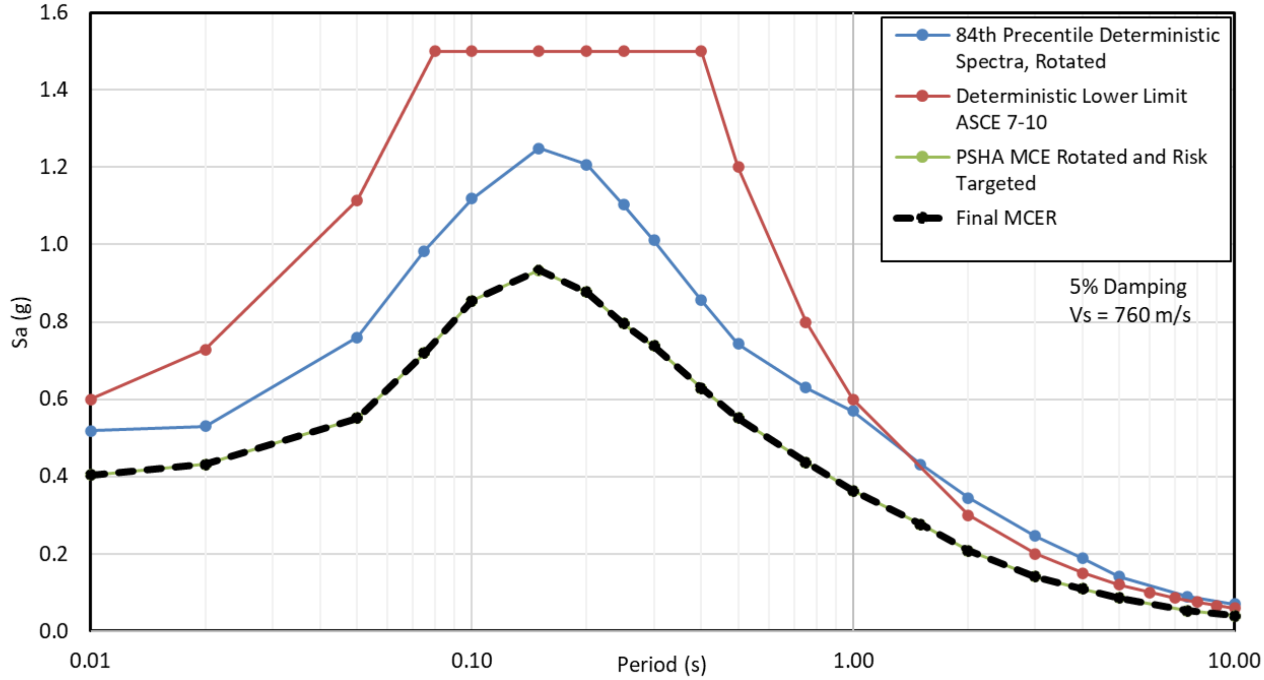
2.3 Development of site-specific MCER

The site-specific MCE_R per ASCE 7-10 Section 21.2 is provided below in Table 6 and Figure 7. The probabilistic spectra controls the final site-specific MCE_R.

Table 6. Site-specific MCE_R for the Kirkland Renaissance Boardwalk

Period (sec)	Spectral Acceleration, Sa (g)
0.01	0.40436
0.02	0.43204
0.05	0.55075
0.075	0.71945
0.1	0.85482
0.15	0.93298
0.2	0.87636
0.25	0.79570
0.3	0.73737
0.4	0.62815
0.5	0.55086
0.75	0.43684
1	0.36254
1.5	0.27611
2	0.20739
3	0.14157
4	0.10975
5	0.08525
7.5	0.05242
10	0.03915

Figure 7: Development of the target MCER spectrum



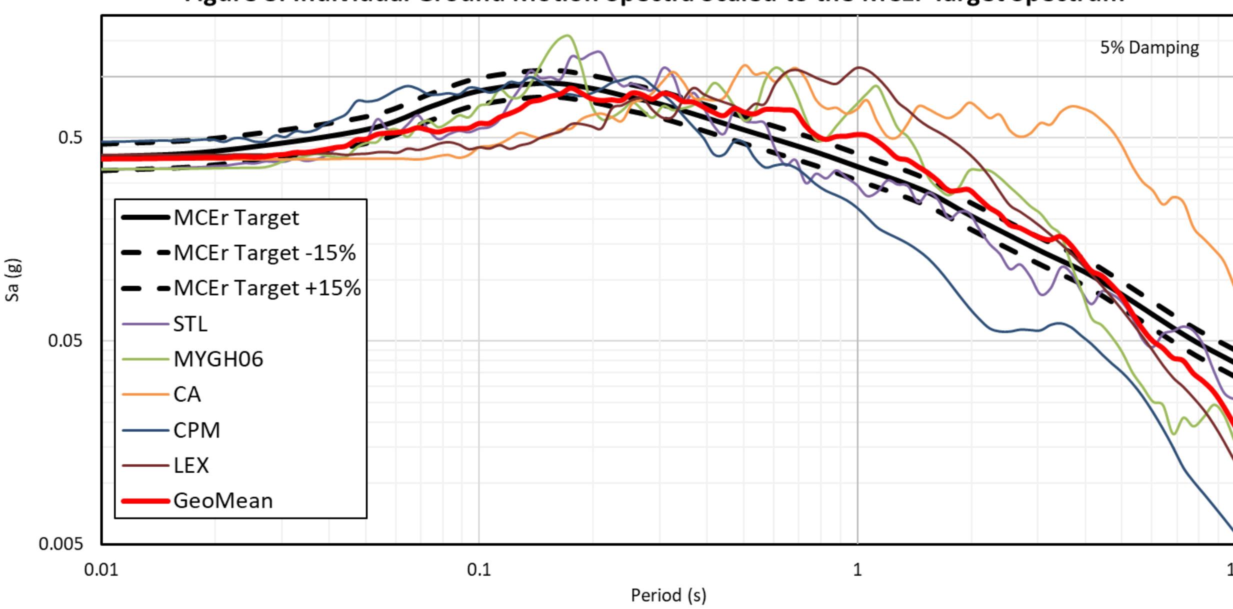
2.4 Ground Motions Scaling

Two interface subduction motions, one interslab subduction motion, and two shallow crustal motions were selected for ground motion scaling. Table 7 below summarizes the horizontal ground motions and scaling factors used to scale to the target MCER spectrum. Figure 8 provides the ground motion spectra scaled with the factors provided in Table 7.

Table 7. Scale factors for ground motions

Scale Factor	2011 Tohoku, Japan	2010 Maule, Chile	2001 El Salvador	1992 Cape Mendocino, CA	1989 Loma Prieta, CA
	Tajiri (MYGH06)	Cerro Santa Lucia (STL)	Acajutla Cepa (CA)	Cape Mendocino (CPM)	Los Gatos-Lex. Dam (LEX)
	1.3	1.4	4.0	0.3	1.1

Figure 8: Individual Ground Motion Spectra Scaled to the MCEr Target Spectrum

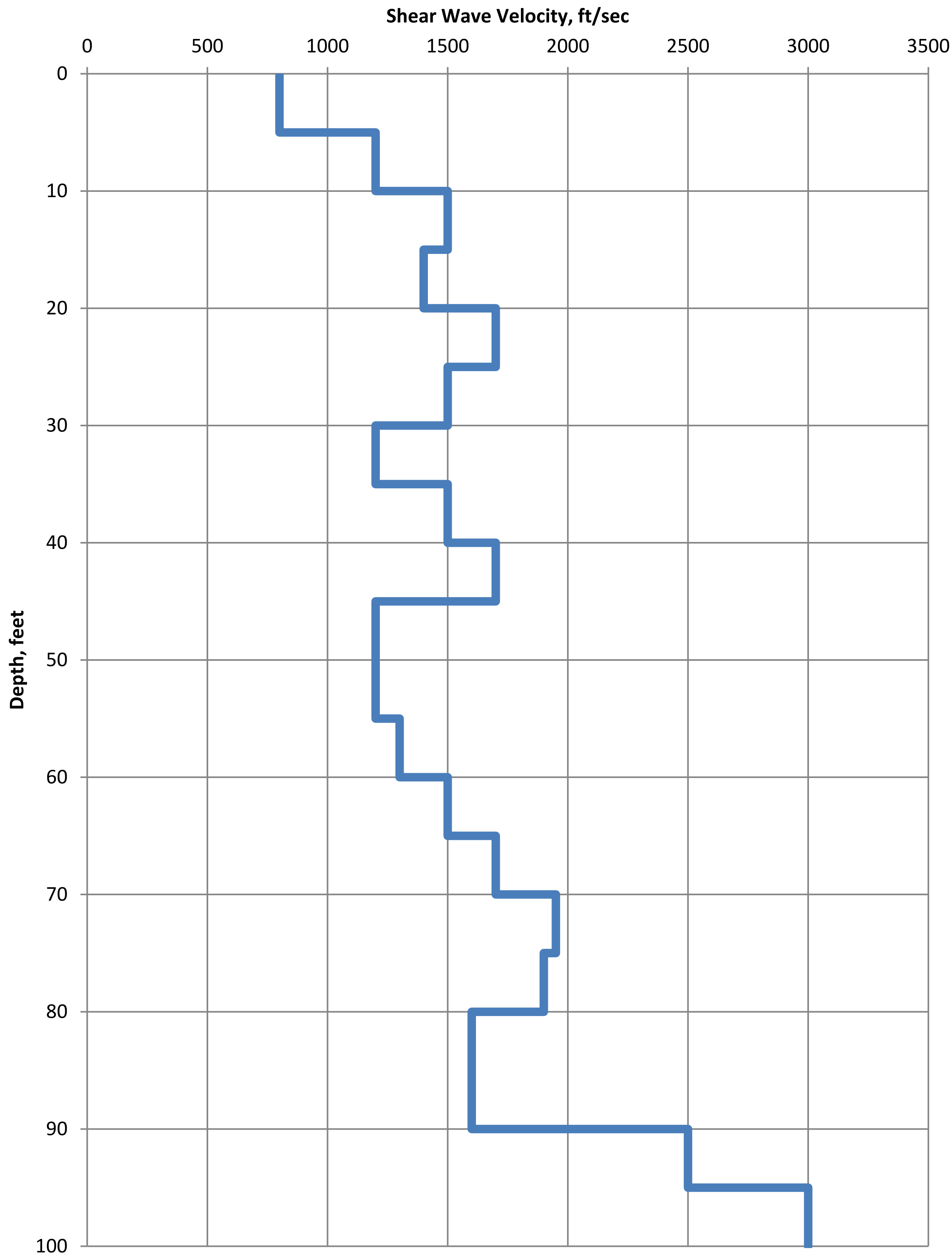


3.0 SITE-SPECIFIC SITE RESPONSE ANALYSES

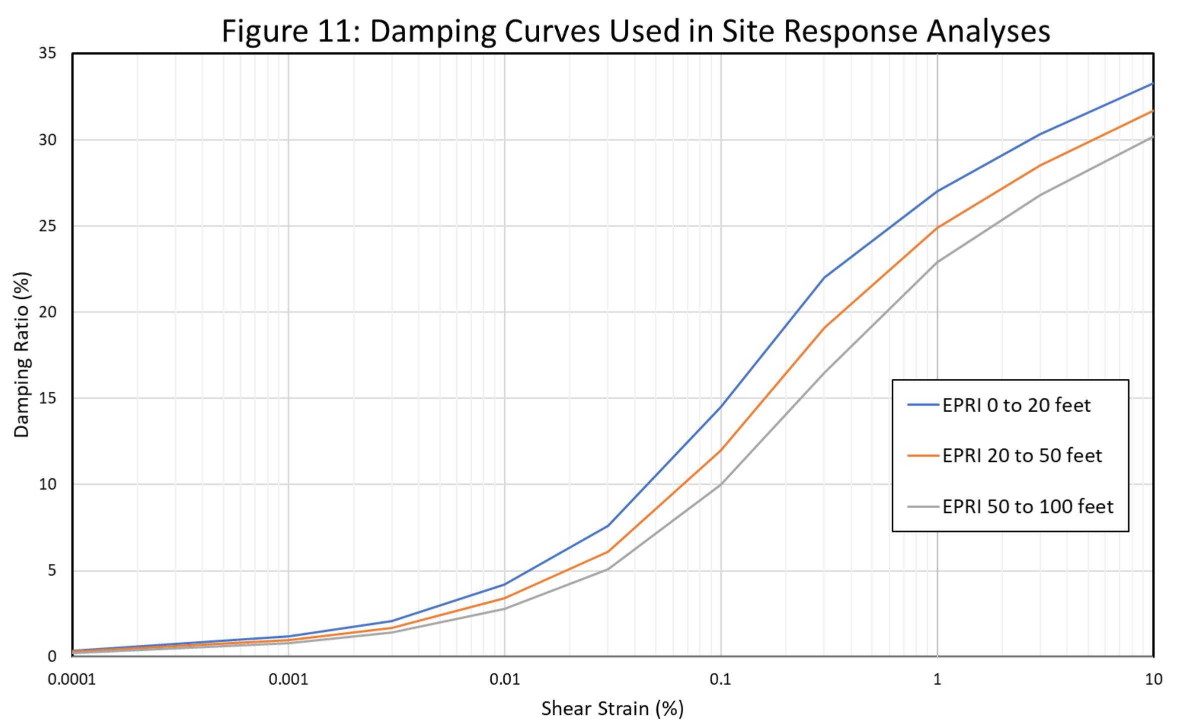
3.1 Development of Site Response Model

Figure 9, on the following page, presents the Vs profile for the site. The Vs profile was determined using shear wave velocity testing completed within the project vicinity. The shear wave velocity testing was completed in December 2010, by Shannon & Wilson, Inc., for the I-5 Columbia River Crossing Main River Crossing Draft Geotechnical Foundation Design Report.

Figure 9. Shear Wave Velocity Profile for Kirkland Renaissance Boardwalk



Figures 10 and 11, below, show the representative modulus reduction factors and damping curves for the subsurface, modeled as per EPRI (1993) as modified by Idriss (1999).



3.2 Site-Response Analyses

Site response analyses were completed using DEEPSOIL, by applying the 5 scaled ground motions in Table 7. The DEEPSOIL analyses was completed with the following parameters:

- Analysis Method: Equivalent Linear
- Solution Type: Frequency Domain
- Frequency Domain:
  - Number of Iterations: 20
  - Effective Shear Strain Ratio: 0.65
  - Complex Shear Modulus Formulation: Frequency Independent
- Time Domain:
  - Step Control: Flexible
  - Integration Scheme: Implicit - Newmark Beta Method
  - Time-history Interpolation Method: Linear in time domain

Peak shear stresses and peak shear strains with depth for the 5 input motions is shown in Figures 12 and 13, respectively, on the following pages.

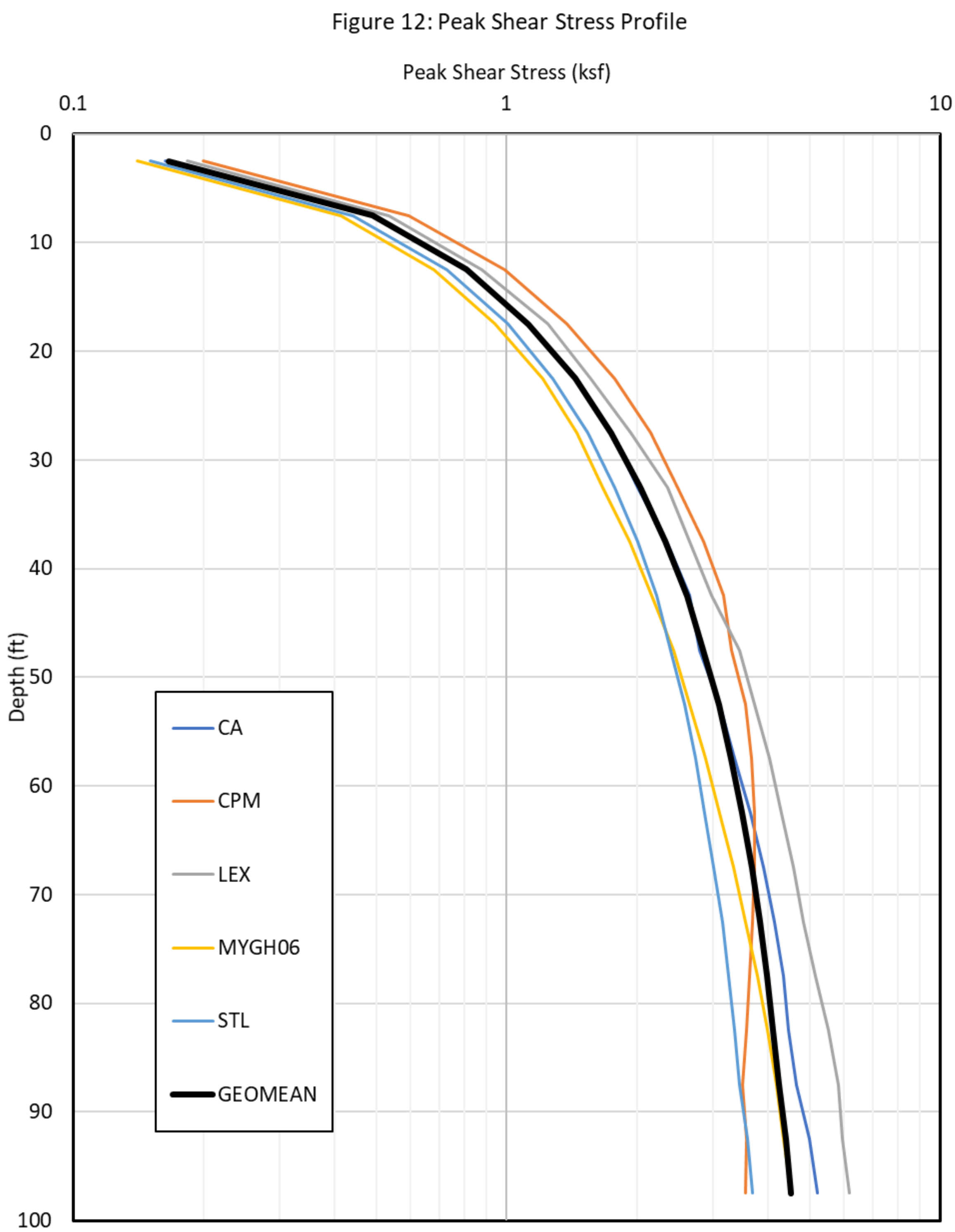


Figure 12: Peak Shear Stress Profile
Peak Shear Stress (ksf)
0.1
1
10
0
10
20
30
40
50
60
70
80
90
100
Depth (ft)
CA
CPM
LEX
MYGH06
STL
GEOMEAN

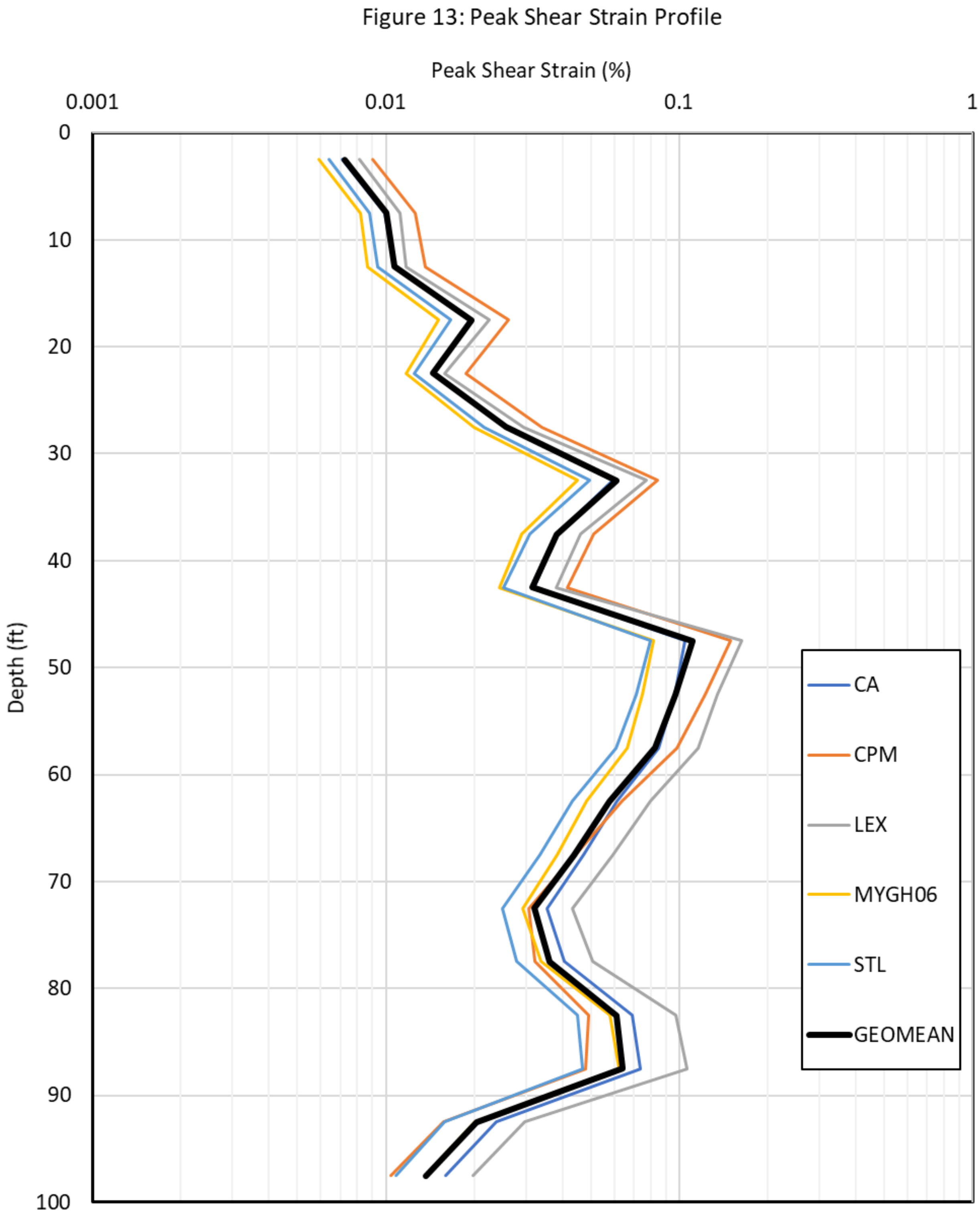
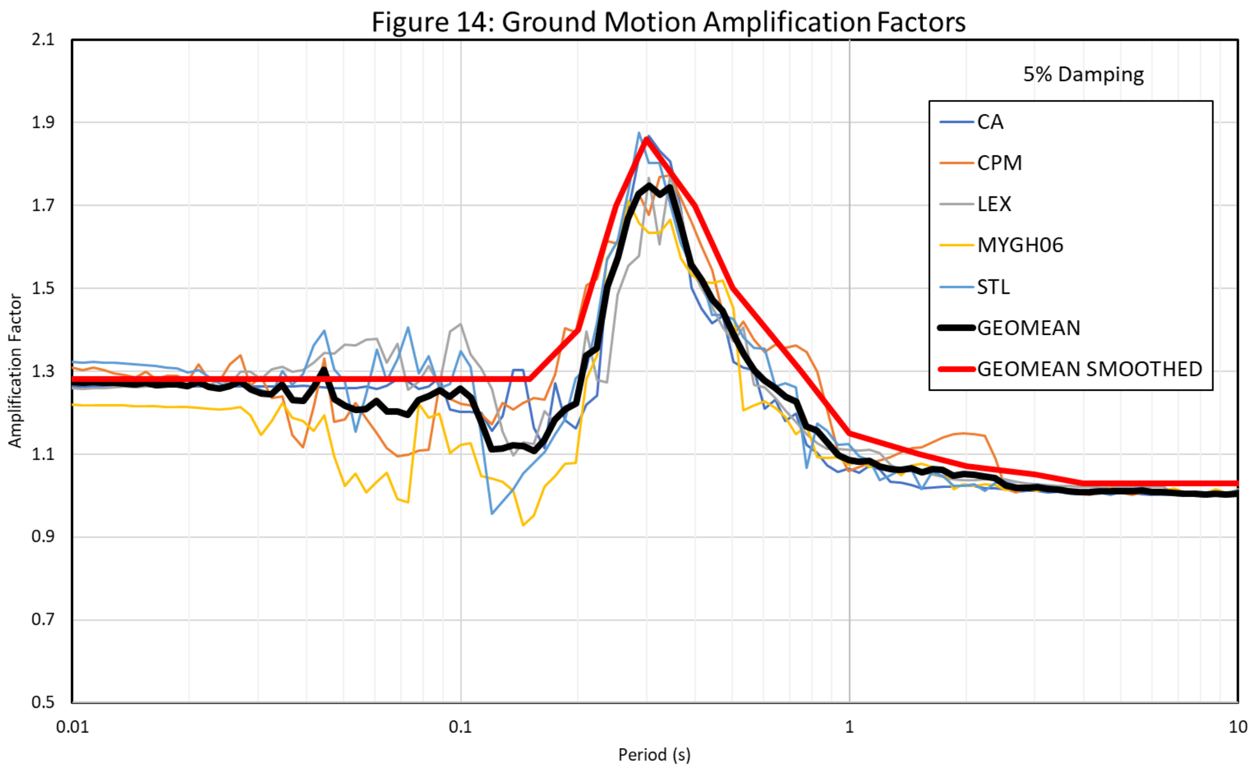


Figure 13: Peak Shear Strain Profile
Peak Shear Strain (%)
0.001
0.01
0.1
1
0
10
20
30
40
50
60
70
80
90
100
Depth (ft)
CA
CPM
LEX
MYGH06
STL
GEOMEAN

Figure 14, below, shows the amplification factors between the ground surface and outcrop from the 5 input motions, as well as the smoothed and non-smoothed geometric mean of the 5 input motions.



3.3 Development of MCE_R Spectra

Figure 15, below includes the site-specific MCE_R response spectrum for bedrock based on the guidance from ASCE 7-10 21.2.3, as well as the final MCE_R response spectrum at the ground surface calculated during the site response analyses following ASCE 7-10 21.1.3. In addition, the risk-targeted MCE_R response spectrum based on guidance from ASCE 7-10 11.4.7 has also been plotted.

Figure 15: Development of the MCER spectra

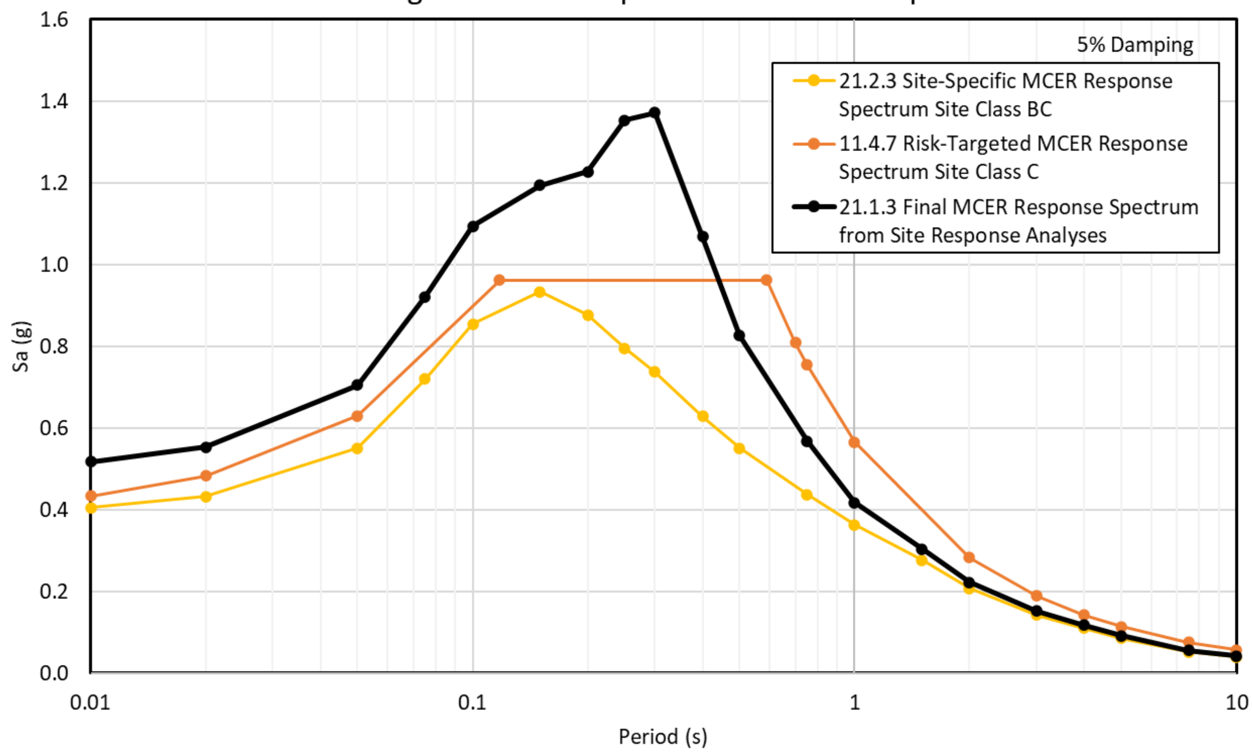


Table 8 below contains the MCE_R response spectrum at bedrock based on the guidance from ASCE 7-10 21.2.3, as well as the final MCE_R response spectrum at the ground surface calculated from the site response analyses following ASCE 7-10 21.1.3.

Table 8. MCE_R Response Spectrum at Bedrock and Ground Surface

Period (sec)	Spectral Acceleration at Bedrock, Sa (g)	Spectral Acceleration at Ground Surface, Sa (g)
0.01	0.40436	0.51758
0.02	0.43204	0.55301
0.05	0.55075	0.70496
0.075	0.71945	0.92090
0.1	0.85482	1.09417
0.15	0.93298	1.19422
0.2	0.87636	1.22690
0.25	0.79570	1.35270
0.3	0.73737	1.37150
0.4	0.62815	1.06786
0.5	0.55086	0.82629
0.75	0.43684	0.56789
1	0.36254	0.41692
1.5	0.27611	0.30372
2	0.20739	0.22191
3	0.14157	0.15148
4	0.10975	0.11743
5	0.08525	0.09121
7.5	0.05242	0.05609
10	0.03915	0.04189

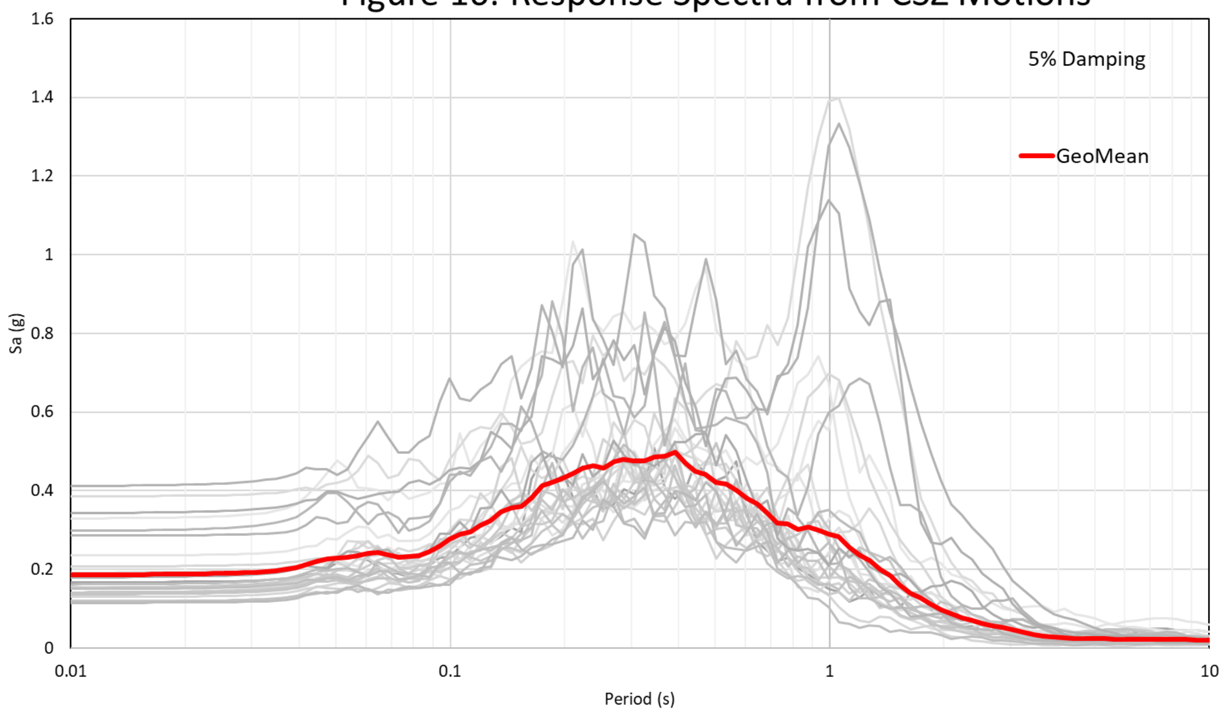
4.0 CSZ STRONG MOTION EVALUATION

4.1 Site-Specific Site Response Analyses

The CSZ @ PDX webtool considers various earthquake realizations from 3-D simulations of full rupture earthquakes along the CSZ. 28 CSZ strong motions acceleration time histories were obtained using the webtool. The synthetic broadband ground motions have been developed by Frankel et al. (2018).

The response spectra from each of the 28 CSZ strong motions was calculated using DEEPSOIL. Figure 16, below, includes the response spectra from each of the 28 CSZ motions, as well as the geometric mean of these motions.

Figure 16: Response Spectra from CSZ Motions



Site-specific site response analyses were completed using DEEPSOIL. Each of the 28 CSZ strong motions were entered into the DEEPSOIL model developed and discussed in Section 3 of this report. The DEEPSOIL analyses was completed with the following input parameters:

- Analysis Method: Equivalent Linear
- Solution Type: Frequency Domain
- Frequency Domain:
  - Number of Iterations: 20
  - Effective Shear Strain Ratio: 0.65
  - Complex Shear Modulus Formulation: Frequency Independent
- Time Domain:
  - Step Control: Flexible
  - Integration Scheme: Implicit - Newmark Beta Method
  - Time-history Interpolation Method: Linear in time domain

Figure 17, below, shows the amplification factors between the ground surface and outcrop from the 28 input CSZ strong motions, as well as the geometric mean of the amplification factors.

Figure 17: Amplification Factors from CSZ Motions

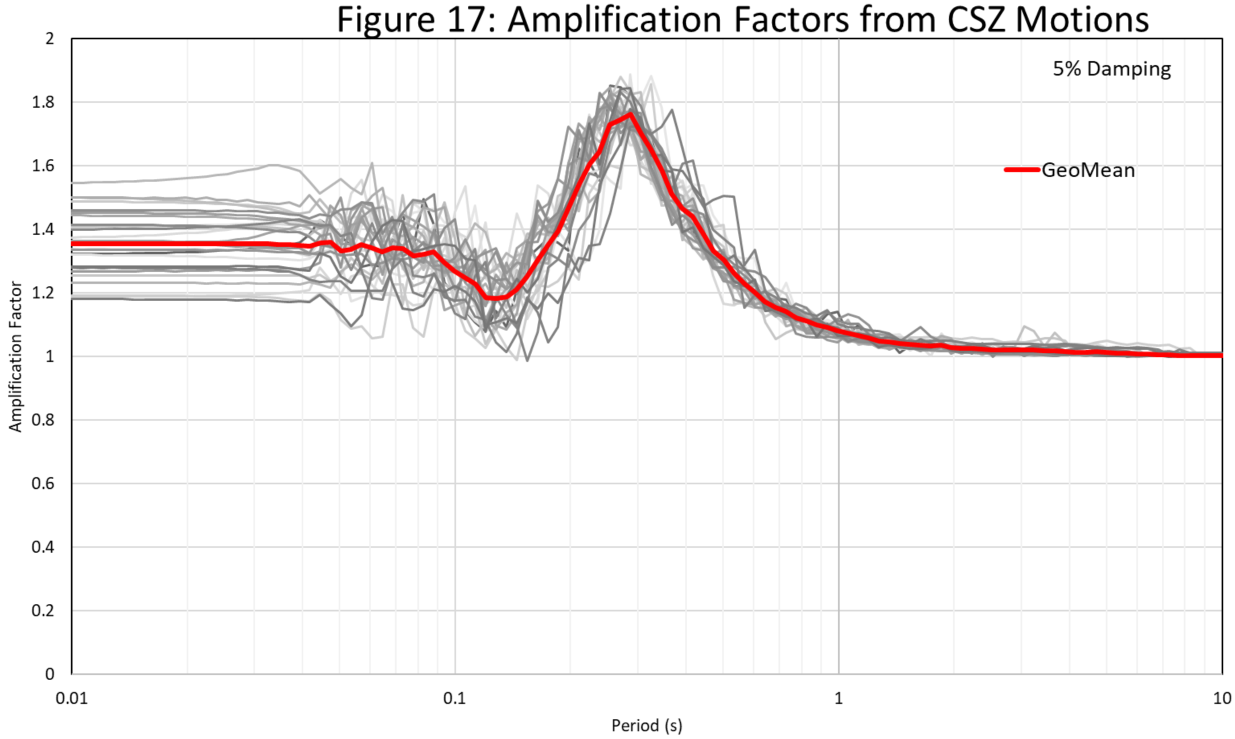


Figure 18, below, includes a comparison of the geometric means of the amplification factors of the 28 CSZ strong motions, and the 5 historical motions evaluated in Section 3 of this report.

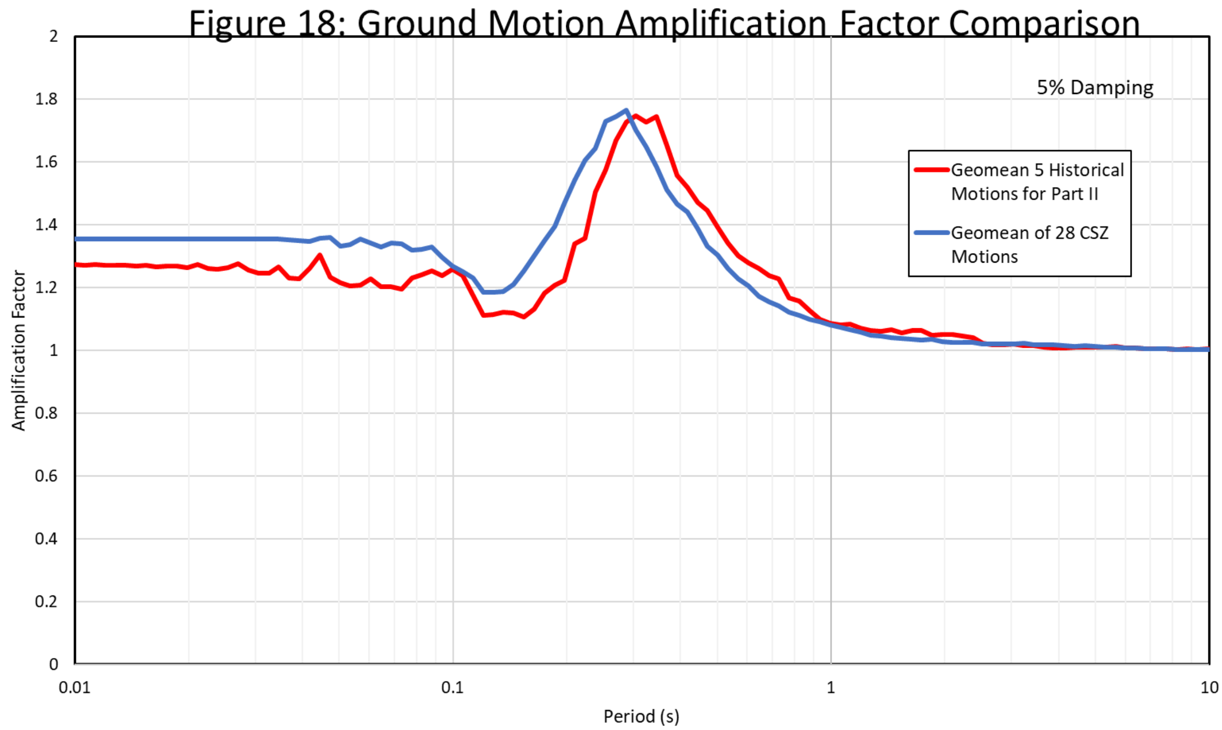


Figure 19, below, includes a plot of PGA compared to the amplification factor at PGA for the 28 CSZ strong motions and 5 historical motions considered in Section 3 of this report.

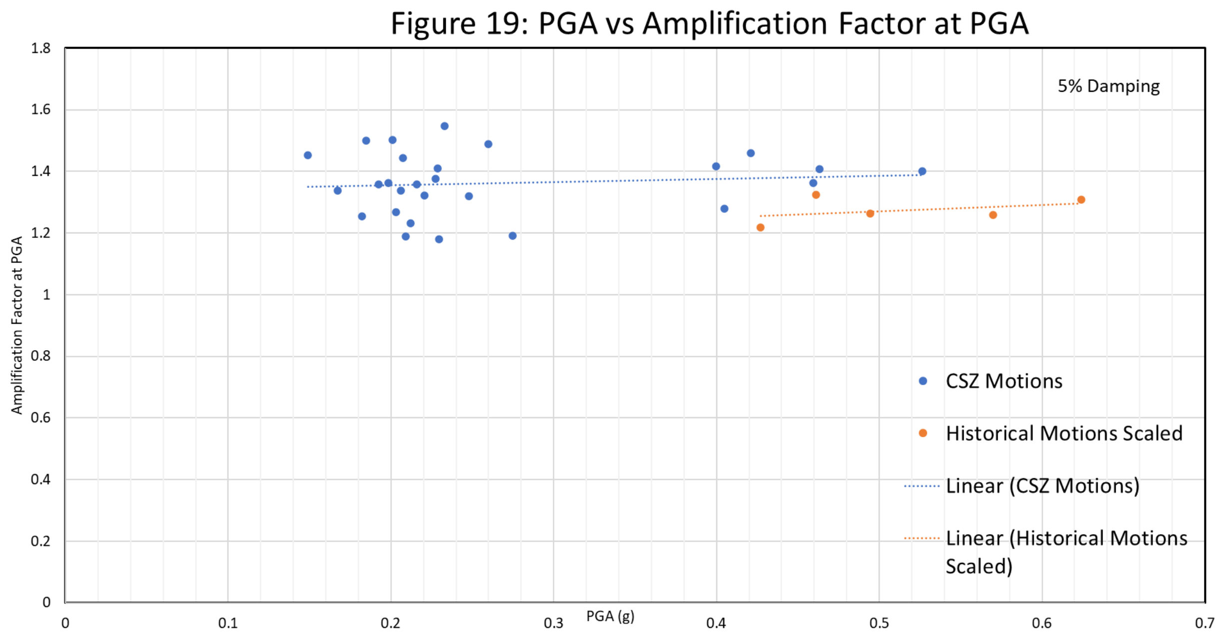
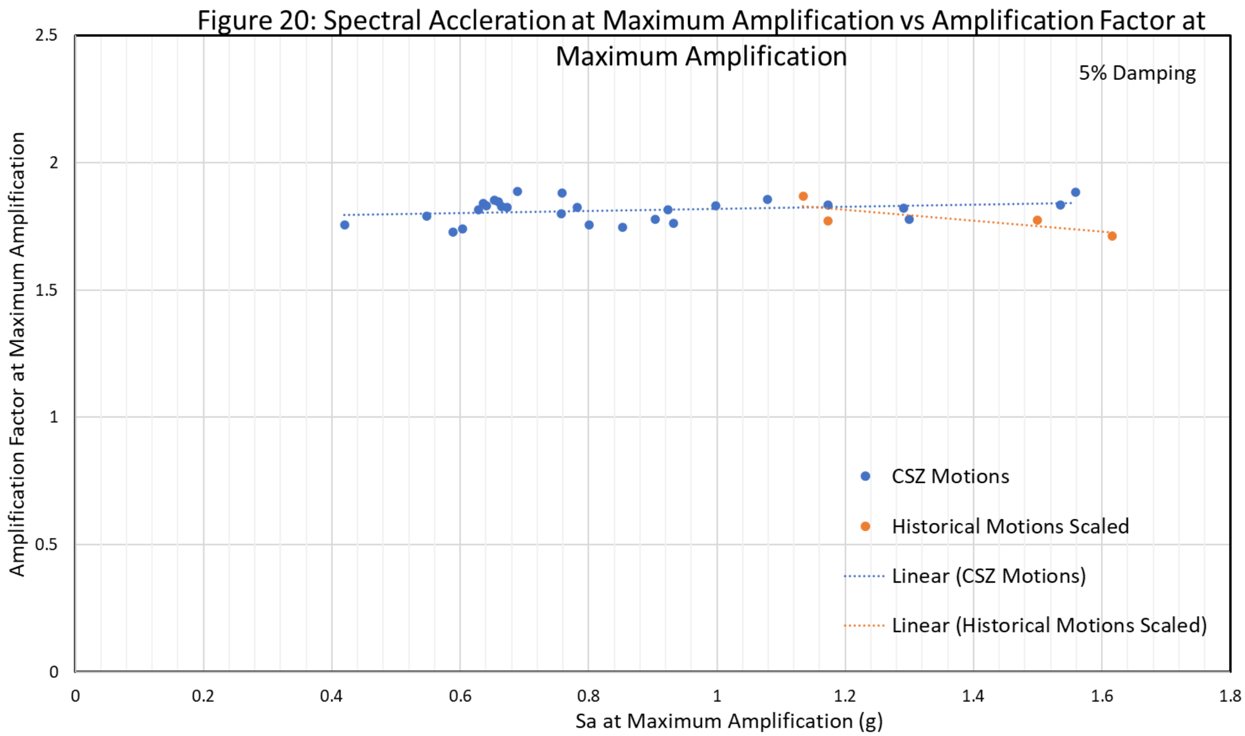


Figure 20, below, includes a plot of spectral acceleration at maximum amplification compared to amplification factor at maximum amplification for the 28 CSZ strong motions and 5 historical motions considered in Section 3 of this report.



4.2 Ground Motion Intensity Measurements

Several intensity measurements were evaluated for each of the 28 CSZ strong motions, as summarized in Table 9 below.

Table 9. Intensity Measurements from CSZ Strong Motions

Motion	Significant Duration (sec)	Arias Intensity (m/sec)	Cumulative Absolute Velocity (g*sec)
2	152.58	1.85	2.13
3	132.68	3.45	2.56
4	98.84	2.32	2.17
5	108.12	1.94	2.07
6	156.28	1.81	1.96
7	161.48	1.61	1.71
8	131.42	1.61	1.86
9	118.58	5.22	3.66
10	124.76	2.84	3.05
12	145.50	2.55	2.60
13	143.00	1.37	1.51
14	159.20	1.96	2.13
17	138.80	1.41	1.75
18	149.48	1.40	1.43
19	164.76	1.34	1.42
20	133.26	1.70	2.06
21	174.38	1.77	1.91
22	120.24	1.94	2.36
23	76.68	1.44	1.62
24	139.60	1.17	1.52
25	128.88	1.55	1.70
26	167.20	1.44	1.72
27	103.32	1.13	1.32
29	118.12	2.70	2.48
30	135.60	4.12	3.61
31	103.56	4.86	2.94
32	60.26	5.73	3.22
33	114.42	3.12	3.36

Plots of amplification factor at PGA, compared to significant duration, Arias intensity, and cumulative absolute velocity are provided in figures 21, 22, and, 23 respectively, on the following pages.

Figure 21: Ground Motion Amplification Factors at PGA vs Significant Duration

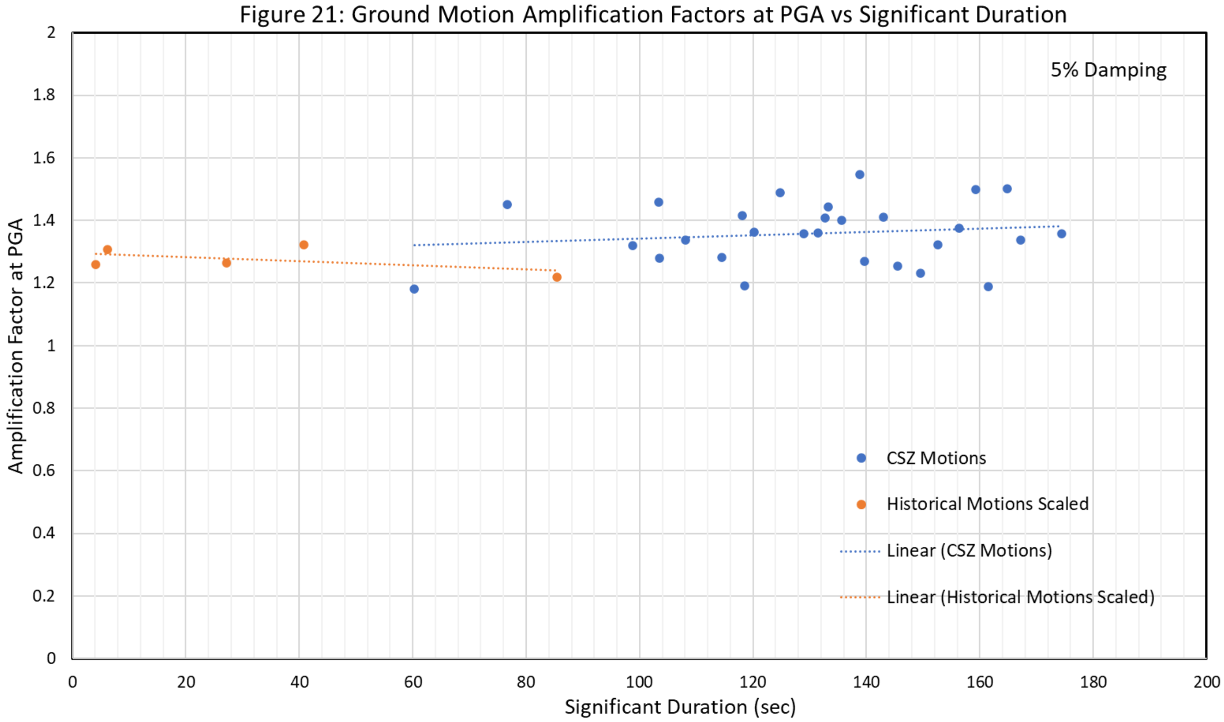


Figure 22: Ground Motion Amplification Factors at PGA vs Arias Intensity

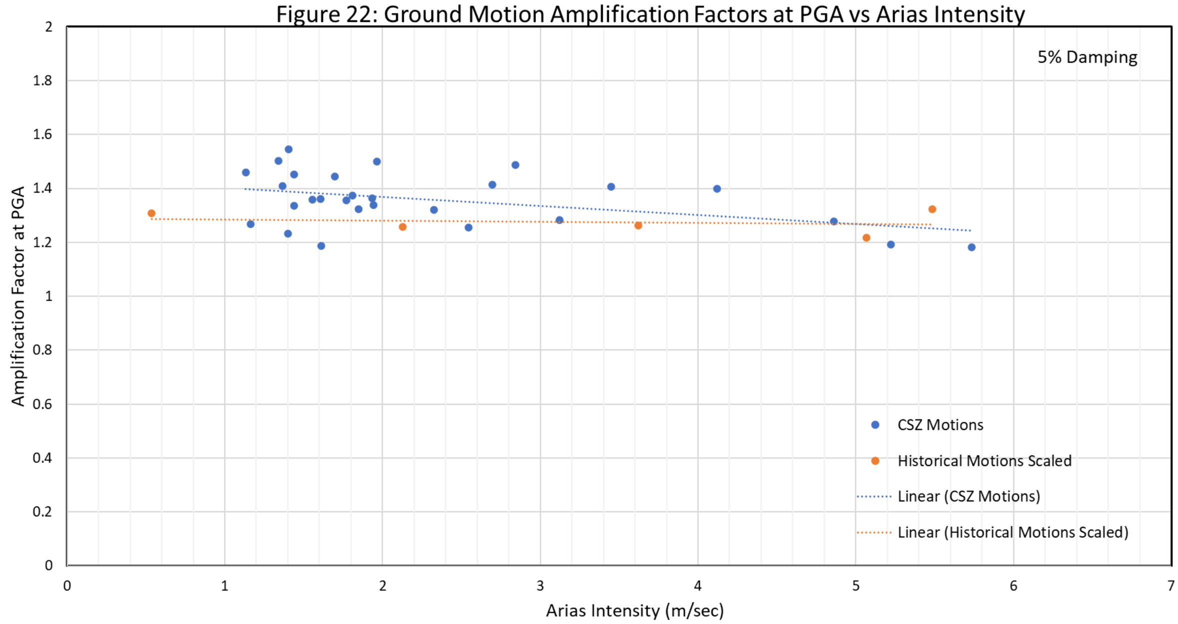
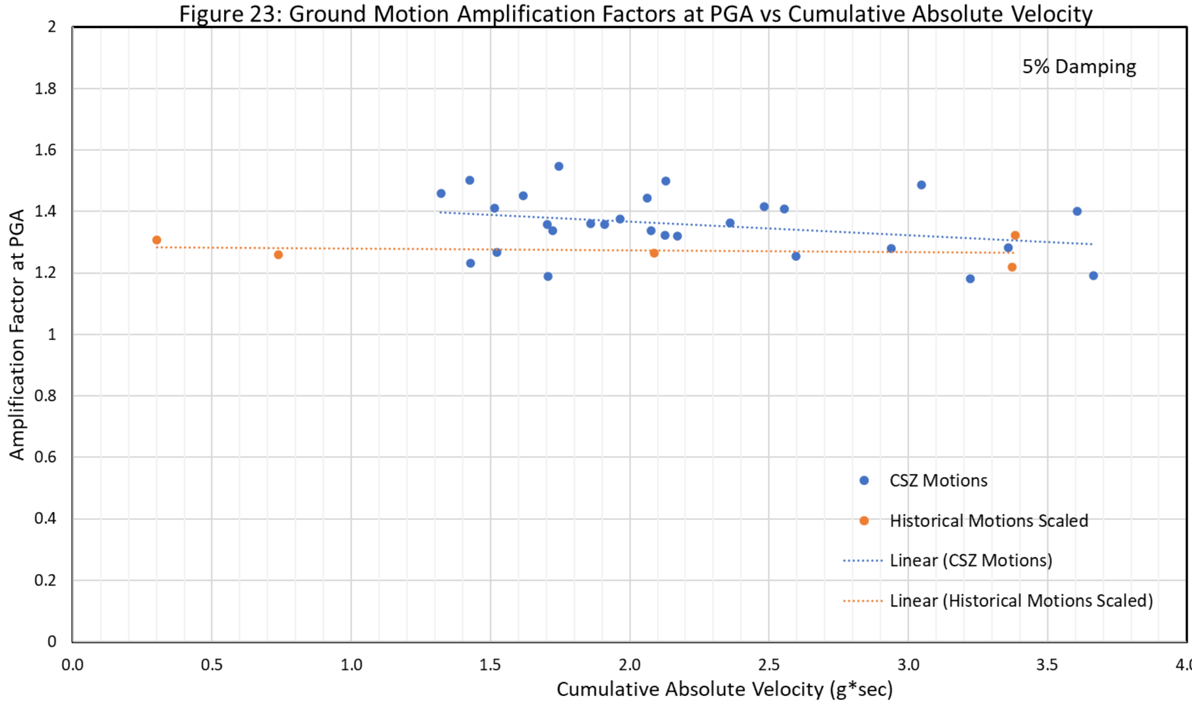
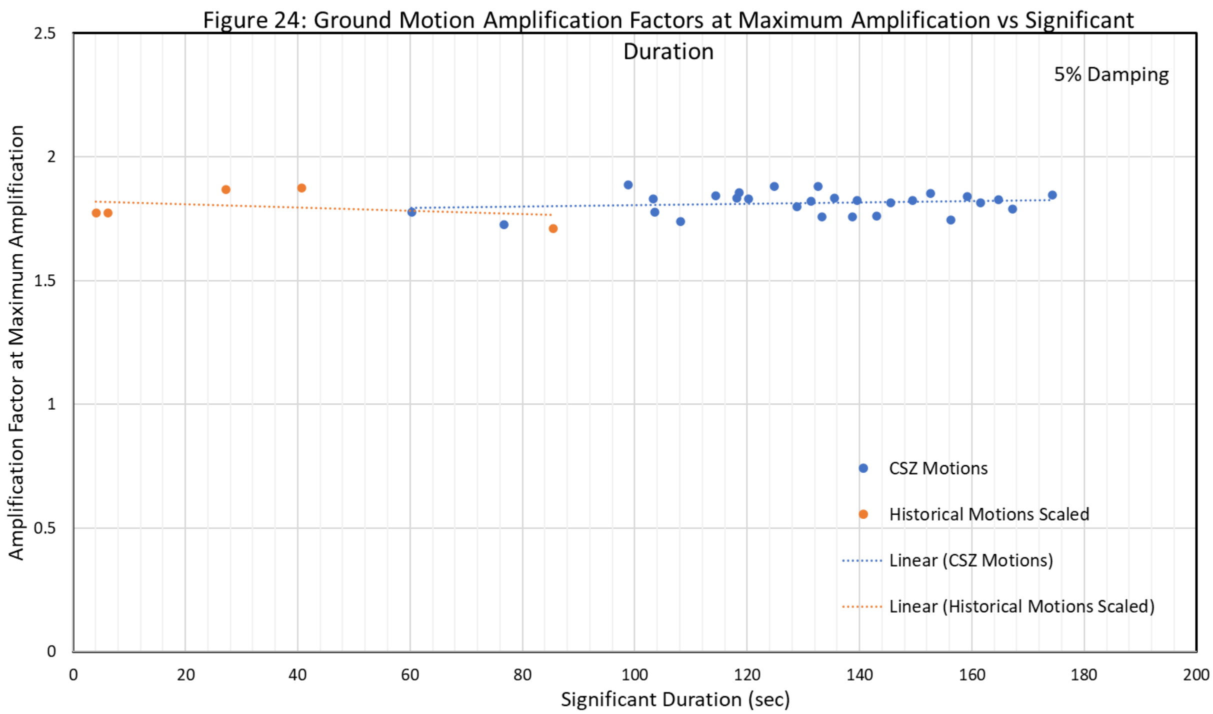


Figure 23: Ground Motion Amplification Factors at PGA vs Cumulative Absolute Velocity



Plots of amplification factor at maximum amplification, compared to significant duration, Arias intensity, and cumulative absolute velocity are provided in figures 24, 25, and 26 respectively, on the following pages.



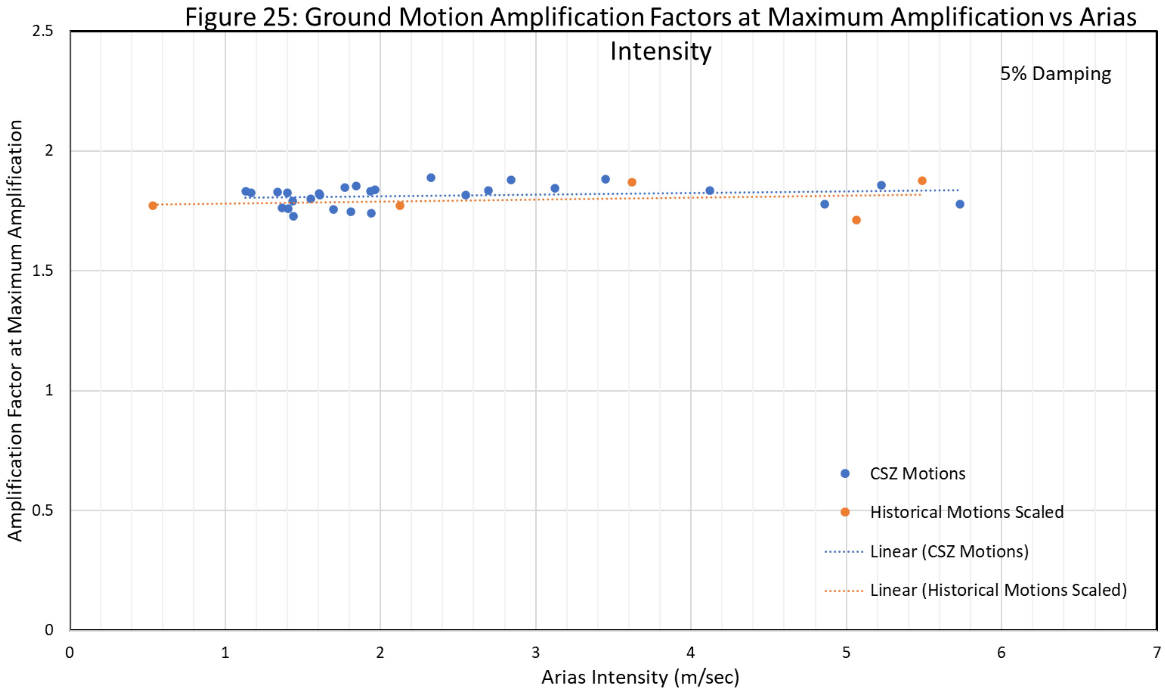


Figure 25: Ground Motion Amplification Factors at Maximum Amplification vs Arias Intensity

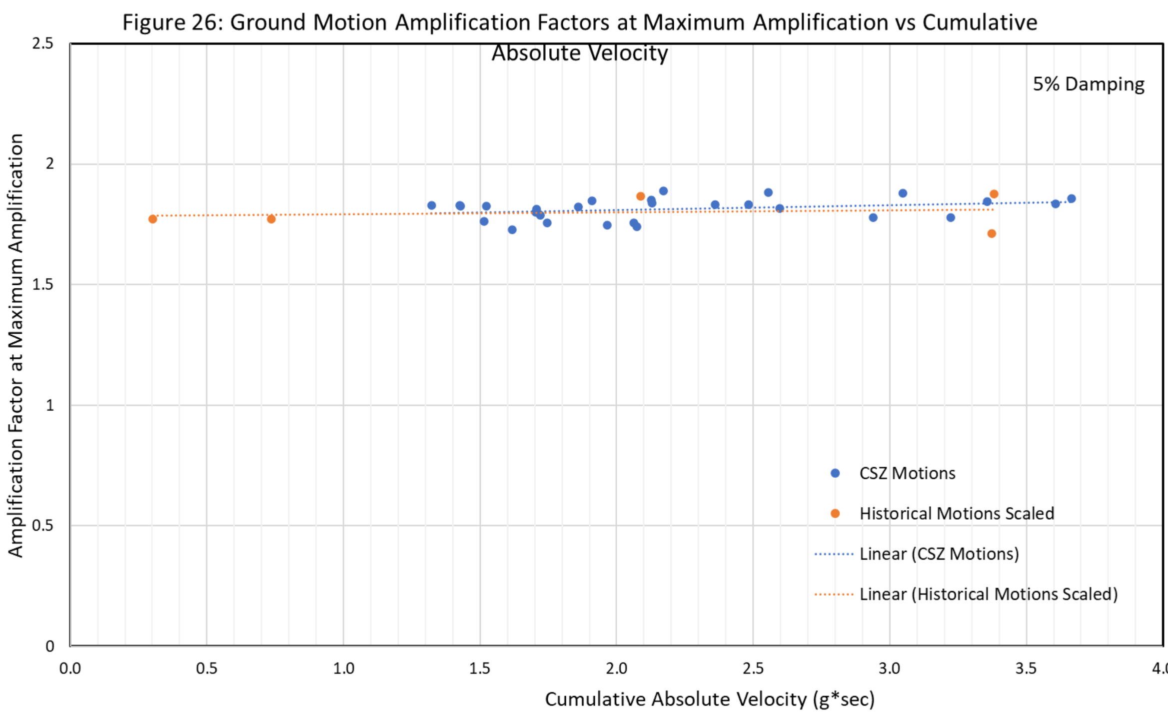


Figure 26: Ground Motion Amplification Factors at Maximum Amplification vs Cumulative Absolute Velocity

5.0 CONCLUSIONS

This project involved the development of site-specific ground motions, site-specific site response analysis, and site-specific acceleration ground spectra at the ground surface per ASCE 7-10 for the Kirkland Renaissance Boardwalk, a site in Vancouver, Washington. CSZ long duration motions were then analyzed to compare the results of site-specific site response analysis and to investigate the effect of motion duration and other intensity measures on resulting amplification factors.

The historical motions evaluated in Section 3 of this report generally produced lower amplification factors at PGA than the CSZ motions considered in Section 4. The maximum amplification factors in response to the CSZ motions were similar to the 5 historical motions considered in Section 3, however maximum amplification occurred at different periods. The geomean of the maximum amplification factors in response to the 5 historical motions considered in Section 3 was approximately 1.75 at a period of approximately 0.35 seconds, while the geomean of the maximum amplification factor in response to the CSZ motions considered in Section 4 was approximately 1.75 at a period of 0.25 seconds. This indicates greater period elongation by approximately 0.1 seconds for the 5 historical motions compared to the CSZ motions. As a result of the applied scaling factors, the 5 historical motions generally had higher PGAs than the CSZ motions. The higher PGAs likely resulted in increased nonlinearity in the soil response, causing greater dissipation of energy as the soil response softened, and thus a longer period of maximum amplification as elongation of the fundamental period of the soil column occurred during loading. Comparatively, the CSZ motions generally had lower PGAs, and therefore less nonlinearity in the soil response, resulting in a period of maximum amplification approximately 0.1 seconds lower.

The similarity in the resulting amplification factors between the suite of CSZ motions and the 5 historical motions considered in Section 3 shows the applicability of broadband synthetic CSZ ground motions for the purpose of performing site response analysis. The broadband synthetic CSZ motions considered for this project are being increasingly utilized in practice for projects throughout the Pacific Northwest where CSZ often contributes a high seismic hazard. The similarity of the resulting amplification factors obtained from site-specific site response analyses completed for this project indicate their utilization in practice may be considered reasonable.

The maximum amplification factors developed using the 5 historic motions or CSZ-specific synthetic motions did not show a strong correlation with strong motion duration and other considered ground motion intensity measures. In general, maximum amplification was relatively consistent at approximately 1.75 for both the CSZ motions and 5 historical motions, even though the intensity measures varied significantly.

As the arias intensity and cumulative absolute velocity of the CSZ motions increased, the amplification at PGA tended to slightly decrease. However, as the significant durations of the CSZ motions increased, the amplification at PGA generally slightly increased. The trends were less noticeable for the 5 historical motions, where in general the intensity measures and significant durations of the ground motions did not indicate strong correlation to the resulting amplification at PGA.

This study also highlighted the advantages of performing site-specific site response analysis in reducing uncertainty in design accelerations. In Section 3 of this report, it was determined that for periods less than 0.4 seconds, the final MCE_R response spectrum at the ground surface obtained following the site response procedures documented in ASCE 7-10 21.1.3 was higher than the risk-targeted MCE_R response spectrum based on the guidance from ASCE 7-10 11.4.7. This indicates that the seismic demands obtained from the site-specific site response analysis were actually higher for a significant portion of the response spectrum than the code-based procedure documented in ASCE 7-10 11.4.7. It is important to note that based on the ASCE 7-10 code, site-specific site response analysis was not required for this site, but its completion demonstrated that the simpler procedure documented in ASCE 7-10 11.4.7 may have underestimated the seismic demands at the Kirkland Renaissance Boardwalk site for a significant portion of the response spectrum.

6.0 REFERENCES

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