Evaluating Liquefaction Triggering Potential Using Seismic Input Parameters That Are Consistent with ASCE 7-16

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ABSTRACT

ASCE 7-16 details how the peak ground acceleration (PGA) should be determined for evaluating liquefaction triggering, with this PGA reflecting the influence of a range of earthquake magnitudes on a site's seismic hazard. Similarly, the Finn and Wightman magnitude-weighting scheme can be used to account for the full range of magnitudes influencing the seismic hazard at a site, where the weights are derived from a site's seismic hazard deaggregation data. However, the deaggregation data for the seismic hazard maps for the Central/Eastern U.S. are only available for rock motions and not motions at the surface of the soil profile. The authors explore this issue by comparing the weighted average magnitude scaling factors (MSF) and depth-stress weighting factor (r_d) values for multiple sites in the Western U.S. developed using deaggregation data for rock motions and for motions at the surface of the soil profiles. Based on these comparisons, the authors found that using the PGA deaggregation data for rock conditions yield similar weighted averages for MSF and r_d as those computed using deaggregation data for the PGA at the surface of the soil profile.

INTRODUCTION

Despite refinements made in ASCE 7-16 (ASCE 2017) regarding how the peak ground acceleration (PGA) is determined for evaluating liquefaction triggering and related phenomena, little is mentioned on how to account for earthquake magnitude in the evaluations. This is an issue because the PGAs obtained following ASCE 7-16 are based on results from Probabilistic Seismic Hazard Analysis (PSHA), which reflect the influence of a range of earthquake magnitudes on a site's seismic hazard. Specifically, the only guidance provided in ASCE 7-16 is that the earthquake magnitude should be consistent with the PGA used in the evaluations. In the commentary section of ASCE 7-16, reference is made to 2009 NEHRP Recommended Seismic Provisions (FEMA 2010) wherein it is stated that the magnitude used in liquefaction evaluations can be obtained as the "dominant magnitude(s) determined from deaggregation information" of the seismic hazard.

Finn and Wightman (2007, 2010) refine and formalize the use of PSHA for evaluating liquefaction potential by proposing a magnitude-weighting scheme that accounts for the full range of magnitudes influencing the seismic hazard at a site, where the weights are derived from the seismic hazard deaggregation data for the site. However, use of this approach is inhibited in the Central/Eastern United States (CEUS) because the seismic hazard deaggregation data for the ASCE 7-16 seismic hazard maps are only available for rock motions and not the ground motions at the surface of the soil profile, consistent with the PGA used in the liquefaction evaluations. Specifically, the deaggregation data is only available via the USGS Unified Hazard Tool web application (USGS 2014) for PGA (0 s), 0.2 s, 1.0 s, and 2.0 s spectral accelerations for rock site conditions (i.e., NEHRP Seismic Site Classes A and B/C boundary) in the CEUS, while they are available for both rock and soil surface motions in the Western United States (WUS). The question then becomes whether the deaggregation data for the PGA for rock site conditions should be used in the Finn and Wightman magnitude-weighting scheme, or should the deaggregation data for one of the other oscillator periods be used (e.g., deaggregation data for the oscillator period closest to the fundamental period of the soil profile).

Herein, the authors explore this issue by comparing the weighted average Magnitude Scaling Factors (MSF) and depth-stress reduction factor (r_d) values for multiple sites in the WUS developed using deaggregation data for rock motions and for motions at the surface of the soil profiles. Based on these comparisons, recommendations are made regarding which oscillator period deaggregation dataset for CEUS rock motions can be expected to yield weighted average MSF and r_d values that are most consistent with the PGA at the surface of the soil profile.

ASCE 7-16 EARTHQUAKE SCENARIO FOR EVALUATING LIQUEFACTION

PGA

Per the general procedure for ground motion estimation, ASCE 7-16 (ASCE 2017) specifies that the Maximum Considered Earthquake Geometric Mean (MCE_G) peak ground acceleration adjusted for site effects (PGA_M) be used to evaluate liquefaction triggering and related phenomena. The use of PGA_M, versus the PGA associated with the design earthquake (DE), to evaluate liquefaction results in a significant increase by a factor of 1.5 in the PGA and was first introduced in ASCE 7-10 (ASCE 2010). Crouse et al. (2010) state the reason for this change: “The requirement to evaluate liquefaction at the Maximum Considered Earthquake (MCE) rather than the DE assures that the full potential for liquefaction is addressed at the MCE during the evaluation of building stability, rather than a lesser level when DE is used.” However, this largely ignores the fact that liquefaction triggering and lateral spreading present little to no risk to building stability from a life safety perspective (e.g., Hakuno 2004; Bird and Bommer 2004; Green and Bommer 2020). Nevertheless, ASCE 7-16 includes maps for MCE_G PGA for Seismic Site Class B/C boundary (i.e., rock) conditions and tabulated site coefficients (F_{PGA}) to adjust these mapped PGA values for site effects (i.e., $PGA_M = F_{PGA} \cdot PGA$).

Magnitude (M)

As stated in the Introduction, the only guidance provided in ASCE 7-16 regarding the earthquake magnitude (M) to use in the liquefaction evaluations is that it should be consistent with the PGA used in the evaluations. However, because the PGAs are based on results from PSHA, they reflect the influence of a range of earthquake magnitudes on a site’s seismic hazard. In the commentary section of ASCE 7-16, reference is made to 2009 NEHRP Recommended Seismic Provisions (FEMA 2010) wherein it is stated that the magnitude used in liquefaction evaluations can be obtained as the “dominant magnitude(s) determined from deaggregation information” of the seismic hazard. Based on the authors’ experience, this is commonly interpreted as: (1) the magnitude corresponding to the mode of the deaggregation data; or (2) the weighted mean magnitude of the deaggregation data.

Shortcomings of these interpretations are that for regions of the US far from a dominant seismic source, the modal earthquake scenario often contributes less than 10% of the overall seismic hazard at the site and the mean earthquake scenario may not represent a realistic earthquake scenario for the site. This is illustrated in Figure 1, which is a histogram showing the percent contribution to the site's overall seismic hazard (PGA) as a function of earthquake scenario (i.e., site-to-source distance, r_{Rup}, and moment magnitude, M_w) for Chico, CA, for a return period of 2473 years for a site having a time-weighted average small strain shear wave velocity of the upper 30 m (V_{S30}) of 180 m/s (i.e., Seismic Site Class D/E boundary). Based on this figure, the modal earthquake scenario is $r_{Rup} \approx 11$ km and $M_w = 5.1$, but this scenario only contributes ~10% to the overall seismic hazard at the site. The mean earthquake scenario is $r_{Rup} \approx 34$ km and $M_w \approx 6.4$, but this scenario is one that contributes little to the overall seismic hazard at the site (i.e., it does not represent a realistic earthquake scenario for the site).

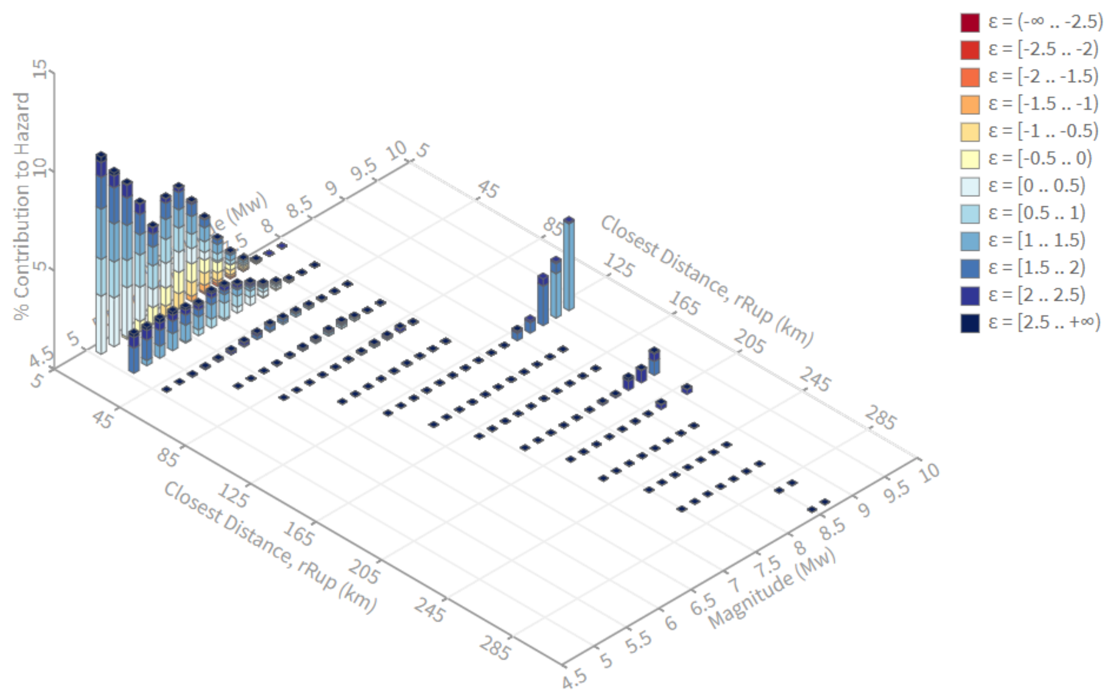
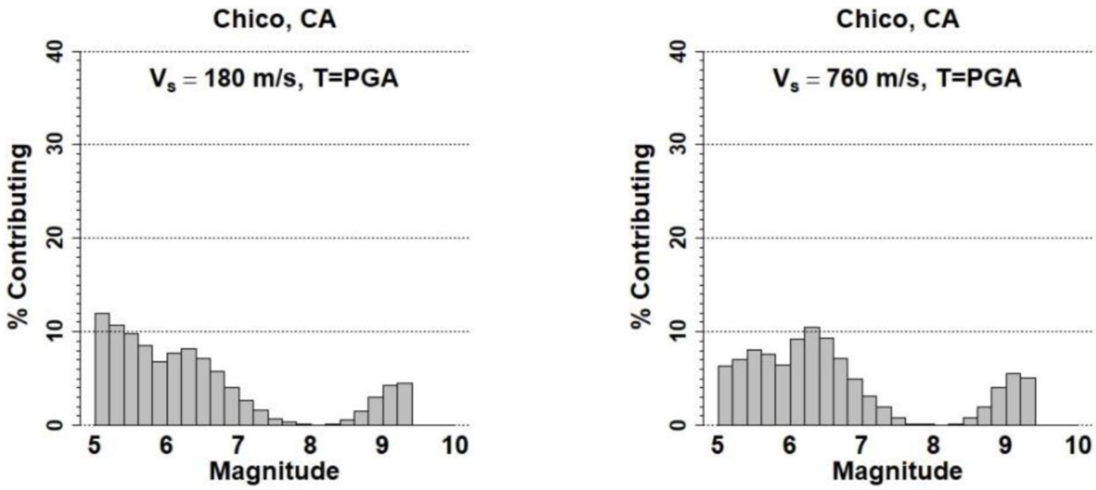


Figure 1. Magnitude-distance deaggregation for PGA for Chico, CA, for a 2473-year return period for a site having V_{S30} = 180 m/s (i.e., Seismic Site Class D/E boundary).

FINN AND WIGHTMAN MAGNITUDE-WEIGHTING SCHEME

Similar to ASCE 7-16, the National Building Code for Canada (NBCC 2015) uses a probabilistic approach for determining seismic hazard. To address the issue of what magnitude to use in conjunction with a PGA computed from a PSHA for liquefaction evaluations, Finn and Wightman (2007, 2010) proposed a weighting scheme that accounts for the full range of magnitudes influencing the seismic hazard at a site, where the weights are derived from the seismic hazard deaggregation data for the site. Because the relationships in the simplified liquefaction evaluation procedure that are functions of magnitude (e.g., MSF and r_d) are not functions of site-to-source distance, Finn and Wightman (2007, 2010) proposed summing the percent contributions of the various earthquake scenarios to a site's overall seismic hazard across site-to-source distance. The resulting histogram is the percent contribution to the site's overall seismic hazard (e.g., PGA) as a function of earthquake magnitude.

Figure 2a shows the deaggregation data shown in Figure 1 for Chico, CA, summed across site-to-source distance. Finn and Wightman (2007, 2010) compute the factor of safety (FS) against liquefaction triggering at a site using the PGA_M based on the seismic hazard maps and the magnitudes corresponding to the center of each of the magnitude deaggregation bins. They then compute the weighted average FS for the site, using the percent contribution of each magnitude to the overall seismic hazard as the weights.



(a) (b)

Figure 2. Magnitude deaggregation for PGA for Chico, CA, for a 2473-year return period for a site having: (a) V_{S30} = 180 m/s (i.e., Seismic Site Class D/E boundary); and (b) V_{S30} = 760 m/s (i.e., Seismic Site Class B/C boundary).

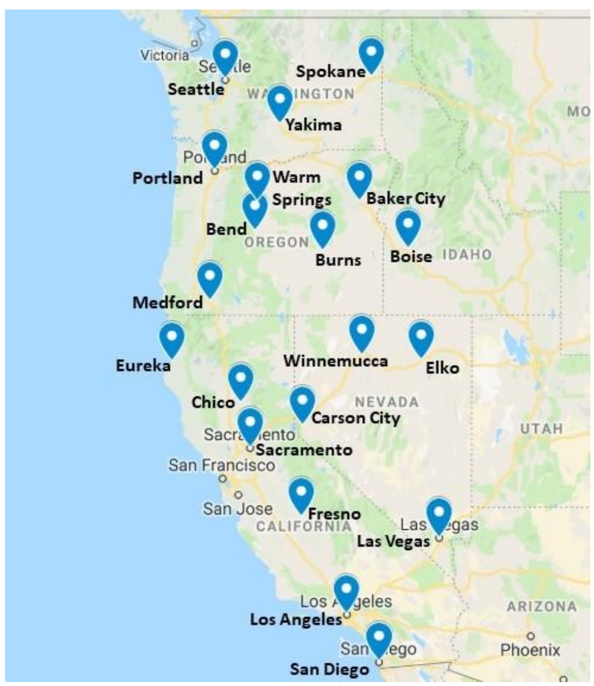


Figure 3. Locations of the 20 sites spatially distributed across the WUS analyzed in this study.

However, use of this approach is inhibited if the magnitude deaggregation data are only available for bedrock, not the site conditions corresponding PGA_M (e.g., Figure 2a vs. 2b). Specifically, this is an issue for the CEUS because the seismic hazard deaggregation data for the

ASCE 7-16 seismic hazard maps are only available rock motions and not the ground motions at the surface of the soil profile. As a result, when the Finn and Wightman magnitude-weighting scheme is used in the CEUS, the question becomes whether the bedrock deaggregation data for PGA or for the spectral acceleration corresponding oscillator period (T) closest to the fundamental period of the profile, for example, should be used. Using the deaggregation data for an oscillator period other than zero (i.e., other than the deaggregation data for bedrock PGA), inherently assumes that site effects are dominated by the first mode of vibration of the profile, which is a reasonable assumption for many profile-earthquake scenarios. However, even when justified, this approach requires the fundamental period of the profile to be determined, and the deaggregation data are only available via the USGS Unified Hazard Tool web application (USGS 2014) for PGA (T = 0 s), 0.2 s, 1.0 s, and 2.0 s spectral accelerations for Seismic Site Classes A and B/C boundary in the CEUS. As a result, using the deaggregation data for rock motions for an oscillator period other than PGA requires additional effort and approximations.

Table 1. WUS Sites Analyzed.

Location	Longitude (deg)	Latitude (deg)	PGA (g)				
			V_{S30}: 180 m/s	V_{S30}: 259 m/s	V_{S30}: 360 m/s	V_{S30} : 537 m/s	V_{S30}: 760 m/s
Baker City, OR	-117.830	44.774	0.2551	0.2307	0.2079	0.1766	0.1500
Bend, OR	-121.315	44.058	0.2830	0.2572	0.2345	0.2064	0.1748
Boise, ID	-116.193	43.608	0.2426	0.2156	0.1925	0.1613	0.1369
Burns, OR	-119.055	43.586	0.2135	0.1906	0.1688	0.1422	0.1207
Carson City, NV	-119.767	39.165	1.3459	1.1821	1.1259	1.0456	0.9414
Chico, CA	-121.842	39.732	0.5558	0.5100	0.4748	0.4232	0.3608
Elko, NV	-115.768	40.836	0.3580	0.3266	0.2982	0.2547	0.2175
Eureka, CA	-124.160	40.803	1.9310	1.6695	1.6162	1.5848	1.4624
Fresno, CA	-119.786	36.741	0.4557	0.4113	0.3744	0.3229	0.2777
Las Vegas, NV	-115.140	36.172	0.3921	0.3750	0.3522	0.3114	0.2696
Los Angeles, CA	-118.245	34.053	1.2248	1.0865	1.0388	0.9603	0.8497
Medford, OR	-122.876	42.324	0.4731	0.4346	0.4050	0.3763	0.3193
Portland, OR	-122.676	45.512	0.5873	0.5521	0.5251	0.4840	0.4175
Sacramento, CA	-121.491	38.579	0.4206	0.3741	0.3383	0.2912	0.2488
San Diego, CA	-117.162	32.716	0.8532	0.8637	0.8674	0.8120	0.7261
Seattle, WA	-122.329	47.604	0.8312	0.7932	0.7679	0.7160	0.6246
Spokane, WA	-117.412	47.657	0.2354	0.2129	0.1920	0.1618	0.1378
Warm Springs, NV	-116.370	38.191	0.4265	0.3994	0.3706	0.3237	0.2791
Winnemucca, NV	-117.735	40.973	0.3843	0.3495	0.3184	0.2739	0.2332
Yakima, WA	-120.507	46.604	0.3397	0.3114	0.2854	0.2467	0.2108

WHICH DEAGGREGATION DATA SHOULD BE USED?

To provide insights about which bedrock deaggregation data should be used in implementing the Finn and Wightman magnitude-weighting scheme for evaluating liquefaction potential in the CEUS, 20 sites spatially distributed across the WUS were analyzed (Figure 3). The reason for analyzing WUS sites is that deaggregation data are available from the USGS Unified Hazard Tool (USGS 2014) for both rock and soil surface motions in the WUS. This allows a comparison of the weighted-average MSF and r_d values computed using bedrock deaggregation data for a range of oscillator periods and using the deaggregation data for the PGA_M.

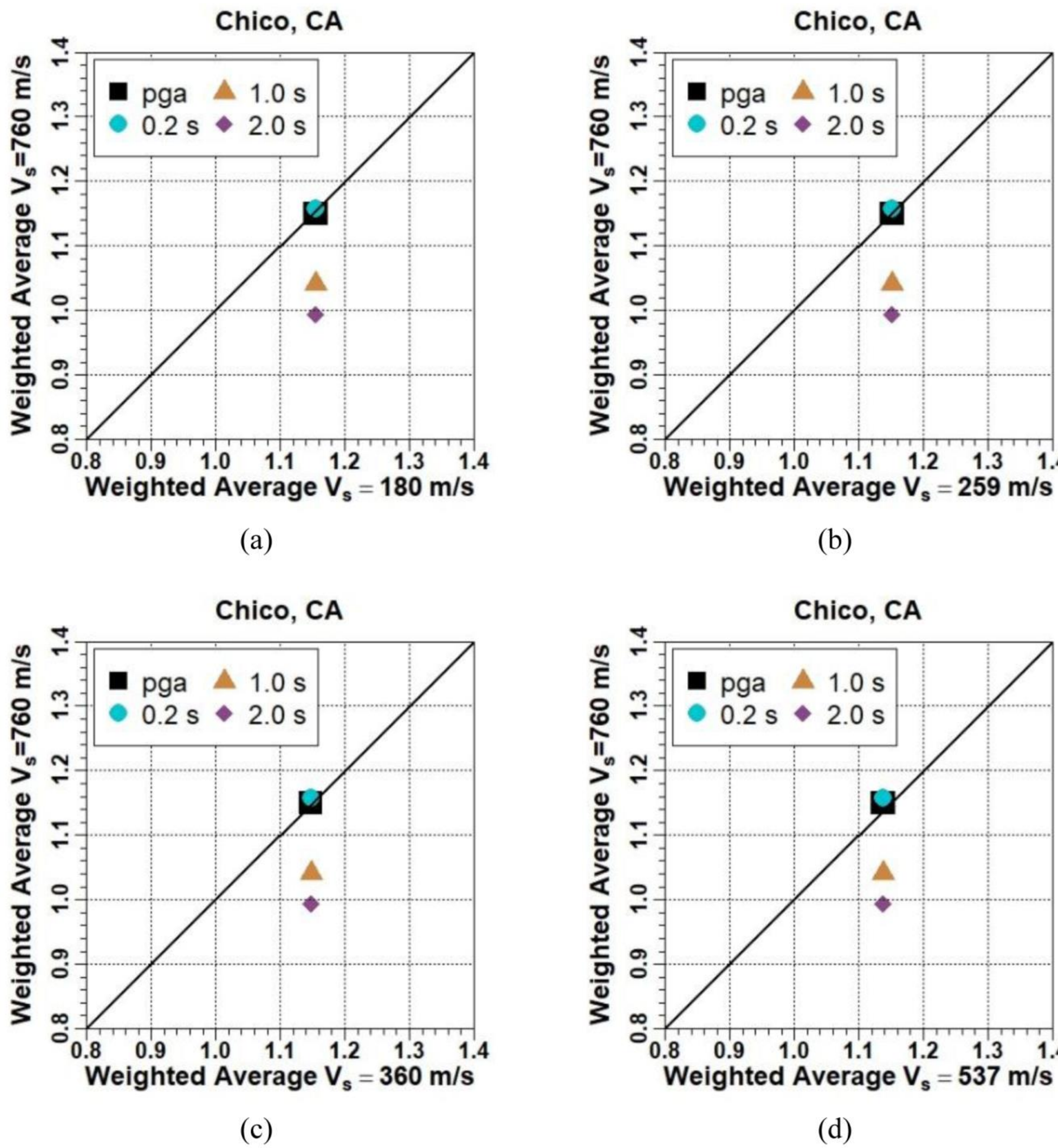


Figure 4. Weighted Average MSFs for Chico, CA, for V_{s30}=760 m/s (T = 0 s, 0.2 s, 1.0 s, and 2.0 s) vs. Weighted Average MSFs for: (a) V_{S30}=180 m/s (PGA); (b) V_{S30}=259 m/s (PGA); (c) V_{S30}=360 m/s (PGA); and (d) V_{S30}=537 m/s (PGA).

The WUS sites analyzed (Figure 3) are listed in Table 1, which were selected to represent a range of seismic hazards. For each of the sites, magnitude deaggregation data were obtained for PGA (0 s), 0.2 s, 1.0 s, and 2.0 s spectral accelerations for Seismic Site Class B/C boundary (V_{S30} = 760 m/s) and for PGA for Seismic Site Classes C (V_{S30} = 537 m/s), C/D boundary (V_{S30}

= 360 m/s), D (V_{S30} = 259 m/s), and D/E boundary (V_{S30} = 180 m/s). These data were used to compute weighted averages of MSF and r_d proposed by Green et al. (2019) and Lasley et al. (2016), respectively.

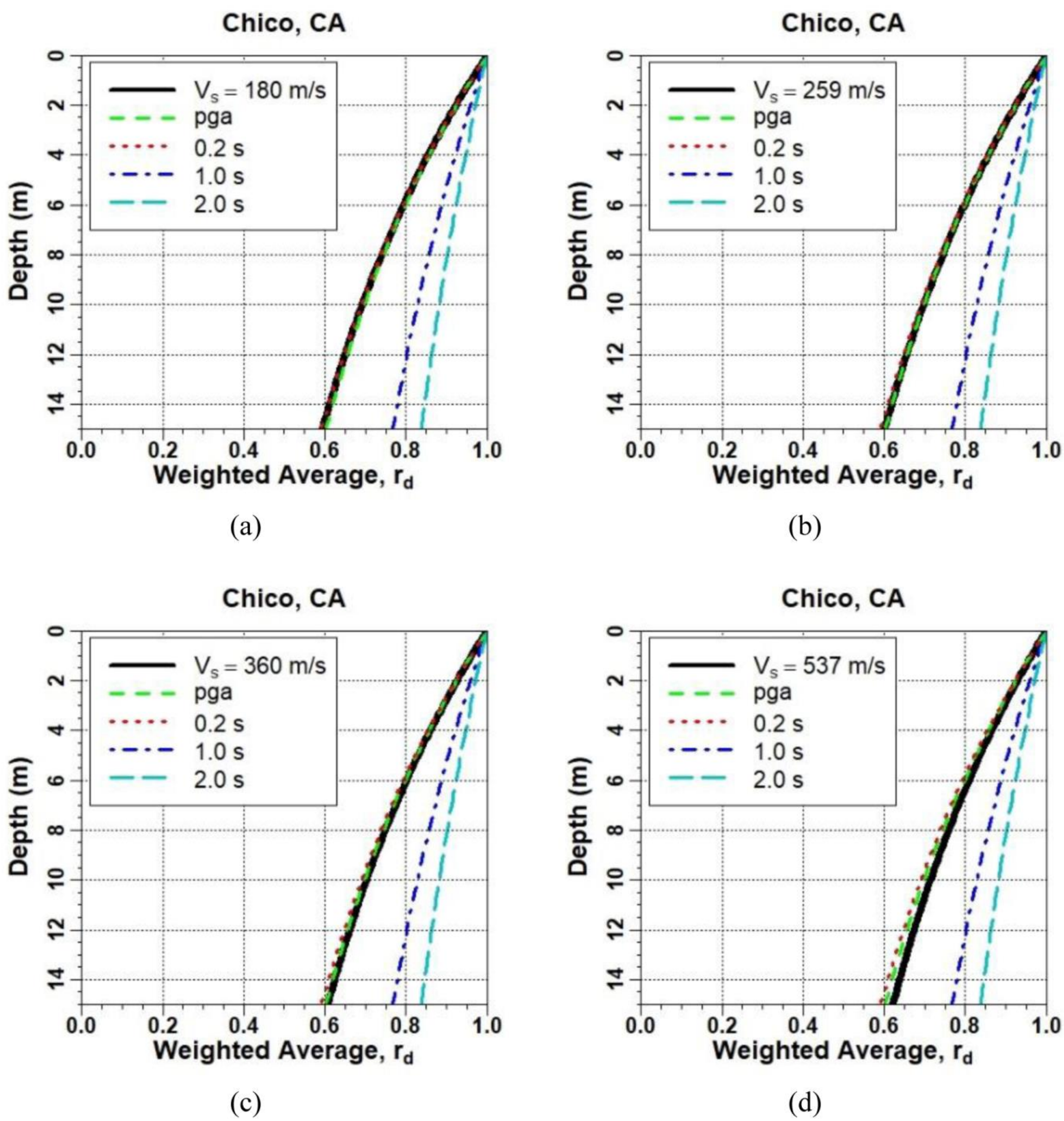


Figure 5. Depth vs. Weighted Average of r_d for Chico, CA, for V_{s30}=760 m/s (T = 0 s, 0.2 s, 1.0 s, and 2.0 s) and for: (a) V_{S30}=180 m/s (PGA); (b) V_{S30}=259 m/s (PGA); (c) V_{S30}=360 m/s (PGA); and (d) V_{S30}=537 m/s (PGA).

Figures 4 and 5 show these comparisons of MSF and r_d, respectively, for Chico, CA. As may be observed from these plots, the weighted average MSF and r_d computed using the deaggregation data for V_{S30} = 760 m/s for PGA and 0.2 s spectral acceleration best match the weighted average MSF and r_d for the PGA_M for the range of seismic site classes. This same trend was observed for all 20 WUS sites analyzed. Based on this, the authors recommend that the Finn and Wightman magnitude-weighting scheme be implemented using the deaggregation data for PGA for Seismic Site Class B/C boundary (V_{S30} = 760 m/s) when evaluating liquefaction potential in the CEUS. For WUS sites, the deaggregation data for PGA_M should be used.

SUMMARY AND CONCLUSIONS

The Finn and Wightman (2007, 2010) magnitude-weighting scheme was explored for use in evaluating liquefaction triggering potential in the Central/Eastern US (CEUS). Specifically, implementation of this scheme is inhibited in the CEUS because the seismic hazard deaggregation data for the ASCE 7-16 seismic hazard maps are only available rock motions and not the ground motions at the surface of the soil profile. The question then becomes whether the deaggregation data for the PGA for rock site conditions should be used in the Finn and Wightman magnitude-weighting scheme, or should the deaggregation data for one of the other spectral accelerations be used (e.g., deaggregation data for the spectral acceleration having an oscillator period closest to the fundamental period of the soil profile). Using the deaggregation data for an oscillator period other than zero, inherently assumes that site effects are dominated by the first mode of vibration of the profile, which is reasonable for many profile-earthquake scenarios.

To provide insights into the answer to this question, 20 sites spatially distributed across the western US (WUS) were analyzed. The reason for analyzing WUS sites is that deaggregation data are available for both rock and soil surface motions in the WUS, which allows a comparison of the weighted-average Magnitude Scaling Factors (MSF) and depth-stress reduction factor (r_d) using bedrock deaggregation data for a range of oscillator periods and using the deaggregation data for the PGA at the surface of the soil profile. For each of the sites, magnitude deaggregation data were computed for PGA, 0.2 s, 1.0 s, and 2.0 s spectral accelerations for Seismic Site Class B/C boundary (V_{S30} = 760 m/s) and for PGA for Seismic Site Classes C (V_{S30} = 537 m/s), C/D boundary (V_{S30} = 360 m/s), D (V_{S30} = 259 m/s), and D/E boundary (V_{S30} = 180 m/s). This data was used to compute weighted averages of MSF and r_d proposed by Green et al. (2019) and Lasley et al. (2016), respectively. It was shown that the weighted average MSF and r_d computed using the deaggregation data for V_{S30} = 760 m/s for PGA and T = 0.2 s spectral acceleration best match the weighted average MSF and r_d for the PGA at the surface of the soil profile for the range of seismic site classes analyzed. Based on this, the authors recommend that the Finn and Wightman magnitude-weighting scheme be implemented using the deaggregation data for PGA for Seismic Site Class B/C boundary (V_{S30} = 760 m/s) when evaluating liquefaction potential in the CEUS. For WUS sites, the deaggregation data for PGA_M should be used.

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