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Optimum Grid Spacing for Simplified Performance-based Liquefaction and Lateral Spread Displacement Parameter Maps

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ABSTRACT

Seismically-induced soil liquefaction and lateral spread displacements present a serious risk of damage to infrastructure. To evaluate hazards associated with liquefaction and lateral spread, performance-based design procedures have recently been developed by numerous researchers. Though these performance-based procedures offer many advantages over deterministic or conventional procedures, they are rarely performed on routine projects due to a lack of necessary tools and training. To make performance-based methods more available to the engineering community, simplified performance-based procedures have recently been developed and validated. These simplified procedures utilize uniform hazard reference maps to characterize liquefaction and lateral spread hazard, and whose hazard values can subsequently be corrected for site-specific soil and topographic conditions. However, the development of these liquefaction and lateral spread reference maps can pose significant challenges to researchers due to spatial bias that can be introduced from an inadequate (i.e., too coarse) grid spacing. Conversely, grid spacing that is too fine can cause the development of reference maps to be numerically and computationally expensive. This paper presents the results of a study evaluating the impact of grid spacing in the development of reference maps for simplified performance-based liquefaction triggering and lateral spread displacement procedures. A variety of grid spacing alternatives was evaluated for bias in multiple seismic environments across the United States. A correlation between mapped peak ground acceleration (PGA) hazard values and optimum grid spacing associated with a maximum of 5% error in the simplified performance-based liquefaction and lateral spread hazard procedures was developed and is presented. This correlation allows researchers to define the grid spacing for liquefaction and lateral spread reference maps by simply referring to seismic hazard maps for the PGA at the targeted return period. Maps created using this procedure are expected to have maximum errors of 5% or less, while remaining computationally efficient.

Introduction

Seismically induced liquefaction and lateral spread displacements have been observed to cause significant damage to infrastructure during earthquake events including recent events such as the 2010 Haiti; 2010-2011 Christchurch, New Zealand; and the 2011 Tohoku, Japan earthquakes. Researchers have developed numerous numerical/analytical methods (e.g., Parra 1996; Yang 2000; Elgamal et al. 2003; Seid-Karbasi and Byrne 2007; Bray and Travasarou 2007; Olson and Johnson 2008; Rathje and Saygili 2009; McGann and Arduino 2014) and empirical/semi-empirical methods (e.g., Seed and Idriss 1971; Bartlett and Youd 1995; Bardet et al. 1999; Rauch and Martin 2000; Youd et al. 2001; Youd et al. 2002; Cetin et al. 2004; and Idriss and Boulanger

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2008) to estimate hazards associated with liquefaction triggering and lateral spread displacements. Performance-based implementation of these methods has been shown to produce more consistent prediction of liquefaction hazards over conventional deterministic methods, and has also demonstrated more objective consideration of probabilistic estimates of seismic loading and model uncertainties (e.g., Marrone et al. 2003; Kramer and Mayfield 2007; Juang et al. 2008; Baker and Faber 2008; Franke and Kramer 2014). Unfortunately, these performance-based methods are not commonly used on routine projects due to many reasons including the lack of simple analytical tools and inadequate understanding of probabilistic methods. In response to this dilemma, researchers have developed and validated simplified performance-based procedures which closely approximate the results of full performance-based procedures (e.g., Mayfield et al. 2010; Franke et al. 2014; Ulmer and Franke 2015; Ekstrom and Franke 2015). These simplified performance-based procedures require the use of hazard-targeted reference maps that are developed through thousands of full performance-based analyses of a single reference soil profile across a grid of geographic locations. These maps provide a reference value (i.e. uniform hazard estimate of SPT resistance required to resist or prevent liquefaction associated with the reference profile, N_{req}^{ref}; uniform hazard estimate of cyclic stress ratio associated with the reference soil profile expressed as a percent, *CSR*(%); or the logarithm of lateral spread displacement corresponding to the reference conditions, [logD_H^{ref}]), which can be corrected with a few simple equations to reflect the site-specific soil and topographic conditions.

The accuracy of these simplified liquefaction triggering and lateral spread displacement hazard estimates depends upon an important decision: what is the appropriate grid spacing (i.e. distance between geographic points to be analyzed) for the development of these reference maps? A grid spacing that is too coarse may not provide sufficient detail for the maps to be accurate and may introduce spatial bias, while a grid spacing that is too fine may be computationally expensive because of the numerous points requiring analysis. This paper evaluates the appropriate grid spacing to develop these reference maps such that the interpolated liquefaction and lateral spread hazard estimates from the simplified performance-based methods are generally within 5% of the hazard estimates from the full performance-based methods.

Preliminary Study of the Correlation with Peak Ground Acceleration

The objective of this study was to develop a simple, well-defined set of "rules" for determining optimum grid spacing for the development of liquefaction reference parameter maps and lateral spread displacement parameter maps. It was initially hypothesized that optimum grid spacing would correlate well with peak ground acceleration (i.e. *PGA*), which is one of the input parameters in the Cetin et al. (2004) and Boulanger and Idriss (2012) probabilistic liquefaction initiation models. Specifically, it was hypothesized that areas of high seismicity would require finer grid spacing and areas of low seismicity would not require such high resolution to achieve the desired accuracy of <5% error. To explore the effects of *PGA* on optimum grid spacing, this preliminary study focused on four cities in the United States with varying levels of seismicity: Berkeley, California; Salt Lake City, Utah; Butte, Montana; and Clemson, South Carolina with *PGA* values as shown in Table 1.

Table 1. Cities used in preliminary grid spacing study.

City	Anchor Point		*PGA* (g) (T_R = 2475 years)
	Latitude	Longitude	
Berkeley, CA	37.872	-122.273	1.1340
Salt Lake City, UT	40.755	-111.898	0.6478
Butte, MT	46.003	-112.533	0.1785
Clemson, SC	34.683	-82.837	0.1439

Using a square grid (like the one shown in Figure 1) with the city's anchor point as the center of the square, several grid spacings were tested. This preliminary testing process included grid spacings of 1, 2, 4, 8, 16, 25, 35, and 50 km (0.62, 1.24, 2.49, 4.97, 9.94, 15.5, 21.7 and 31.1 miles, respectively). A full performance-based liquefaction analysis was performed at each corner point and the center anchor point to solve for N_{req}, *CSR*%, and D_H at three return periods (475, 1033, and 2475 years). Values of N_{req} and *CSR*% were calculated based on both the Cetin et al. (2004) and Boulanger and Idriss (2012) probabilistic models while values of D_H were calculated based on the Youd et al. (2002) model. This process was repeated for each city in the preliminary study.

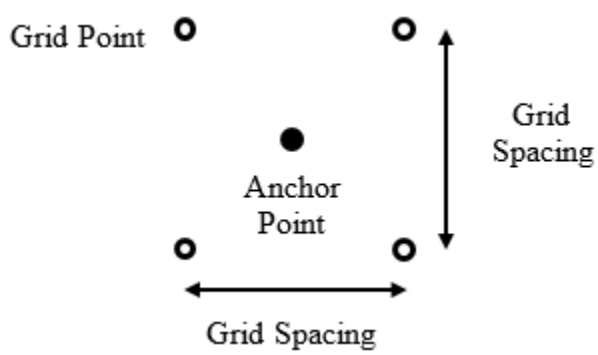

Figure 1. Layout of grid points centered on city's anchor point

An estimate of the liquefaction hazard at the center point (i.e., the interpolated value of either N^{ref}_{req}, CSR^{ref} % or D_H) was calculated using the four corner points. This interpolated value was then compared to the actual value of the center point as calculated using a full performance-based liquefaction analysis. The difference between the interpolated value and the true value at the center is called the error term. The error terms were normalized to the actual values at the anchor points by calculating the percent error term as follows:

$$PercentError = \frac{|InterpolatedValue - ActualValue|}{ActualValue} \times 100\% \quad (1)$$

The maximum percent error (i.e., the maximum percent error across all return periods for a given

anchor point) became the deciding parameter in selecting optimum grid spacing for a given location. The relationship between maximum percent error and grid spacing was analyzed for each city. These relationships were observed to be different for each city. Berkeley had the highest *PGA* value (1.1340g) out of the cities used in this preliminary study and required the smallest grid spacing (approximately 5 km or 3.1 miles) to restrict the maximum percent error to 5%. On the other hand, the maximum percent error for Clemson, which had the lowest *PGA* value (0.1439g), never exceeded 1% error, even with 50km (31.07 miles) grid spacing. Based on these results, it appears that seismicity (for which *PGA* proxies in this study) has an impact on optimum grid spacing.

Correlation between *PGA* and Optimum Grid Spacing

Based on the data from the preliminary study, it was assumed that *PGA* has an effect on the relationship between grid spacing and maximum percent error. Specifically, it was hypothesized that as *PGA* increases, the optimum grid spacing decreases. To estimate the effect of *PGA* on optimum grid spacing, a similar study was conducted focusing on 21 cities in the United States, for which a wide range of probabilistic *PGA* values was observed (Figure 2). These probabilistic values of PGA were obtained from the 2008 U.S. Geological Survey's (USGS) National Seismic Hazard Maps at a hazard level of 2% probability of exceedance in 50 years (i.e., return period of 2,475 years).

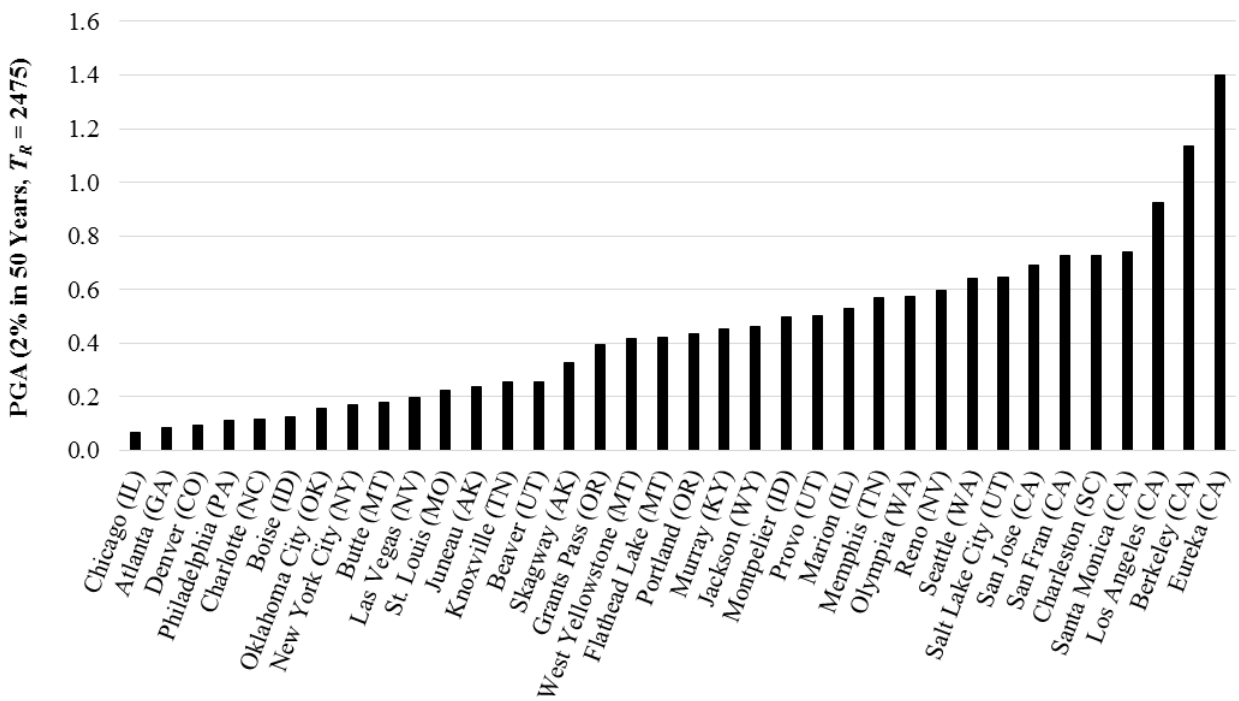

Figure 2. Range of *PGA* values for cities included in final grid spacing study

The desired outcome of the final grid spacing study was to create a correlation between *PGA* and optimum grid spacing in km. An equation for the best-fit trend line alone would not be sufficient, because defining grid points to use in an analysis does not work well with non-integer

values for grid spacing and constantly changing distances between points. Therefore, it was necessary to divide the different cities into *PGA* "bins" or defined ranges of values. These bins were determined using the USGS 2008 *PGA* hazard map (T_r = 2475 years) as shown in Figure 3. This *PGA* hazard map was chosen because it could be easily incorporated into a mapping application to define grid points across geographic areas. The objective of this study was to determine the optimum grid spacing for each color bin.

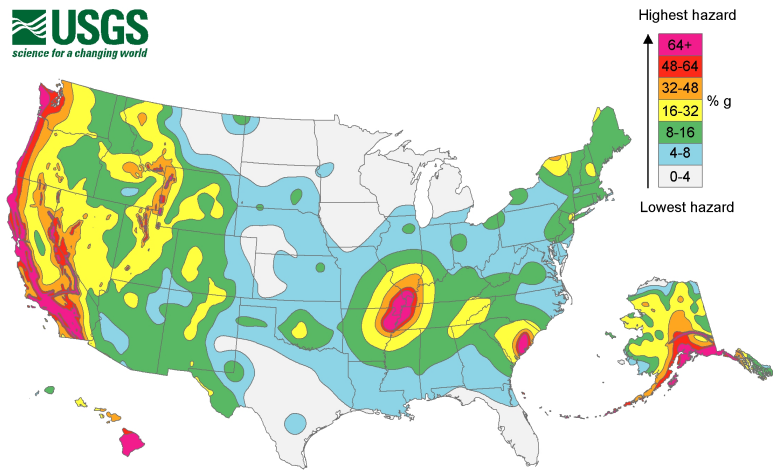

Figure 3. USGS 2008 *PGA* hazard map (T_R = 2475 years)

As in the preliminary study, a full performance-based analysis was performed at the anchor point of each city and at the corners of the grid surrounding the anchor point. This was repeated for multiple grid spacings until the percent error was within a reasonable amount. It was determined that "optimum grid spacing" would be defined as the smallest grid spacing (i.e shortest distance between grid points) which yielded a maximum percent error of 5% across the 2,475 year return period based on *CSR*% (for liquefaction triggering) or D_H (for lateral spread displacement). *CSR*% is used for the liquefaction triggering error definition because if the maximum percent error based on *CSR*% is limited to 5%, the interpolated value of N_{req} is within 1.2 blow counts of the actual value calculated at the anchor point, as shown in Figure 4. This was accepted as a reasonable amount of error, considering the significant and inherent parametric and spatial uncertainties that are typically encountered with in-situ SPT testing at a site. If, for example, the definition of optimum grid spacing was defined as the smallest grid spacing which yielded a maximum difference of 1.5 blow counts for N_{req}, then the values of percent error based on *CSR*% would be as high as 22.7%, which could cause substantial inaccuracies in estimating liquefaction hazards using the simplified performance-based methods. Thus the definition of optimum grid spacing was defined using *CSR*% and not N_{req}.

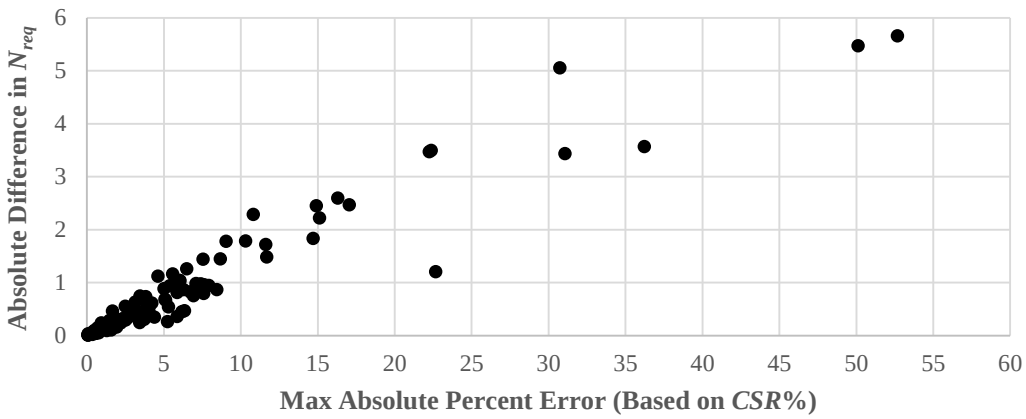

Figure 4. Comparison of difference in N_{req} to max absolute percent error based on *CSR*%

Optimum grid spacing was estimated for each city in the study by plotting the grid spacing that reached a maximum of 5% error based on *CSR*% and D_H against *PGA* as shown in Figure 5 and Figure 6. The vertical dashed lines indicate the boundaries between *PGA* bins as defined in the USGS 2008 *PGA* hazard map. Best-fit linear regression lines are shown on each of these scatterplots, as well as a conservative, recommended set of bounds to use when developing parameter maps.

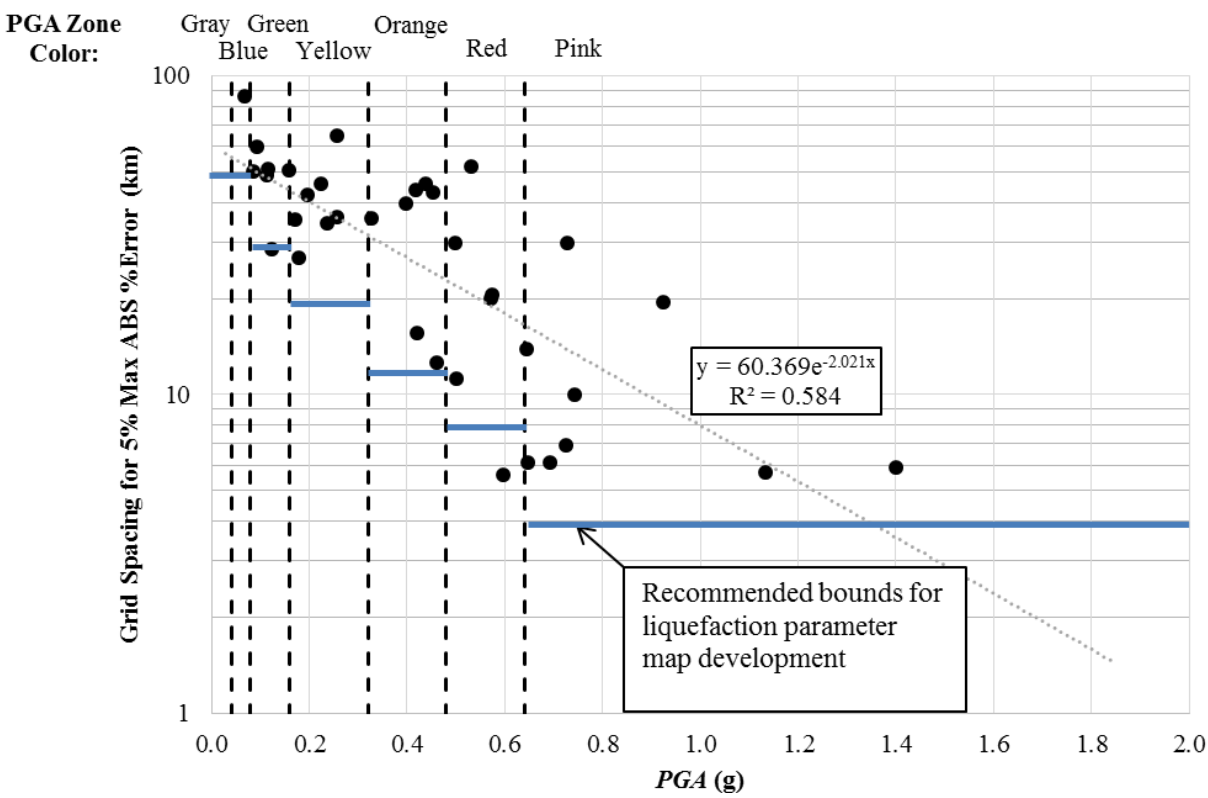

Figure 5. Correlation between *PGA* and optimum grid spacing to achieve 5% maximum absolute percent error (based on *CSR*%)

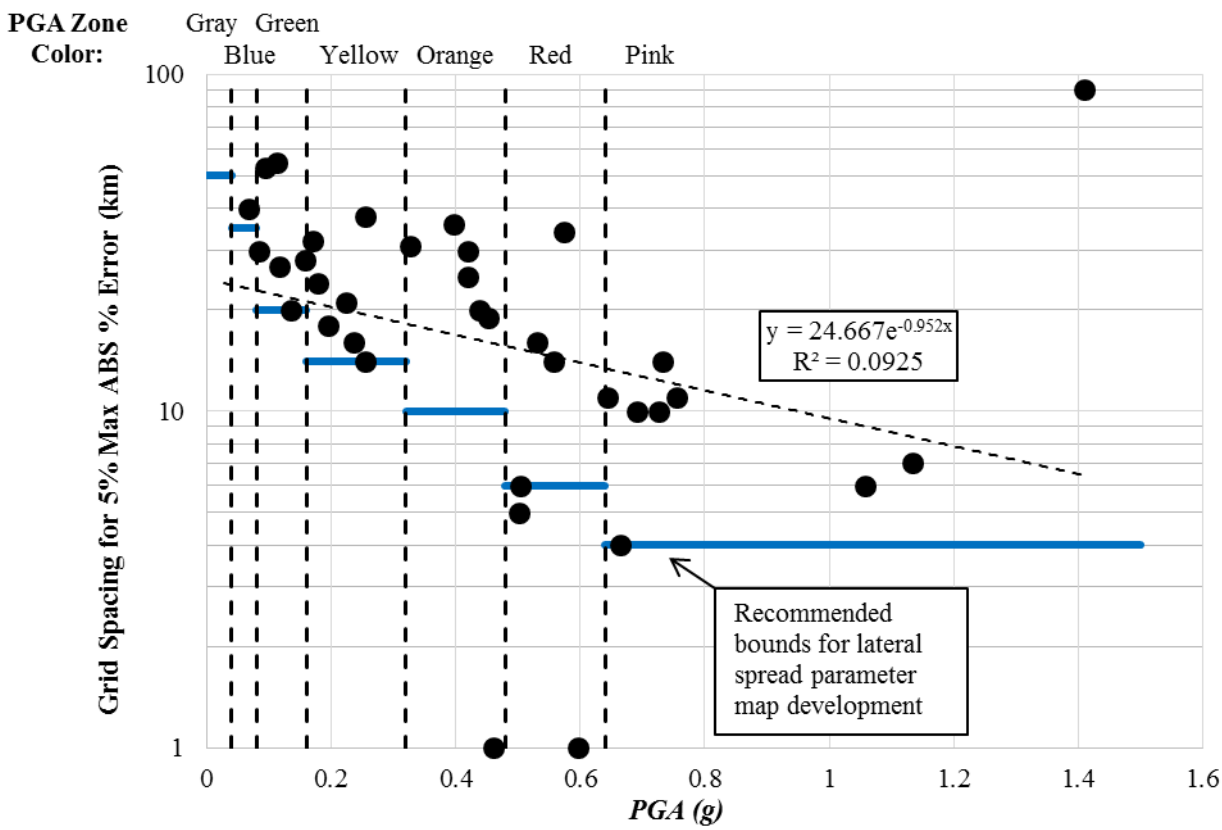

Figure 6. Correlation between *PGA* and optimum grid spacing to achieve 5% maximum absolute percent error (based on D_H)

The hand-drawn lower bound shown in Figure 5 and Figure 6 was used to determine the set of rules for selecting grid spacing in the mapping procedure. Within each *PGA* bin, a lower-bound value for optimum grid spacing was selected. The set of rules includes one optimum grid spacing distance for each *PGA* bin included in the study. Table 2 summarizes this set of rules.

Table 2. Proposed Set of Rules to Determine Optimum Grid Spacing within a *PGA* Range

PGA	Color	Liquefaction Triggering		Lateral Spread	
		Spacing (km)	Spacing (mi)	Spacing (km)	Spacing (mi)
0 - 0.04	Gray	50	31.1	50	31.1
0.04 - 0.08	Blue	50	31.1	30	18.6
0.08 - 0.16	Green	30	18.6	20	12.4
0.16 - 0.32	Yellow	20	12.4	13	8.1
0.32 - 0.48	Orange	12	7.5	9	5.6
0.48 - 0.64	Red	8	5	6	3.7
0.64+	Pink	4	2.5	4	2.5

Discussion

For the liquefaction triggering grid spacing study, the results are relatively straightforward. The general trend of the points (R^2 = 0.584) suggests that as *PGA* increases, the optimum grid spacing decreases. There is reasonable scatter in the results, and the trend of the plot in Figure 5 is clear. For the lateral spread study, the results are not as clear. Generally, the trend of the data is consistent with the liquefaction triggering study. But the data start to deviate from this trend in areas with $PGA > 0.5g$, as can be seen in Figure 6. Some sites like Eureka, CA seemed insensitive to grid spacing entirely, not reaching 5% error even with a grid spacing of 90 km. At the same time, two locations - Reno, NV and Jackson, WY - did not achieve <5% error with any grid spacing, even as small as 1 km.

The atypical behavior observed in predicted lateral spread displacements at Reno and Jackson was examined carefully, and some potentially important observations were made. First, these two sites are located near the edges of the Intermountain Seismic Belt (ISB) of the United States. The ISB is characterized by extensive normal faulting in north-south trending valleys. The 2008 USGS seismic source model (Petersen et al. 2008), which was used in this study, becomes quite complex in these areas as the model transitions from the ISB to other seismic regions characterized by different faulting types, recurrence rates, attenuation relationships, and logic tree weighting factors. Second, the Youd et al (2002) empirical lateral spread model is very sensitive to source-to-site distance at low to medium magnitude events (Franke and Kramer 2014), which are commonly assigned to the individual and gridded seismic sources located near (i.e., < 5km) the Jackson and Reno sites. Therefore, even with a grid spacing as small as 1 km, significant bias was observed when performing simplified performance-based interpolations at these two sites.

Conclusions

In summary, the development of simplified performance-based procedures relies heavily on the creation of liquefaction reference maps. To ensure that these maps accurately represent the seismic loading that governs liquefaction triggering and lateral spread displacement, the grid spacing needs to be small enough that interpolation between analyzed points returns and acceptable margin of error. In general, optimum grid spacing decreases as PGA increases. This study recommends the grid spacings listed in Table 2 when creating liquefaction reference maps for *CSR*%, N_{req}, and/or D_H in the future. The study did find some limitations of the grid spacing recommendations. When developing lateral spread parameter maps in areas near the boundaries of different seismic regimes, or near seismic sources that are commonly associated with small to moderate earthquake events (i.e., $M_w < 7.0$), closer grid spacing may be necessary to account for the sensitive near-field behavior of the Youd et al. (2002) model.

The recommended grid spacings presented in Table 2 apply to sites in the U.S. and to the specific liquefaction triggering and lateral spread models analyzed in this study. Though it is expected that the observed trends from this study would be valid for sites outside the U.S. and for other liquefaction prediction models, some level of validation should be performed before the recommended grid spacings are implemented for such cases.

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