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SIMPLIFIED SPT PERFORMANCE-BASED ASSESSMENT OF LIQUEFACTION AND EFFECTS: *TASKS 7 AND 8*

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16. Abstract
Deterministic and performance-based procedures of assessing liquefaction hazard can produce significantly different results, especially for areas of low seismicity. To provide guidance on the application of these differing results, a comparison of the simplified and deterministic procedures was performed for three cities of varying seismicity. These results of this comparison suggest that the deterministic results could be used as an upper-bound in areas of high seismicity, but in areas of low seismicity, the deterministic analysis could be optional. Engineers performing analyses in areas of medium to high seismicity could choose to use a deterministic analysis as a "reality check" against the simplified performance-based results. If both deterministic and performance-based methods are considered, the *lowest* result is the governing value. When deciding whether the deterministic or performance-based results should be accepted, engineers should apply the following rule: the *lowest* value governs.

Additionally, a Simplified Performance-Based Liquefaction Assessment tool was developed, that incorporates the simplified performance-based procedures determined with this research. The components of this tool, as well as step-by-step procedures for the liquefaction initiation and lateral spread displacement models were provided.

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UNIT CONVERSION FACTORS

Units used in this report and not conforming to the UDOT standard unit of measurement (U.S. Customary system) are given below with their U.S. Customary equivalents:

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

LIST OF ACRONYMS

DSHA	Deterministic Seismic Hazard Analysis
EDP	Engineering Demand Parameter
FHWA	Federal Highway Administration
GMPE	Ground Motion Predictive Equation
IM	Intensity Measure
PBEE	Performance-Based Earthquake Engineering
PSHA	Probabilistic Seismic Hazard Analysis
UDOT	Utah Department of Transportation

LIST OF TERMS

Liquefaction Triggering Terms

a_{max}	peak ground surface acceleration
CRR	cyclic resistance ratio
$CRR_{PL=50\%}$	median CRR (CRR corresponding to a probability of liquefaction of 50%)
CSR	cyclic stress ratio
CSR^{ref}	uniform hazard estimate of CSR associated with the reference soil profile
CSR^{site}	site-specific uniform hazard estimate of CSR
ΔCSR_{σ}	correction factor for vertical stress
ΔCSR_{Fpga}	correction factor for soil amplification
ΔCSR_{rd}	correction factor for shear stress reduction
ΔCSR_{MSF}	correction factor for magnitude scaling factor
$\Delta CSR_{K\sigma}$	correction factor for overburden pressure
ΔCSR	difference between CSR^{site} and CSR^{ref} values
FC	fines content (%)
FS_L	factor of safety against liquefaction triggering
FS_L^{site}	site-specific uniform hazard estimate of FS_L
F_{PGA}	soil amplification factor
K_{σ}	overburden correction factor (Idriss and Boulanger model)
MSF	magnitude scaling factor
M_w	mean moment magnitude
N	SPT blow count (uncorrected)
$(N_1)_{60}$	SPT resistance corrected to 60% efficiency and 1 atm pressure
$(N_1)_{60,cs}$	clean sand-equivalent SPT corrected to 60% efficiency and 1 atm pressure
N_{req}	SPT resistance required to resist or prevent liquefaction
N_{req}^{ref}	uniform hazard estimate of N_{req} associated with the reference soil profile
N_{req}^{site}	site-specific uniform hazard estimate of N_{req}
ΔN_L	difference between N_{site} and N_{req} values
P_a	atmospheric pressure (1 atm, 101.3 kPa, 0.2116 psf)
PGA	peak ground acceleration
P_L	probability of liquefaction
r_d	shear stress reduction coefficient
SPT	Standard Penetration Test
$V_{s,12}$	average shear wave velocity in upper 12 m (39.37 ft) of soil profile
z	depth to middle of soil profile layer
γ	unit weight of soil (i.e. pcf, kN/m^3, etc.)
σ_{ε}	error term for either model + parametric uncertainty or parametric uncertainty
σ_T	error term for both model and parametric uncertainty

σ_v	total vertical stress in the soil
σ'_v	effective vertical stress in the soil
Λ_{FS_L*}	mean annual rate of not exceeding some given value of FS_L
$\lambda_{N_{req}*}$	mean annual rate of exceeding some given value of N_{req}
τ_{cyc}	equivalent uniform cyclic shear stress
Φ	standard normal cumulative distribution function

Lateral Spread Displacement Terms

D_H	median computed permanent lateral spread displacement (m)
R	closest horizontal distance from the site to the source (km)
M	earthquake moment magnitude
W	free-face ratio (%)
S	ground slope (%)
T_{15}	cumulative thickness (in upper 20 m) of all saturated soil layers with corrected SPT blowcounts (i.e., $(N_1)_{60}$) less than 15 blows/foot (m)
F_{15}	average fines content of the soil comprising T_{15} (%)
$D50_{15}$	average mean grain size of the soil comprising T_{15} (mm)
$\mathscr{L}$	Loading Parameter
$\mathscr{S}$	Site Parameter
$\mathscr{D}$	transformed (e.g. log, ln, square root) lateral spread displacement
ε	uncertainty term (used in lateral spread displacement model)
$\left[\log D_H\right]^{site}$	logarithm of the lateral spread displacement adjusted for site-specific conditions
$\left[\log D_H\right]^{ref}$	logarithm of the lateral spread displacement corresponding to the reference site
ΔD_H	adjustment factor for lateral spread displacement
D_H^{site}	site-specific hazard-targeted lateral spread displacement

EXECUTIVE SUMMARY

Deterministic and performance-based procedures of assessing liquefaction hazard can produce significantly different results, especially for areas of low seismicity. To provide guidance on the application of these differing results, a comparison of the simplified and deterministic procedures was performed for three cities of varying seismicity. Additionally, these results were compared to pseudo-probabilistic analysis at the same locations.

The results of this comparison show that the deterministic procedure severely over-predicts the hazard in regions of low seismicity and slightly over predicts hazard for areas of medium seismicity. In areas of high seismicity, the deterministic analysis for mean magnitude, distance, and PGA values predicts slightly lower values than the results of the simplified procedure for the 2475 year return period but predicts higher values for the deterministic analysis with 84th percentile values.

These results suggest that the deterministic results could be used as an upper-bound in areas of high seismicity, but in areas of low seismicity, the deterministic analysis could be optional. Engineers performing analyses in areas of medium to high seismicity could choose to use a deterministic analysis as a "reality check" against the simplified performance-based results. If both deterministic and performance-based methods are considered, the *lowest* result is the governing value. When deciding whether the deterministic or performance-based results should be accepted, engineers should apply the following rule: the *lowest* value governs.

Additionally, a Simplified Performance-Based Liquefaction Assessment tool was developed, that incorporates the simplified performance-based procedures determined with this research. The components of this tool, as well as step-by-step procedures for the liquefaction initiation and lateral spread displacement models were provided.

1.0 INTRODUCTION

1.1 Problem Statement

The purpose of the research being performed is to provide the benefit of the full performance-based probabilistic earthquake hazard analysis, without requiring special software, training, and experience. To do this, simplified procedures of liquefaction triggering and lateral spread displacement assessment were developed and validated to approximate the results of full probabilistic analyses. Associated liquefaction loading maps were created to support these simplified procedures. The final simplified performance-based procedure is outlined in this report along with suggestions of how to incorporate deterministic analyses as an upper limit to the performance-based results.

1.2 Objectives

The objective of this report is to compare results of deterministic and probabilistic analyses to assess whether the deterministic results should be used as an upper limit to the performance-based results. In addition, a practical methodology and an associated spreadsheet tool were developed to aid engineers in performing these simplified performance-based liquefaction hazard evaluations. These objectives specifically address the Year 1 portion of Tasks 7 and 8 of the TPF-5(296) research contract.

1.3 Scope

The tasks to be performed in this research will be:

- Determination of liquefaction initiation and lateral spread displacement for: Butte, MT; Salt Lake City, UT; and San Francisco, CA using:
    - Deterministic Method
    - Pseudo-probabilistic Method
    - Simplified Performance-Based Method
- Comparison of the results of the simplified, deterministic, and pseudo-probabilistic analyses

- Creation of the Simplified Performance-Based Liquefaction Assessment tool

1.4 Outline of Report

The research conducted for this report will contain the following:

- Introduction
- Comparison of Probabilistic and Deterministic Analyses
- Development of the Simplified Tool
- Conclusions
- Appendices

2.0 COMPARISON OF PROBABILISTIC AND DETERMINISTIC ANALYSES

2.1 Overview

This section provides comparisons between the pseudo-probabilistic, deterministic, and simplified performance-based procedures for estimating liquefaction initiation hazard and lateral spread displacement. The purpose of these comparisons is to identify how the deterministic procedure should be used in the proposed simplified procedure.

2.2 Methodology

Three cities of varying seismicity were selected for the comparison study: San Francisco (high seismicity), Salt Lake City (medium seismicity), and Butte (low seismicity). For each city, three analyses were performed: probabilistic (simplified performance-based procedure developed as part of this research), pseudo-probabilistic (AASHTO), and deterministic. A description of each analysis type is provided below.

2.2.1 Simplified Performance-Based Seismic Hazard Analysis

The simplified performance-based procedures involve retrieving a specified liquefaction hazard parameter from a hazard-targeted map developed using full probabilistic analyses. The probabilistic analyses which created the liquefaction loading and lateral spread parameter maps involve creating hazard curves which consider all possible combinations of the required seismic hazard analysis variables and their respective likelihoods. Examples of these variables would be: maximum horizontal ground acceleration, a_{max}, moment magnitude, M_w, or site-to-source distance, R. These processes are discussed in greater detail in the previously submitted update reports: Update Report Year 1 Quarter 1 for the simplified performance-based methods, and Update Report Year 1 Quarter 2 for the development of the liquefaction loading and lateral spread parameter maps.

The parameters used for the comparison of deterministic and simplified methods for this study were: for liquefaction initiation, $CSR\%^{ref}$; and for lateral spread, D_H^{ref}. Each of the parameters were found at the target cities for the 475, 1033, and 2475 year return periods.

2.2.1.1 Simplified Liquefaction Initiation

For the simplified liquefaction initiation procedure the appropriate uniform hazard-targeted liquefaction loading map was identified for each site and values of $CSR\%^{ref}$ were obtained for the necessary return periods. These $CSR\%^{ref}$ values were adjusted for soil characteristics associated with an assumed soil profile (shown in Figure 2-1) to estimate $CSR\%^{site}$ values. This same soil profile was used for all three analyses (probabilistic, pseudo-probabilistic, and deterministic). The values of $CSR\%^{site}$ were used to calculate factor of safety against liquefaction (FS_L), and clean-sand equivalent SPT blow count required to resist liquefaction initiation (N_{req}). This process is described in greater detail in the Update Report 1.

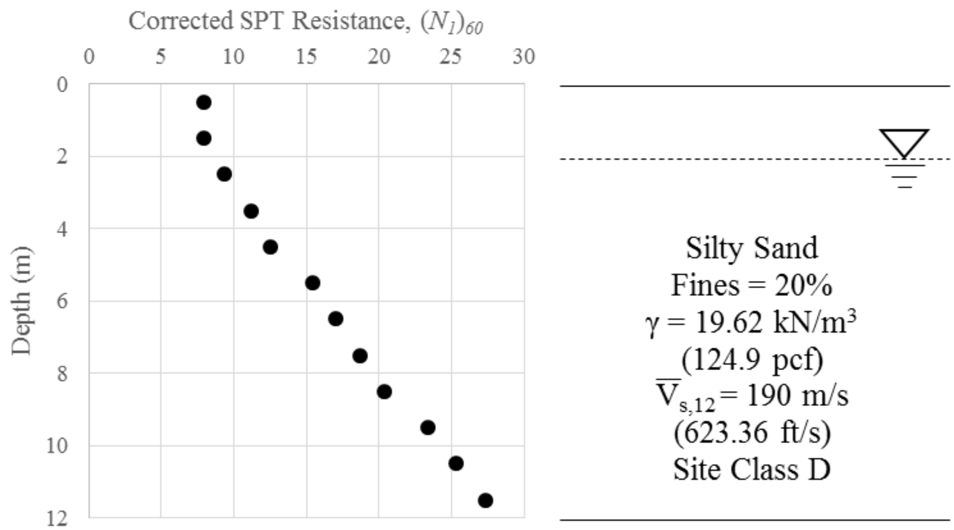

Figure 2-1 Soil profile used for the liquefaction initiation comparison study.

2.2.1.2 Simplified Lateral Spread Displacements

For the simplified performance-based procedure the appropriate lateral spread parameter map was identified for each site and values of D_H^{ref} were obtained for the necessary return periods. Using a generic soil profile (seen in Figure 2.2) the values of D_H^{ref} were corrected and the D_H^{site} was determined for each city at the targeted return periods. The additional analyses (pseudo-probabilistic and deterministic) for the comparison utilized the same soil profile. The simplified procedure is described in greater depth in the Update Report 1.

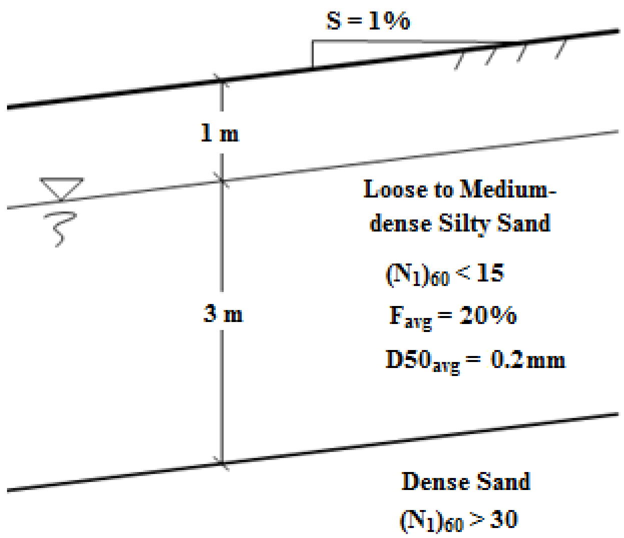

Figure 2-2 Soil profile used for the lateral spread displacement comparison study.

2.2.2 Deterministic Procedure

In the deterministic procedure, ground motions are obtained through a Deterministic Seismic Hazard Analysis (DSHA). A DSHA involves deterministically assessing the seismic sources in the nearby region of the site of interest and identifying the source which produces the highest hazard in the area. The software EZ-FRISK was used to identify the top five seismic sources within 200 km for San Francisco and Salt Lake City. The 2008 USGS Seismic Source Model within EZ-FRISK does not include some smaller faults in low seismic regions, such as Butte. Thus, the governing fault for Butte (Rocker Fault) was identified using the USGS quaternary fault database (USGS et al., 2006). In the case of Salt Lake City and San Francisco, EZ-FRISK provided values of M_w, *PGA*, and *R* for both the 50th (i.e. median) and 84th (i.e. median + σ) percentiles according using the New Generation Attenuation (NGA) models for the Western United States (Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; and Chiou and Youngs, 2008) and weighting schemes shown in Table 2-1. For Butte, the 50th and 84th percentile M_w values were estimated using a correlation with surface rupture length developed by Wells and Coppersmith (1994), and *PGA* was calculated using the same three (NGA) models based on measured dimensions and assumed characteristics of the Rocker Fault. Summaries of the seismic sources considered in this DSHA and details of the Rocker Fault calculations are provided in Tables A.1 and A.2, respectively, in the appendix. Once the model inputs have been determined through the DSHA they are entered into the respective empirical liquefaction hazard models. A summary of the governing input variables utilized in the deterministic liquefaction initiation and lateral spread displacement models are provided in Table 2-2.

Table 2-1 NGA model weights used in the deterministic procedure.

Attenuation Model	Weight
Boore & Atkinson (2008)	0.333
Campbell & Bozorgnia (2008)	0.333
Chiou & Youngs (2008)	0.333

Table 2-2 Input variables used in the deterministic models (a_{max} calculated using F_{pga} from AASHTO code).

Location	Latitude	Longitude	Distance [km]	Mean M_w	Median (50%)		Median + σ (84%)	
					PGA	a_{max}	*PGA*	a_{max}
Butte	46.003	-112.533	4.92	6.97	0.5390	0.5390	0.9202	0.9202
Salt Lake City	40.755	-111.898	1.02	7.00	0.5911	0.5911	1.005	1.005
San Francisco	37.775	-122.418	12.4	8.05	0.3175	0.3754	0.5426	0.5426

2.2.2.1 Liquefaction Initiation

Estimations of liquefaction initiation potential (FS_L, N_{req}, and CSR%) were calculated deterministically using equations from the Idriss and Boulanger (2008) liquefaction triggering model. CSR% is found using the following equation:

$$CSR(\%) = 0.65 \frac{a_{\max}}{g} \frac{\sigma_v}{\sigma_v'} \left(r_d\right) \frac{1}{\left(MSF\right)} \frac{1}{K_\sigma} (100\%) \tag{1}$$

where σ_v is the total vertical stress in the soil; σ_v' is the effective vertical stress in the soil; $a_{\max}/g$ is the peak ground surface acceleration as a fraction of gravity; MSF is the magnitude scaling factor as computed according to Idriss and Boulanger (2008); r_d is the depth reduction factor according to Idriss and Boulanger (2008); and K_σ the depth correction factor and is computed according to Idriss and Boulanger (2008). FS_L is calculated as:

$$FS_L = \frac{CRR}{CSR} = \frac{100 \cdot CRR}{CSR(\%)} \tag{2}$$

$$CRR_{P_L=50\%} = \exp\left[\left(\frac{(N_1)_{60,cs}}{14.1}\right) + \left(\frac{(N_1)_{60,cs}}{126}\right)^2 - \left(\frac{(N_1)_{60,cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60,cs}}{25.4}\right)^4 - 2.8\right] \tag{3}$$

where $(N_1)_{60,cs}$ represents the clean sand-equivalent SPT resistance value corrected to 60% efficiency and 1 atm overburden pressure as computed using the equations provided by Idriss and Boulanger (2008, 2010). N_{req} is solved iteratively from the following polynomial:

$$0 = \left(\frac{N_{req}}{14.1}\right) + \left(\frac{N_{req}{}^2}{126}\right) - \left(\frac{N_{req}{}^3}{23.6}\right) + \left(\frac{N_{req}{}^4}{25.4}\right) - 2.8 - \ln(CSR) \tag{4}$$

2.2.2.2 Lateral Spread Displacement

Estimations of lateral spread displacement for the deterministic process were found using the equation from the Youd et al (2002) empirical lateral spread model. The model is a regression based on seismic loading parameters and site specific soil parameters. The seismic loading inputs are shown in Table 2-2, and the site specific soil inputs were drawn from the soil profile seen in Figure 2-2. With these values the lateral spread displacement, D_H, is found using the following equation:

$$\begin{aligned}\overline{\log D_H} &= b_0 + b_1 M + b_2 \log R^* + b_3 R + b_4 \log W + b_5 \log S \\ &\quad + b_6 \log T_{15} + b_7 \log(100 - F_{15}) + b_8 \log(D50_{15} + 0.1)\end{aligned} \tag{5}$$

where D_H is the median computed permanent lateral spread displacement (m), M is the earthquake moment magnitude, R is the closest horizontal distance from the site to the source (km), W is the free-face ratio (%), S is the ground slope (%), T_{15} is the cumulative thickness (in upper 20 m) of all saturated soil layers with corrected Standard Penetration Test (SPT) blowcounts (i.e., $(N_1)_{60}$) less than 15 blows/foot (m), F_{15} is the average fines content of the soil comprising T_{15} (%), $D50_{15}$ is the average mean grain size of the soil comprising T_{15} (mm), and R* which is computed as:

$$R^* = R + 10^{0.89M - 5.64} \tag{6}$$

The model coefficients b_0 through b_8 are given in Table 2-3.

Table 2-3 Regression coefficients for the Youd et al. (2002) empirical lateral spread model.

Model	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
Ground slope	-16.213	1.532	-1.406	-0.012	0	0.338	0.540	3.413	-0.795
Free Face	-16.713	1.532	-1.406	-0.012	0.592	0	0.540	3.413	-0.795

2.2.3 Pseudo-probabilistic Seismic Hazard Analysis

In the pseudo-probabilistic procedure, the variables used in the empirical liquefaction hazard models are obtained from a Probabilistic Seismic Hazard Analysis (PSHA). Then these variables are used in the same deterministic procedure outlined previously for both the liquefaction initiation and lateral spread displacements. To find these variables using a PSHA the USGS 2008 interactive deaggregation website (USGS 2008) was utilized. This procedure involved entering the latitude and longitude of the target cities, then selecting the return period for the analysis. Using this tool, the mean magnitude (M_w), peak ground acceleration (PGA) for rock, and source-to-site distance (R) were obtained for a return period of 1,039 years for each city of interest. The resulting values are summarized in Table 2-4.

Table 2-4 Input values found using USGS 2008 Deaggregations (T_R = 1,039 years).

Location	Latitude	Longitude	Distance (km)	Mean M_w	*PGA*	F_{pga}
Butte	46.003	-112.533	24.9	6.03	0.1206	1.559
Salt Lake City	40.755	-111.898	4.20	6.84	0.4030	1.097
San Francisco	37.775	-122.418	12.0	7.38	0.5685	1.000

2.3 Results

Each city was evaluated using the three analysis types discussed previously (probabilistic, pseudo-probabilistic, and deterministic). The following plots allow comparisons between the three methods and help explain the purpose of deterministic analyses within the proposed simplified performance-based procedures.

2.3.1 Performance-based Liquefaction Triggering Assessment

2.3.1.1 Pseudo-probabilistic vs. Simplified Performance-based

In each of the three cities analyzed, the results from the pseudo-probabilistic procedure suggested greater liquefaction hazard than the results from the performance-based procedure. The direct comparison of both methods is provided in Figure 2-3.

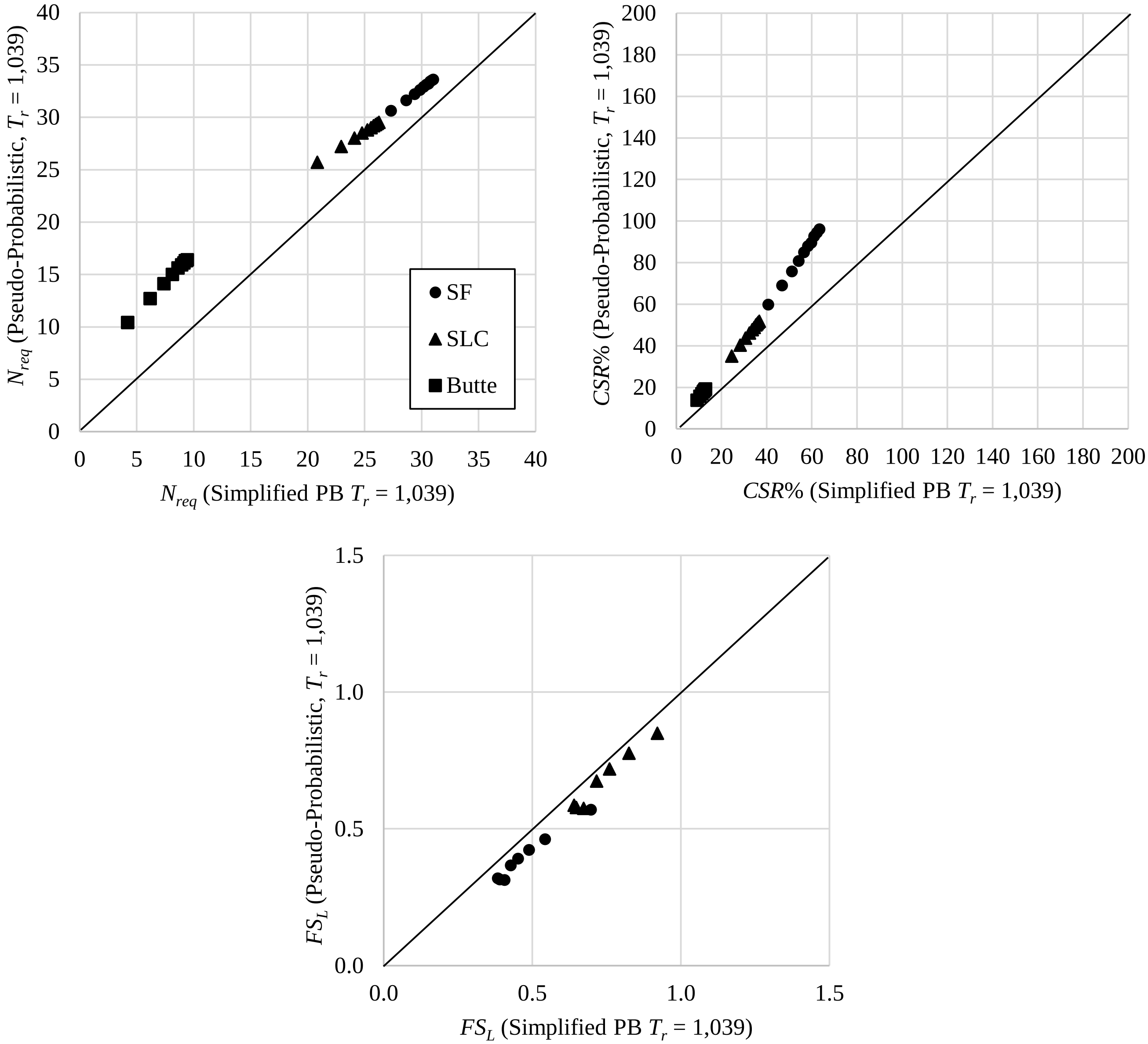

Figure 2-3 Comparison of pseudo-probabilistic and simplified performance-based values of N_{req}, $CSR\%$, and FS_L.

2.3.1.2 Deterministic vs. Simplified Performance-based

Direct comparison plots (Figure 2-4 through Figure 2-6) show that the deterministic analyses frequently over-predicted liquefaction hazard. This over-prediction is especially evident in the case of Butte where the simplified performance-based method estimated N_{req} values as low as 3.1% of the deterministic N_{req} values. This discrepancy could be because the likelihood of the large Rocker Fault near Butte rupturing and achieving the 50% ground motion is very low. Therefore, in the simplified performance-based approach (which incorporates likelihoods of seismic events in the calculations), the associated N_{req} is much lower. These comparison plots also highlight the significant discrepancy between the 50th and 84th percentile ground motions. In the case of San Francisco at the 2,475-year return period, the 50th percentile ground motions under-predict N_{req} while the 84th percentile ground motions over-predict N_{req}. This discrepancy produces a dilemma for the engineer who has to decide which ground motions appropriately characterize the liquefaction hazard for the given site. However, the simplified performance-based procedure does not depend this decision and can provide a more consistent estimate of liquefaction hazard.

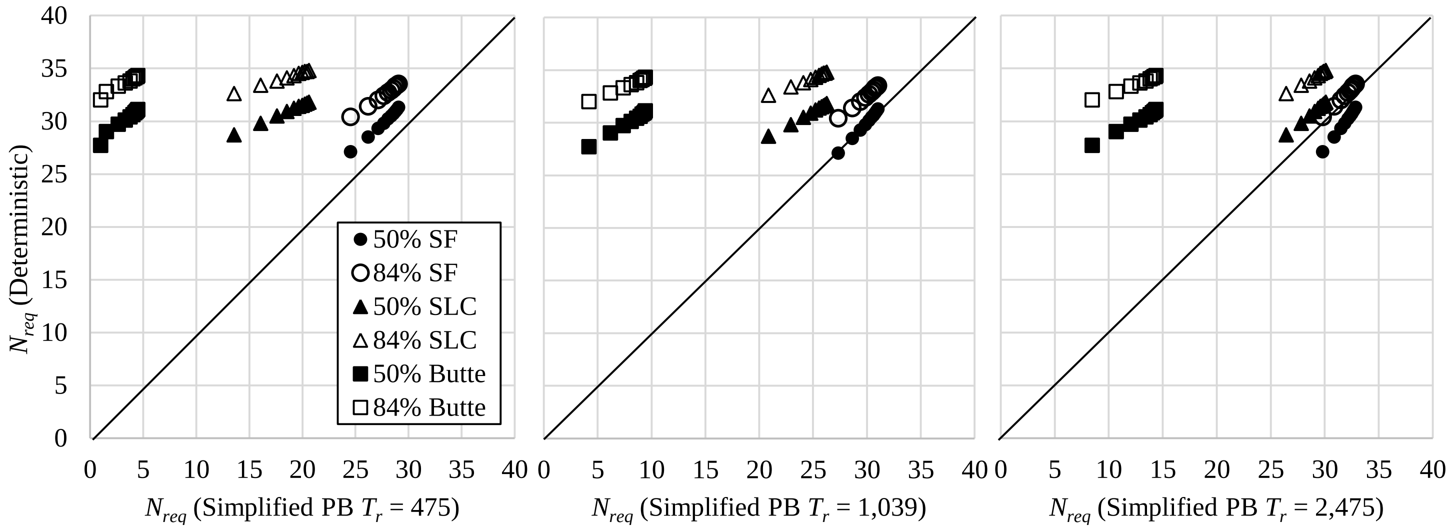

Figure 2-4 Comparison of deterministic and simplified performance-based values of N_{req}.

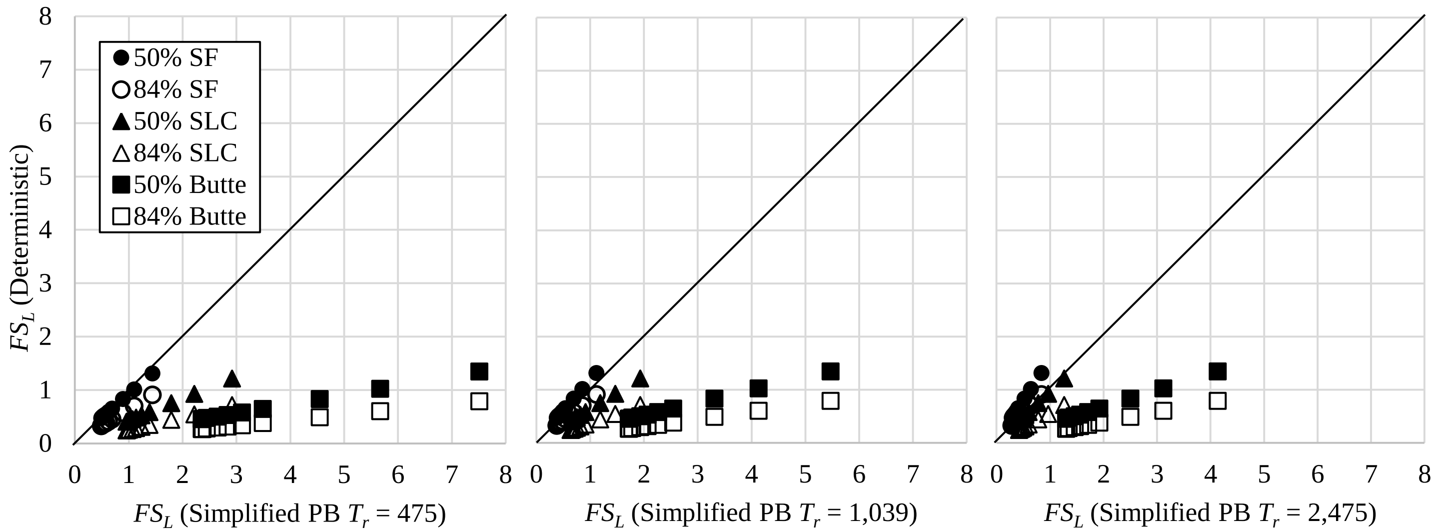

Figure 2-5 Comparison of deterministic and simplified performance-based values of FS_L.

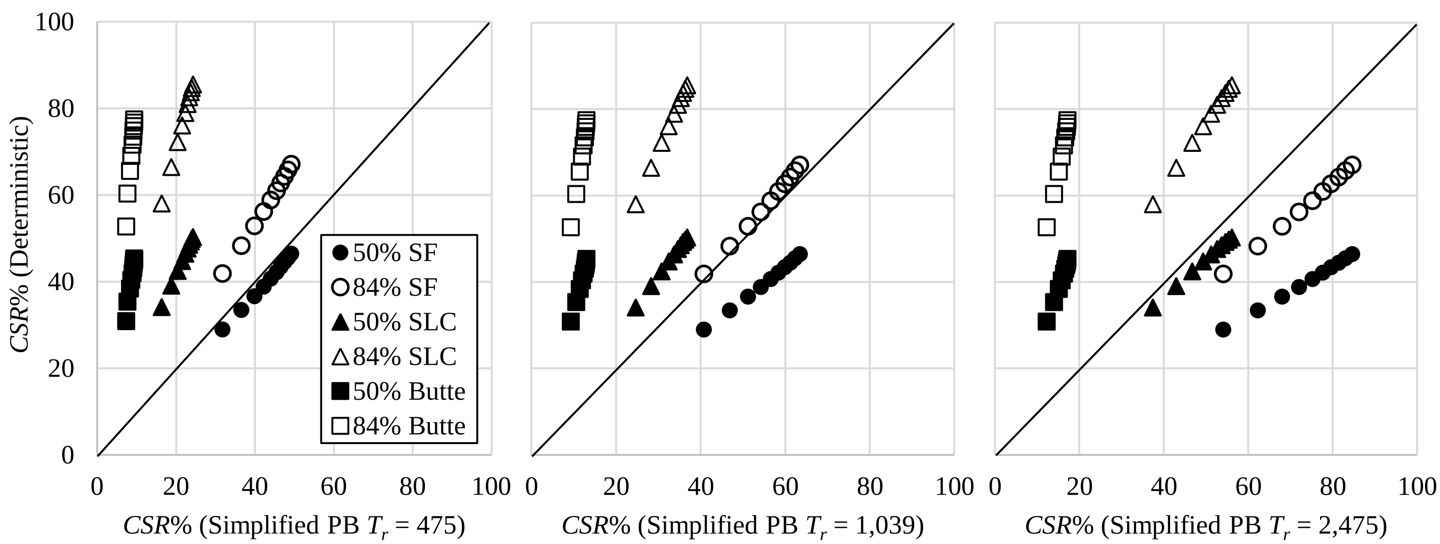

Figure 2-6 Comparison of deterministic and simplified performance-based values of *CSR%*.

2.3.2 Empirical Lateral Spread Displacement Model

Once the analysis of the different methods was completed, the data was examined and several charts were created, one for each city. These charts compare, side by side, the results of the simplified, pseudo-probabilistic, and deterministic analyses. These charts can be seen in Figure 2-7, Figure 2-8, and Figure 2-9.

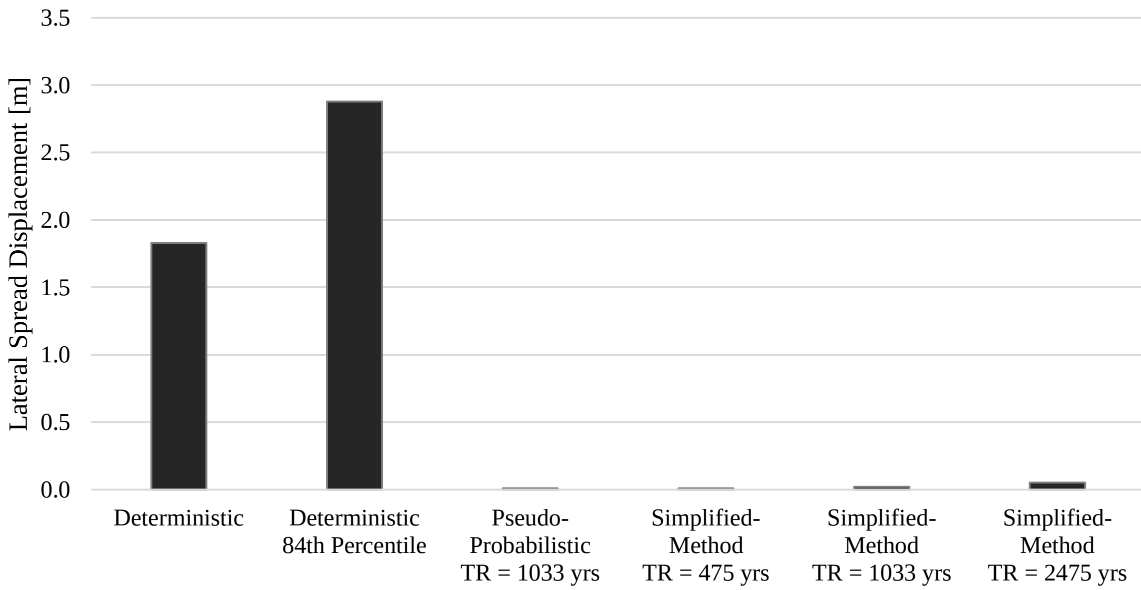

Figure 2-7 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods for Butte, MT (Latitude 46.033, Longitude -112.533).

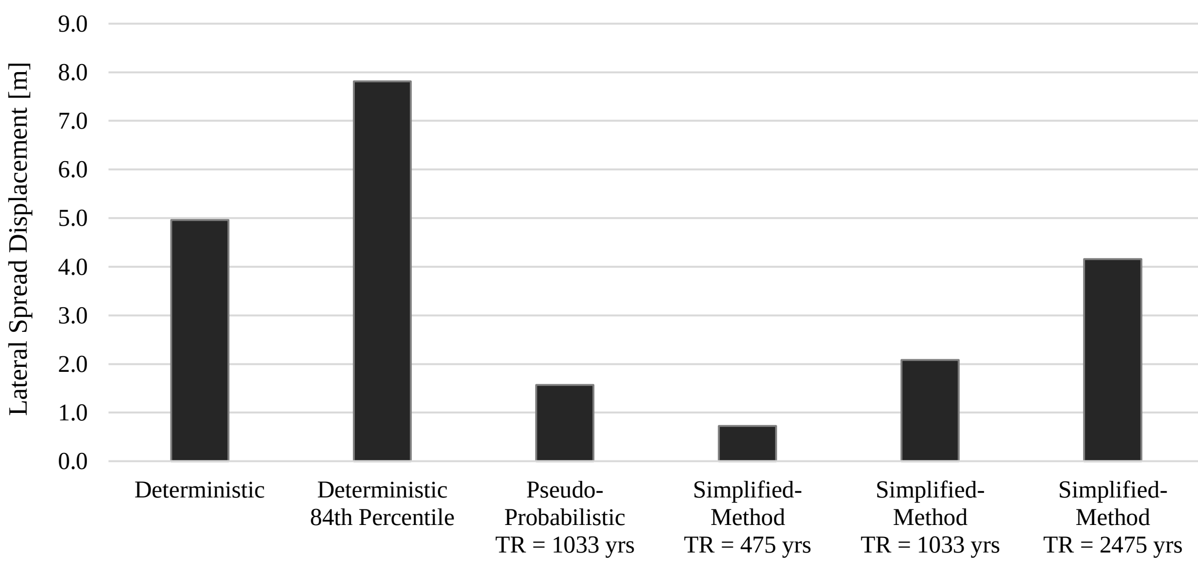

Figure 2-8 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods for Salt Lake City, UT (Latitude 40.755, Longitude -111.898).

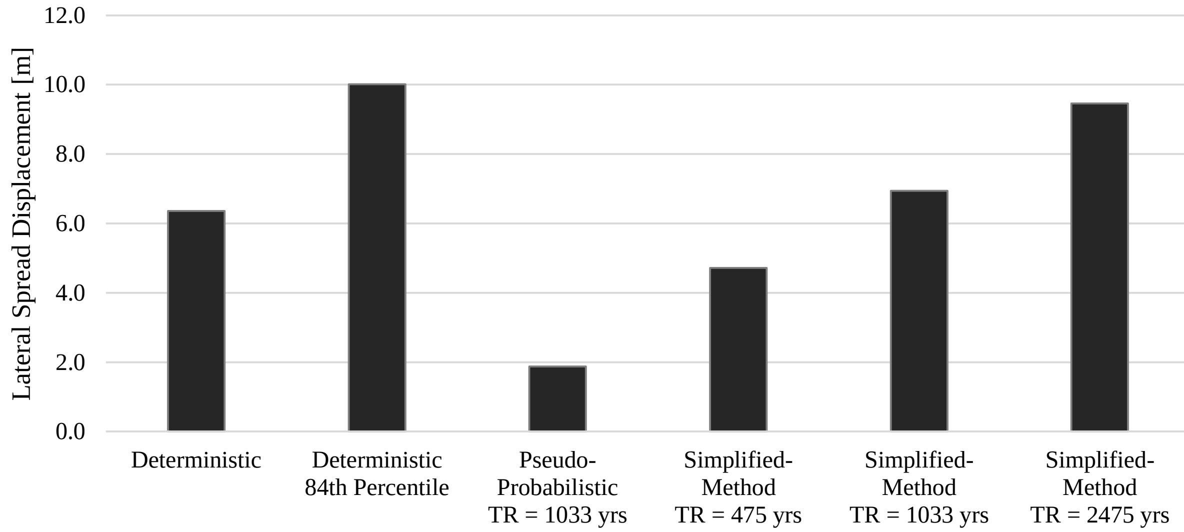

Figure 2-9 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods for San Francisco, CA (Latitude 37.775, Longitude -122.418).

The different cities are associated with regions of differing seismicity, and the deterministic comparisons with the simplified results yield some interesting conclusions. In the city with low seismicity, Butte seen in Figure 2-7, show that the deterministic method massively over predicts the displacements predicted by the simplified and pseudo-probabilistic methods. This result can be attributed to the deterministic procedure not accounting for the likelihood of the Rocker fault rupturing, and predicts a displacement that may have an extremely low probability of occurring. The medium seismicity city, Salt Lake City seen in Figure 2-8, shows as well that the deterministic method predicts displacements higher than the simplified and pseudo-probabilistic procedures. In San Francisco, the high seismicity city, the results are much more similar at the 2475 return period, as can be seen in Figure 2-9. In this area the simplified method for the 2475 year return period predicts a slightly higher displacement than the deterministic mean value. The deterministic 84th percentile still predicts a higher value than the simplified method at the 2475 year return period.

2.4 Summary

The results of this study, for both the liquefaction initiation and lateral spread displacement, show that deterministic methods predicted significantly more liquefaction hazard than probabilistic methods in Butte—an area of low seismicity. The deterministic results also showed more liquefaction hazards than the probabilistic results at high return periods in Salt Lake City—an area of medium seismicity. In San Francisco—an area of high seismicity—the deterministic methods predicted slightly lower liquefaction hazards than the probabilistic method, particularly at higher return periods. These results suggest that the deterministic results could be used as an upper-bound in areas of high seismicity, but in areas of low seismicity, the deterministic analysis could be optional. Engineers performing analyses in areas of medium to high seismicity could choose to use a deterministic analysis as a "reality check" against the simplified performance-based results. If both deterministic and performance-based methods are considered, the *lower of the deterministic and the probabilistic results* would govern the design.

This rule may seem counter-intuitive, but the idea is not completely foreign—when developing a spectral acceleration design envelope, seismic building code (e.g., IBC 2012) permits that the lower of the deterministic and probabilistic accelerations be used in design. Likewise, in a liquefaction hazard analysis, the lower value should govern. If the deterministic value is lower than the performance-based value, the combination of multiple seismic sources in the performance-based analysis may suggest greater liquefaction hazard than would be caused by a single earthquake event. Therefore, the deterministic analysis provides a type of "reality check" against the performance-based analysis, and the deterministic results should be accepted. If the performance-based value is lower than the deterministic value, the nearby governing fault may have a significantly low likelihood of rupturing within the design life of the structure. In this case, the deterministic results could be considered too extreme (especially for some projects which do not need to be designed to withstand such large events). Therefore, the performance-based results should be accepted as a representation of the more *likely* liquefaction hazard.

3.0 DEVELOPMENT OF THE SIMPLIFIED LIQUEFACTION ASSESSMENT TOOL

3.1 Overview

This section explains the components of the simplified liquefaction assessment tool and provides some guidance for how the tool should be used.

3.2 Description of the Spreadsheet Worksheets

3.2.1 Inputs

This section of the spreadsheet is the starting place of the analysis. Here, the user may select which analyses and options he or she would prefer and enter the soil profile information, mapped reference values, and other parameters which are necessary for the simplified performance-based procedure. At the bottom of the sheet, there is a section for deterministic inputs if the user would like to consider a deterministic analysis as well.

3.2.2 Map Help

This section shows an example of a log[D_H^{ref}] map and shows how to retrieve the mapped liquefaction loading value or lateral spread displacement value.

3.2.3 Simplified Performance-based Liquefaction Triggering

3.2.3.1 PB Liquefaction Initiation

This section of the spreadsheet shows the calculations for the simplified performance-based liquefaction initiation procedure. The Boulanger and Idriss (2012) model is simplified as derived in the Year 1 Quarter 1 report of this research. The Cetin et al. (2004) model is simplified as derived in the Mayfield et al. (2010) publication. This section also provides the calculations for correcting field SPT blow counts to values of $(N_1)_{60,cs}$. The user is not required to do anything on this page. This section is simply for reference if the engineer would like to see the calculation process.

3.2.3.2 Deterministic Liquefaction Initiation

This section of the spreadsheet calculates deterministic liquefaction initiation values. The formulas for from the deterministic Idriss and Boulanger (2008) model and from the deterministic Cetin et al. (2004) model are used here. The user is not required to do anything on this page. This section is simply for reference if the engineer would like to see the calculation process.

3.2.4 Simplified Performance-based Lateral Spread Displacement

The portion of the spreadsheet determines the simplified and deterministic lateral spread displacements based on the Youd et al (2002) empirical model and the simplified procedure developed in this study. The deterministic and simplified equations can be seen on this page, and all lateral spread calculations are performed on this page. This sheet does not require any input from the user, the calculations are performed when the "Analyze" button on the input page is clicked. This section is to provide a reference to the engineer.

3.2.5 Final Summary

This section shows the final results of the analyses chosen on the *Inputs* tab. The format of this section is already set up for easy printing. The headers of each page are associated with the project information entered on the *Inputs* tab. The first page provides a summary of inputs from the *Inputs* tab to facilitate easy checking of the inputs. The following pages show the results of the analyses. To print only the pages with the user-specified analyses, return to the *Inputs* tab and click the "Print Final Summary" button. The print preview window will appear and show only the user-specified analyses.

3.2.6 References

This section provides references for the models used in this spreadsheet and further guidance for using this spreadsheet.

3.3 Suggested Simplified Procedure

The following sections describe the suggested simplified procedure for assessing liquefaction triggering hazard and lateral spread displacement.

3.3.1 Simplified Performance-based Liquefaction Triggering

1) Select an appropriate return period (T_R) for your project (this may depend on the intended use of the building, code requirements, etc.).
2) Retrieve the reference liquefaction loading value (i.e. N_{req}^{ref} or CSR%) from the map with the desired return period and model (i.e. Cetin et al, 2004 or Boulanger and Idriss, 2012). Note that provided N_{req}^{ref} maps are based on the Cetin et al. model and CSR% maps are based on the Boulanger and Idriss model.
3) Open the simplified performance-based liquefaction assessment tool (provided as part of this report). Enter the required soil profile information into the *Inputs* tab. Required values include depth to center of the sublayer, field SPT blowcount, unit weight (γ), fines content in percent, and thickness of each sublayer. Enter the hammer information, which is used for $(N_1)_{60,cs}$ corrections.
    a. Soil profile information can be entered in either SI or English customary units. Select the desired option by clicking the associated toggle above the soil profile table.
    b. Even though the zone of interest to the user may not include sublayers near the ground surface, all sublayers above the zone of interest must be included in the inputs tab so that the effective stress calculations will work properly. In other words, begin at the ground surface and include all sublayers down to the end of the zone of interest.
4) On the *Inputs* tab under "Analysis Selections", select the desired models and analyses. If the user wishes to use a deterministic analysis as an upper-bound to the performance-based results, the user should select the appropriate deterministic checkbox.
5) On the *Inputs* tab, enter liquefaction triggering parameters to be used in the simplified performance-based correction factors (derived in the Year 1 Quarter 1 report). The

calculations will be performed in the spreadsheet automatically, but a few parameters must be provided by the user:

a. *PGA*: Peak Ground Acceleration should be retrieved from the 2008 (or 1996, for Alaska) USGS Interactive Deaggregation website (http://geohazards.usgs.gov/deaggint/2008/) at the return period specified in step 1. Note that the website uses exceedance probabilities instead of return periods. Use Table 3-1 to convert return periods to exceedance probabilities.

Table 3-1. Conversions between Return Period and Exceedance Probability

	Exceedance Probability	
Return Period	**Percent**	**Years**
475	10	50
1,039 (1,033)	2 (7)	21 (75)
2,475	2	50

After entering the latitude and longitude of the site, exceedance probability, Spectral Period of 0.0 seconds, and $V_{s,30}$ of 760 m/s, retrieve the *PGA* from the output report. This value is necessary for estimating the F_{pga}. An example of where this number is located in the output report is provided in the *References* tab of the spreadsheet.

b. F_{pga}: If the user checks the "Calculate F_{pga} automatically" checkbox, the spreadsheet will calculate F_{pga} according to the 2012 AASHTO code. However, this cannot be done if the Site Class is F (see notes about Site Class below), and therefore, the user must specify an F_{pga} value based on a site response analysis.

c. M_w: The mean moment magnitude (M_w) is used to calculate the MSF correction factor as discussed in the Year 1 Quarter 1 report. The value for M_w is found in the same output report created to find the *PGA* value. An example of where this number is located in the output report is provided in the *References* tab of the spreadsheet.

d. $V_{s,12}$: The shear wave velocity in the upper 12m (40 ft) is only required when using the Cetin et al (2004) model. For further guidance in calculating this value, see the *References* tab of the spreadsheet.

e. Site Class: The site class is necessary for calculating the F_{pga}. Site class is determined based on soil type and soil properties. See the *References* tab of the spreadsheet for further help in determining site class.

6) On the *Inputs* tab under "Mapped Reference Values", enter the mapped values retrieved as part of step 2. At least one of the two parameters ($CSR(\%)^{ref}$ or N_{req}^{ref}) is necessary for analysis, but be aware of which model each of these parameters is associated with (see step 2). Also report the return period associated with the chosen map (this value will not be used in any calculations, but will be displayed on the final summary page for reference).

7) If the user wishes to use a deterministic analysis as an upper-bound to the performance-based results, the user should enter the deterministic values of PGA, M_w, and percentile of the PGA to be considered. This percentile value is not used in any calculations, but will be displayed on the final summary page for reference.

   a. Deterministic values of PGA and M_w should be assessed by an experienced individual with proper training in deterministic seismic hazard analysis (DSHA).

   b. It is suggested (as explained previously in this report) that a deterministic analysis should be considered when the engineer suspects that the project could benefit from a deterministic cap. In areas of low seismicity, this is likely unnecessary.

8) Several checkboxes are displayed near the top of the *Inputs* tab which allow the user to select which analyses (liquefaction initiation, settlement, lateral spread, or seismic slope stability), models (Cetin et al or Boulanger and Idriss), and options (P_L or FS_L) the user would like to consider. Select the desired analyses, models, and options before proceeding to the next step.

9) Once everything is correctly entered into the *Inputs* tab, click "Analyze". The calculations will be displayed on the *PB Liquefaction Initiation* and *Det Liquefaction Initiation* tabs.

10) The *Final Summary* tab displays plots, tables and a summary of inputs in a printable format. The headers of these pages will reflect information such as company name, project name/number, date, etc. entered at the top of the *Inputs* tab.

3.3.2 Simplified Performance-based Lateral Spread Displacement

1) Select an appropriate return period (T_R) for your project (this may depend on the intended use of the building, code requirements, etc.).
2) Retrieve the logged reference lateral spread value (D_H^{ref}) from the map with the desired return period.
3) Open the simplified performance-based liquefaction hazard assessment tool (provided as part of this report). Enter the required soil profile information into the *Inputs* tab. Required values include T_{15} (cumulative thickness of sand or gravel layers with SPT blow counts less than 15), W or S (which are terms based on site geometry), D_{50} (the mean grain size of the T_{15} layers), and F_{15} (the fines content of the T_{15} layers).
   a. The user must choose whether the analysis is for the Free Face or Ground Slope conditions.
   b. Soil profile information can be entered in either SI or English customary units. Select the desired option by clicking the associated toggle above the soil profile table.
4) On the *Inputs* tab under "Analysis Selections", select the desired models and analyses. If the user wishes to use a deterministic analysis as an upper-bound to the performance-based results, the user should select the appropriate deterministic checkbox.
5) On the *Inputs* tab under "Mapped Reference Values", enter the mapped values retrieved as part of step 2. Also report the return period associated with the chosen map (this value will not be used in any calculations, but will be displayed on the final summary page for reference).
6) If the user wishes to use a deterministic analysis as an upper-bound to the performance-based results, the user should enter the deterministic values of M_w (moment magnitude of fault), R (source-to-site distance), and percentile of the M_w to be considered. This percentile value is required for the deterministic calculations.

a. Deterministic values of M_w and R should be assessed by an experienced individual with proper training in deterministic seismic hazard analysis (DSHA).

b. It is suggested (as explained previously in this report) that a deterministic analysis should be considered when the engineer suspects that the project could benefit from a deterministic cap. In areas of low seismicity, this is likely unnecessary.

7) Several checkboxes are displayed near the top of the *Inputs* tab which allow the user to select which analyses (liquefaction initiation, settlement, lateral spread, or seismic slope stability), models (Cetin et al or Boulanger and Idriss), and options (P_L or FS_L) the user would like to consider. Select the desired analyses, models, and options before proceeding to the next step.

8) Once everything is correctly entered into the *Inputs* tab, click “Analyze”. The calculations will be displayed on the *Lateral Spread* tab.

9) The *Final Summary* tab displays plots, tables and a summary of inputs in a printable format. The headers of these pages will reflect information such as company name, project name/number, date, etc. entered at the top of the *Inputs* tab.

3.4 Summary

This section introduced the simplified performance-based liquefaction assessment tool, described the various components and aspects of the tool, and provided step-by-step instructions for the user to use the tool. With this tool and description, the engineer will be able to use the simplified methods developed in the study without additional training or expertise.

4.0 CONCLUSIONS

4.1 Summary

The purpose of the research being performed is to provide the benefit of the full performance-based probabilistic earthquake hazard analysis, without requiring special software, training, and experience. The objective of this report was to provide a comparison of the simplified performance-based methods and conventional deterministic analyses. This will provide some clarity and guidance for the application of the simplified procedures and their relationship with deterministic procedures. Additionally, the simplified performance-based liquefaction assessment tool was introduced, with guidance on its various aspects and use.

4.2 Findings

4.2.1 Comparison of Probabilistic and Deterministic Analyses

The results of this study, for both the liquefaction initiation and lateral spread displacement, show that deterministic methods significantly over-predicted liquefaction hazard in areas of low seismicity, slightly over-predicted liquefaction hazards in areas of medium seismicity, and that the simplified methods predict slightly higher results at high return periods in areas of high seismicity. These results suggest that the deterministic results could be used as an upper-bound in areas of high seismicity, but in areas of low seismicity, the deterministic analysis could be optional. Engineers performing analyses in areas of medium to high seismicity could choose to use a deterministic analysis as a "reality check" against the simplified performance-based results. If both deterministic and performance-based methods are considered, the *lowest* result is the governing value. When deciding whether the deterministic or performance-based results should be accepted, engineers should apply the following rule: the *lowest* value governs.

4.2.2 Development of Simplified Liquefaction Assessment Tool

The simplified performance-based liquefaction assessment tool was developed and introduced. Step-by-step instructions for its use were provided.

4.3 Limitations and Challenges

The comparison between simplified performance-based and deterministic methods was performed in three different cities with varying seismicity. Though the results of this comparison are expected to be representative for most locations, the conclusions reached may not be as clear and apparent as outlined for some locations.

REFERENCES

Bartlett, S.F., and Youd, T.L. (1995). Empirical prediction of liquefaction-induced lateral spread. *J. Geotech. Eng.*, 121(4), 316-329.

Boulanger, R. W., and Idriss, I. M. (2012). Probabilistic standard penetration test-based liquefaction-triggering procedure. *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE)GT.1943-5606.0000700, 1185–1195.

Boulanger, R. W., and Idriss, I. M. (2014). CPT and SPT based liquefaction triggering procedures. *Rep. UCD/CGM-14/01*, Dept. of Civil and Environmental Engineering, Univ. of California–Davis, Davis, CA.

Cetin, K. O., et al. (2004). Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. *J. Geotech. Geoenviron. Eng*., 10.1061/(ASCE)1090-0241(2004)130:12(1314), 1314–1340.

Cornell, C.A., and Krawinkler, H. (2000). Progress and challenges in seismic performance assessment. *PEER News,* April, 1-3.Deierlein, G.G., Krawinkler, H., and Cornell, C.A. (2003). A framework for performance-based earthquake engineering, Proc., 2003 Pacific Conference on Earthquake Engineering.

Ekstrom, L.T., and Franke, K.W. (2015) A Simplified Procedure for the Performance-Based Prediction of Lateral Spread Displacements. *J. Geotech. Geoenviron. Eng.* ASCE (pending)

Franke, K. and Wright, A. (2013) An Alternative Performance-Based Liquefaction Initiation Procedure for the Standard Penetration Test. *Geo-Congress 2013*, 10.1061/9780784412787.086, 846-849.

Franke, K.W. and Kramer, S.L. (2014). A procedure for the empirical evaluation of lateral spread displacement hazard curves. *J. Geotech. Geoenviron. Eng.*, ASCE, 140(1), 110-120.

Franke, K.W., Lingwall, B.N., Youd, T.L. (2014a). Sensitivity of empirical liquefaction assessment to seismic loading in areas of low seismicity and its implications for sustainability, Geo-Congress 2014 Technical Papers, p. 1284-1293.

Franke, K., Wright, A., and Ekstrom, L. (2014b). Comparative Study between Two Performance-Based Liquefaction Triggering Models for the Standard Penetration Test. *J. Geotech. Geoenviron. Eng.* , 10.1061/(ASCE)GT.1943-5606.0001094 , 04014010.

Franke, K.W., Wright, A.D., and Hatch, C.K. (2014c). PBLiquefY: A new analysis tool for the performance-based evaluation of liquefaction triggering. Proceedings, 10th National Conference on Earthquake Engineering, Paper No. 87, EERI, Oakland, CA.

Franke, K.W., Mayfield, R.T., and Wright, A.D. (2014d). Simplified uniform hazard analysis for bridges, *Transportation Research Record*, TRB, in press, Washington D.C.

Idriss, I.M., and Boulanger, R.W. (2008). *Soil liquefaction during earthquakes.* Monograph MNO-12, Earthquake Engineering Research Institute, Oakland, CA 261 pp.

Idriss, I. M., and Boulanger, R. W. (2010). SPT-based liquefaction triggering procedures. *Rep. UCD/CGM-10/02*, Dept. of Civil and Environmental Engineering, Univ. of California–Davis, Davis, CA.

Kramer, S.L. (2008). Evaluation of liquefaction hazards in Washington State. WSDOT Report WA-RD 668.1, 152 pp.

Kramer, S.K., Franke, K.W., Huang, Y.-M., and Baska, D. (2007). Performance-based evaluation of lateral spreading displacement. *Proceedings, 4th International Conference on Earthquake Geotechnical Engineering*, Paper No. 1208, Thessaloniki, Greece, June 2007.

Krawinkler, H. (2002). A general approach to seismic performance assessment, Proc., Int. Conf. on Advances and New Challenges in Earthquake Engineering Research, ICANCEER, Hong Kong.

Mayfield, R. T., Kramer, S. L., and Huang, Y.-M. (2010). Simplified approximation procedure for performance-based evaluation of liquefaction potential. *J. Geotech. Geoenviron. Eng*., 10.1061/(ASCE) GT.1943-5606.0000191, 140–150.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S. (2008). Documentation for the 2008 Update of the United States National Seismic Hazard Maps. Open-File Report 2008–1128, United States Geological Survey, Denver, CO: available at website: http://pubs.usgs.gov/of/2008/1128/.

Risk Engineering. (2013). EZ-FRISK, ver. 7.60. Boulder, Colorado.

Seed, H.B. (1979). Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. *J. Geotech. Eng. Div*., 105(GT2), p. 201-255.

Seed, H.B. and Idriss, I.M. (1971). Simplified procedure for evaluating soil liquefaction potential," *J. Soil Mech. and Found. Div*., 97(SM9), p. 1249-1273.

Seed, H.B. and Idriss, I.M. (1982). *Ground Motions and Soil Liquefaction During Earthquakes*. EERI, Oakland, CA, 134 pp.

Seed, H.B., Tokimatsu, K., Harder, L.F. Jr., and Chung, R. (1985). Influence of SPT procedures in soil liquefaction resistance evaluations, *J. Geotech. Eng*., 111(12), p. 1425-1445.

Stewart, J.P., Liu, A.H., and Choi, Y. (2003). Amplification factors for spectral acceleration in tectonically active regions. *Bull. Seismol. Soc. Am.,* 93(7): 332-352.

Ulmer, K.J., and Franke, K.W. (2015) Simplified Performance-Based Assessment of Liquefaction Triggering using Liquefaction Loading Maps. *J. Geotech. Geoenviron. Eng.* ASCE (pending)

USGS. (2008). “USGS 2008 interactive deaggregation.” https://geohazards.usgs.gov/deaggint/2008/ (date accessed: January 21, 2015).

USGS and Montana Bureau of Mines and Geology. (2006). “Quaternary Fault and Fold Database of the United States.” http://earthquake.usgs.gov/hazards/qfaults/ (date accessed: January 21, 2015).

Wells, D.L., Coppersmith, K.J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*. 84(4), 974-1002.

Youd, T.L., Hansen, C.M., and Bartlett, S.F. (2002). Revised multilinear regression equations for prediction of lateral spread displacement. *J. Geotech. Geoenviron. Eng.,* ASCE. 128(12), 1007-1017.

APPENDIX A:

Table A.1 Faults Considered in Deterministic Analysis

					Median Acceleration			(Median + 1 St. Dev) Acceleration		
					T_R = 1033			T_R = 1033		
San Francisco		**Seismic Source**	**Dist (km)**	**Mag**	***PGA***	F_{pga}	a_{max}	***PGA***	F_{pga}	a_{max}
	1	Northern San Andreas	10.77	8.05	0.3175	1.183	0.3754	0.5426	1.0	0.5426
	2	San Gregorio Connected	16.64	7.5	0.2139	1.372	0.2935	0.3660	1.134	0.4150
	3	Hayward-Rodgers Creek	18.23	7.33	0.1918	1.416	0.2717	0.3282	1.172	0.3846
	4	Mount Diablo Thrust	36.08	6.7	0.1050	1.590	0.1670	0.1811	1.438	0.2604
	5	Calaveras	34.28	7.03	0.0981	1.6	0.1570	0.1682	1.464	0.2462
Salt Lake City										
	1	Wasatch Fault, SLC Section	1.02	7	0.5911	1.0	0.5911	1.0050	1.0	1.0050
	2	West Valley Fault Zone	2.19	6.48	0.5694	1.0	0.5694	0.9842	1.0	0.9842
	3	Morgan Fault	25.04	6.52	0.0989	1.6	0.1583	0.1713	1.457	0.2497
	4	Great Salt Lake Fault zone, Antelope Section	25.08	6.93	0.1016	1.597	0.1622	0.1742	1.452	0.2529
	5	Oquirrh-Southern, Oquirrh Mountain Fault	30.36	7.17	0.0958	1.6	0.1532	0.1641	1.472	0.2415
Butte										
	1	Rocker Fault	4.92	6.97	0.5390	1.0	0.5390	0.9202	1.0	0.9202
	2	Georgia Gulch Fault	45.91	6.42	0.0435	1.6	0.0696	0.0754	1.6	0.1206
	3	Helena Valley Fault	75.56	6.6	0.0294	1.6	0.0470	0.0507	1.6	0.0812
	4	Canyon Ferry Fault	81.32	6.92	0.0327	1.6	0.0523	0.0561	1.6	0.0898
	5	Blacktail Fault	84.27	6.94	0.0317	1.6	0.0508	0.0545	1.6	0.0872
	6	Madison Fault	86.51	7.45	0.0420	1.6	0.0671	0.0719	1.6	0.1150

Table A.2 Characteristics of Rocker Fault (near Butte) and Calculations to Determine *PGA* and M_w.

Rocker Fault

*M_w calculated based on
Wells and Coppersmith (1994): Length = 43 km
(Use "all" slip type, because it's a normal fault and the # of normal events is small)

*PGA calculated based on NGA equations (Linda Al Atik, PEER 2009)
BA08, CB08, and CY08 used with equal weighting

M_w =	6.97		
Dip =	70	degrees	(Another fault near Butte, has a dip of 70-75 degrees)
Depth to bottom of rupture =	16	km	(Assumed)
R_x =	4.92	km	(measured using Google Earth)
Z_TOR =	0	km	(Assumed)
Width =	17.03	km	
R_jb =	0	km	(Assuming the site is on the hanging wall side)
R_rup =	1.68	km	
V_s30 =	760	m/s	
U=	0		
F_RV=	0		
F_NM =	1		
F_HW =	1		
F_measured =	0		
Z_1 =	DEFAULT		
Z_2.5=	DEFAULT		
F_AS=	0		
HW Taper =	1		
--> PGA (50%) =	0.5390	g	(From NGA spreadsheet)
--> PGA (84%) =	0.9202	g	(From NGA spreadsheet)