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4501 South 2700 West - P.O. Box 148410 - SLC,UT 84114-8410

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

Prepared For:

Utah Department of Transportation
Research Division

Submitted By:

Brigham Young University
Department of Civil and Environmental Engineering

Authored By:

Kevin W. Franke
Lucy Astorga
Braden Error

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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 post-liquefaction settlement and seismic slope displacement models were provided.

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TABLE OF CONTENTS

LIST OF TABLES ... v
LIST OF FIGURES ... vi
UNIT CONVERSION FACTORS ... viii
LIST OF ACRONYMS ... x
LIST OF TERMS ... 1
EXECUTIVE SUMMARY ... 4
1.0 INTRODUCTION ... 5
1.1 Problem Statement ... 5
1.2 Objectives ... 5
1.3 Scope ... 5
1.4 Outline of Report ... 6
2.0 COMPARISON OF PROBABILISTIC AND DETERMINISTIC ANALYSES ... 7
2.1 Overview ... 7
2.2 Methodology ... 7
2.2.1 Simplified Performance-Based Seismic Hazard Analysis ... 7
2.2.2 Deterministic Procedure ... 9
2.2.3 Pseudo-probabilistic Seismic Hazard Analysis ... 12
2.3 Results ... 13
2.3.1 Post-Liquefaction Settlement Model ... 13
2.3.2 Seismic Slope Displacement Model ... 18
2.4 Summary ... 22
3.0 DEVELOPMENT OF THE SIMPLIFIED LIQUEFACTION ASSESSMENT TOOL ... 24
3.1 Overview ... 24
3.2 Description of the Spreadsheet Worksheets ... 24
3.2.1 Inputs ... 24
3.2.2 Map Help ... 26
3.2.3 Simplified Performance-based Post- Liquefaction Settlement ... 26
3.2.4 Simplified Performance-based Seismic Slope Displacement ... 26
3.2.5 Final Summary ... 27

3.2.6 References 27
3.2.7 Interpolation 27
3.3 Suggested Simplified Procedure 29
3.3.1 Simplified Performance-based Post-Liquefaction Settlement 29
3.3.2 Simplified Performance-based Seismic Slope Displacement 32
3.4 Summary 37
4.0 CONCLUSIONS 38
4.1 Summary 38
4.2 Findings 38
4.2.1 Comparison of Probabilistic and Deterministic Analyses 38
4.2.2 Development of Simplified Liquefaction Assessment Tool 38
4.3 Limitations and Challenges 39
REFERENCES 40
APPENDIX A: 42

LIST OF TABLES

Table 2-1 NGA model weights used in the deterministic procedure. 9
Table 2-2 Input variables used in the deterministic models (a_{max} calculated using F_{pga} from AASHTO code). 10
Table 2-3 Input values found using USGS 2008 Deaggregations (T_R = 1,039 years). 13
Table 3-1. Conversions between Return Period and Exceedance Probability...............................30

LIST OF FIGURES

Figure 2-1 Soil profile used for the liquefaction initiation comparison study. 8
Figure 2-2 Comparison of pseudo-probabilistic and simplified performance-based values of vertical strain using the Cetin et al. (2009) model. 14
Figure 2-3 Comparison of pseudo-probabilistic and simplified performance-based values of vertical strain using the Ishihara and Yoshimine (1992) model. 14
Figure 2-4 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 475 years). 15
Figure 2-5 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 1,033 years). 16
Figure 2-6 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 2,475 years). 16
Figure 2-7 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 475 years)...................................17
Figure 2-8 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 1,033 years)................................17
Figure 2-9 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 2,475 years)................................18
Figure 2-10 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for Butte, MT (Latitude 46.033, Longitude -112.533).19
Figure 2-11 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for Salt Lake City, UT (Latitude 40.755, Longitude -111.898). 19
Figure 2-12 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for San Francisco, CA (Latitude 37.775, Longitude -122.418). 20
Figure 2-13 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for Butte, MT (Latitude 46.033, Longitude -112.533). 20

Figure 2-14 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for Salt Lake City, UT (Latitude 40.755, Longitude -111.898). 21
Figure 2-15 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for San Francisco, CA (Latitude 37.775, Longitude -122.418). 21
Figure 3-1 Analysis Selections section on the *Inputs* tab. 25
Figure 3-2 Soil profile input section. 25
Figure 3-3 Ground motion and reference input parameters. 26
Figure 3-4 Inverse distance weighted interpolation scheme as performed in the Simplified Tool.28
Figure 3-5 Inputs required for the included interpolation tool. 28
Figure 3-6 Example final summary for liquefaction initiation and settlement. 32
Figure 3-7 Analysis Selections for Slope Displacement....33
Figure 3-8 Site Slope Displacement Parameter Inputs 34
Figure 3-9 Mapped/Interpolated Slope Displacement Values 35
Figure 3-10 Deterministic Analysis Parameters for Slope Displacement 36
Figure 3-11 Final check of all inputs and “Analyze” 36
Figure 3-12 Example of Final Summary of Slope Displacement Analysis 37

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

Post-Liquefaction Free-Field Settlement Terms

CRR	cyclic resistance ratio
CRR^{ref}	cyclic resistance ratio associated with the reference soil profile
CRR^{site}	cyclic resistance ratio for the site profile
CSR	cyclic stress ratio
CSR^{ref}	uniform hazard estimate of CSR associated with the reference soil profile
CSR^{site}	uniform hazard estimate of CSR associated with the site specific soil profile
$CSR_{SS,20,1D,atm}$	adjusted CSR to account for multi-directional shaking effects
CSR^{site}	site-specific uniform hazard estimate of CSR
DF_i	depth factor for soil sub-layer
D_R	relative density
FC	fines content (%)
F_{PGA}	soil amplification factor
FS_{Liq}	factor of safety against liquefaction triggering
FS_L^{site}	site-specific uniform hazard estimate of FS_L
F_α	limiting factor of safety (used in Ishihara and Yoshimine model)
F_α^{ref}	limiting factor of safety associated with reference soil profile
F_α^{site}	limiting factor of safety associate with site soil profile
K_{md}	multidirectional correction factor for unidirectional applied loading
K_{Mw}	magnitude correction factor
K_σ	non-linear increase in cyclic resistance correction factor
min(.)	use minimum value inside parentheses mathematical operator
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}
N_{site}	standard penetration test resistance of site profile layer

P_a	atmospheric pressure (1 atm, 101.3 kPa, 0.2116 psf)
PGA	peak ground acceleration
P_L	probability of liquefaction
$s_{profile}$	estimated total settlement for soil profile using equivalent strain approach
SPT	Standard Penetration Test
t_i	thickness of soil sub-layer
$V_{s,12}$	average shear wave velocity in upper 12 m (39.37 ft) of soil profile
z_{cr}	maximum depth at which vertical strain can occur (z_{cr} = 18 *meters)*
$\Delta\varepsilon$	site-specific adjustment factor
ε_v	vertical strain
$\varepsilon_{v,calibrated}^{site}$	site-specific strain calibrated for model non-linearity
ε_v^{ref}	vertical strain for the reference soil profile
$\varepsilon_{Cetin}^{ref}$	vertical strain for the reference soil profile as calculated from Cetin (2009)
$\varepsilon_{IshaharaYoshimine}^{ref}$	vertical strain for the reference soil profile from Ishihara & Yoshimine (1992) model
ε_v^{site}	site-specific vertical strain
$\varepsilon_{v,eqv.}$	equivalent vertical strain for entire soil profile
$\varepsilon_{v,max}$	maximum limiting vertical strain for a soil layer
γ	unit weight of soil (e.g. pcf, kN/m^3, etc.)
γ_{max}	maximum limiting shear strain
γ_{min}	minimum limiting shear strain
$\lambda_{\varepsilon,v,i}$	mean annual rate of exceeding vertical strain
$\mu_{\ln\varepsilon}$	mean value of the natural logarithm of vertical strain
σ_ε	error term for either model + parametric uncertainty or parametric uncertainty
σ'_{vo}	effective vertical stress in the soil
Φ	standard normal cumulative distribution function
Φ^{-1}	inverse standard normal cumulative distribution function

Seismic Slope Displacement Terms

$\ln D$	natural logarithm of seismic slope displacement (cm)
k_y	yield acceleration (g)
PGA	peak ground acceleration (g)
M	earthquake moment magnitude (g)
σ_{ln}	standard deviation for the scalar model
λ_D	mean annual rate of not exceeding a seismic slope displacement value
D	seismic slope displacement (cm)
GM_i	single ground motion parameter
T_s	initial fundamental period of the sliding mass (s)
f_a	soil amplification factor (from AASHTO 2012 Values of site factor table)
$\ln D^{site}$	natural log of seismic slope displacement adjusted for the site-specific conditions
$\ln D^{ref}$	natural log of seismic slope displacement corresponding to the reference site
$\Delta \ln D$	adjustment factor for seismic slope displacement
k_y^{site}	yield acceleration adjusted for site-specific conditions (g)
PGA^{site}	peak ground acceleration adjusted for site-specific conditions (g)
k_y^{ref}	yield acceleration for the corresponding to the reference site (g)
PGA^{ref}	peak ground acceleration corresponding to the reference site (g)
f_a^{site}	soil amplification factor adjusted for site-specific conditions
f_a^{ref}	soil amplification factor corresponding to the reference site

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 generally predicts a lower hazard than the performance-based procedure.

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 should be used for design. 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 post-liquefaction settlement and seismic slope displacement models are provided.

1.0 INTRODUCTION

1.1 Problem Statement

The purpose of the performed research 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 post-liquefaction settlement and seismic slope 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 2 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 post-liquefaction settlement and seismic slope 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 post-liquefaction settlement and seismic slope 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 post-liquefaction settlement and seismic slope displacement 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}, or moment magnitude, M_w. These processes are discussed in greater detail in the previously submitted update reports: Update Report Year 2 Quarter 1 for the simplified performance-based methods, and Update Report Year 2 Quarter 2 for the development of the post-liquefaction settlement and seismic slope displacement parameter maps.

The parameters used for the comparison of deterministic and simplified methods for this study were: for post-liquefaction settlement, ε^{ref}; and for seismic slope displacement, D^{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 Post-Liquefaction Settlements

For the simplified liquefaction settlement procedure the appropriate uniform hazard-targeted liquefaction loading map was identified for each site and values of $\varepsilon_{v,Cetin}(\%)^{ref}$ and $\varepsilon_{v,I\&Y}(\%)^{ref}$ were obtained for the necessary return periods. These reference strain values were adjusted for soil characteristics associated with an assumed soil profile (shown in Figure 2-1) to estimate $\varepsilon_{v,Cetin}^{site}$ and $\varepsilon_{v,\mathrm{I\&Y}}^{site}$ values. This same soil profile was used for all three analyses (probabilistic, pseudo-probabilistic, and deterministic) to compute site strains at the selected locations. This process is described in greater detail in the Update Report 1.

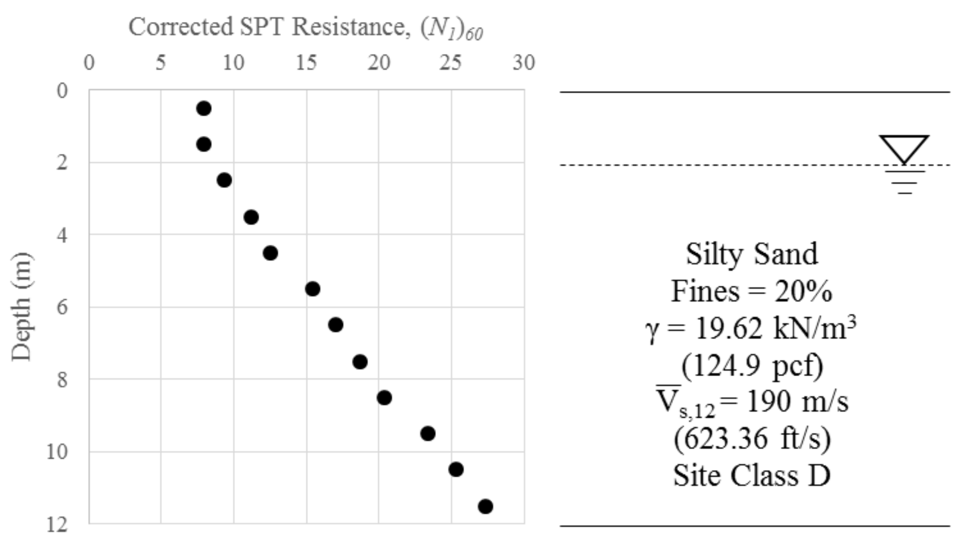


Figure 2-1 Soil profile used for the liquefaction initiation comparison study.

2.2.1.2 Simplified Seismic Slope Displacements

For the simplified performance-based procedure the appropriate seismic slope displacement parameter map was identified for each site and values of D^{ref} were obtained for the necessary return periods, D^{ref} values could also be obtained using the reference parameter interpolation tool with the known latitude and longitude of the site in question. Using a generic yield acceleration value, k_y = 0.1 g, the values of D^{ref} were corrected and the D^{site} was determined for each city at the targeted return periods. The additional analyses (pseudo-probabilistic and deterministic) for the comparison utilized the same k_y reference value. The simplified procedure is described in greater depth in the Update Report 1.

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 manually 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 ground motions have been determined through the DSHA they are entered into the respective empirical hazard models. A summary of the governing input variables utilized in the deterministic post-liquefaction settlement and seismic slope 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(g)	a_{max}	*PGA(g)*	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

A review of Table 2-2 may cause alarm upon seeing that the estimated accelerations for San Francisco, which is considered a high seismicity area, are lower than both Salt Lake City and Butte. This highlights one of the weaknesses of the deterministic method. Butte deterministic ground motions were developed from the Rocker Fault and Salt Lake City ground motions were developed from the Wasatch Fault. Both of these faults are in close proximity to the sites analyzed and are estimated to produce large deterministic ground motions; however, a deterministic analysis does not account for the likelihood of an earthquake. Deterministic analyses only account for the possibility of an earthquake. The likelihood of the Rocker fault or Wasatch fault rupturing is extremely low compared to the surrounding faults in the San Francisco area; the deterministic analysis does not account for this.

2.2.2.1 Post-Liquefaction Settlement

Estimations of liquefaction settlement potential ($\varepsilon_{v,Cetin}$ and $\varepsilon_{v,I\&Y}$) were calculated deterministically using equations from the Ishihara and Yoshimine (1992) and Cetin et al. (2009) liquefaction settlement models. The vertical strain in a soil layer is calculated from the Ishihara and Yoshimine model as:

$$\varepsilon_{v,I\&\mathrm{Y}} = 1.5 \cdot \exp\left(-0.369\sqrt{\left(N_1\right)_{60cs}}\right) \cdot \min\begin{pmatrix} 0.08 \\ \gamma_{\max} \end{pmatrix} \tag{1}$$

where $(N_1)_{60cs}$ is the Idriss and Boulanger (2008) clean sand equivalent standard penetration resistance corrected for overburden of 1 atmosphere and 60 percent hammer efficiency. $\gamma_{\max}$ is a maximum limiting shear strain and is calculated as:

$$\gamma_{\max} = 0 \tag{2}$$

if $FS_{liq} \geq 2$,

$$\gamma_{\max} = \min\begin{pmatrix} \gamma_{\lim} \\ 0.035\left(2 - FS_{liq}\right)\left(\dfrac{1 - F_{\alpha}}{FS_{liq} - F_{\alpha}}\right) \end{pmatrix} \tag{3}$$

if $2 > FS_{liq} > F_{\alpha}$, and

$$\gamma_{\max} = \gamma_{\lim} \tag{4}$$

if $FS_{liq} \leq F_{\alpha}$.

F_{α} and $\gamma_{\lim}$ as introduced in equation (3) are computed as:

$$\begin{aligned} F_{\alpha} &= 0.032 + 0.69\sqrt{(N_1)_{60cs}} - 0.13(N_1)_{60cs} \\ \gamma_{\lim} &= 1.859\left(1.1 - \sqrt{\frac{(N_1)_{60cs}}{46}}\right) \geq 0 \end{aligned} \tag{5}$$

FS_{liq} is the factor of safety against liquefaction and is explained in the Year 1 report of this study.

The vertical strain in a soil layer can be calculated from the Cetin et al. (2009) model as:

$$\begin{aligned} \varepsilon_{v,Cetin} &= 1.879 \cdot \ln\left[\frac{780.416 \cdot \ln\left(CSR_{SS,20,1D,1atm}\right) - N_{1,60,cs} + 2442.465}{636.613 N_{1,60,cs} + 306.732}\right] + 5.583 \\ \lim &: 5 \leq N_{1,60,cs} \leq 40, 0.05 \leq CSR_{SS,20,1D,1atm} \leq 0.6 \end{aligned} \tag{6}$$

where $CSR_{SS,20,1D,1atm}$ is the field cyclic stress ratio value equivalent to unidirectional, 20 loading cycle simple shear test performed under a confining stress of 100 kPa and is computed as explained by Cetin et al. (2009). $N_{1,60,cs}$ is the corrected clean sand equivalent SPT resistance.

2.2.2.2 Seismic Slope Displacement

Estimations of seismic slope displacement for the deterministic process were found using the equation (7) from the Rathje and Saygili (2009) and equation (8) from Bray and Travasarou (2007) seismic slope displacement models. Both models are based on the seismic loading inputs as shown in Table 2-2, and the site specific yield acceleration used is 0.1g. With these values the seismic slope displacement, D^{site}, is found using the following equations for:

$$\ln D = 4.89 - 4.85\left(\frac{\mathrm{k}_y}{PGA}\right) - 19.64\left(\frac{\mathrm{k}_y}{PGA}\right)^2 + 42.49\left(\frac{\mathrm{k}_y}{PGA}\right)^3 - 29.06\left(\frac{\mathrm{k}_y}{PGA}\right)^4 + 0.72\ln(PGA) + 0.89(\mathrm{M} - 6) \tag{7}$$

$$\ln D = -0.22 - 2.83\ln(k_y) - 0.333\left(\ln(k_y)\right)^2 + 0.566\ln(k_y)\ln(\mathrm{PGA}) + 3.04\ln(\mathrm{PGA}) - 0.244\left(\ln(\mathrm{PGA})\right)^2 + 0.278(M - 7) \tag{8}$$

where D is the median computed seismic slope displacement (cm) at the site, k_y is the yield acceleration, *PGA* is the peak ground acceleration, and M is the earthquake moment magnitude.

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 post-liquefaction settlement and seismic slope 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. Since, the USGS 2008 interactive deaggregation website (USGS 2008) does not have the ability to compute exact values for a 1,033 year return period, the values corresponding to the 1,039 year return period were used as the closest approximation. The resulting values are summarized in Table 2-3.

Table 2-3 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 Post-Liquefaction Settlement Model

2.3.1.1 Pseudo-probabilistic vs. Simplified Performance-based

The results from the pseudo-probabilistic procedure suggested greater liquefaction hazard than the results from the performance-based procedure in Salt Lake City and Butte. These two cities are considered medium and low seismicity areas, respectively. The results indicate that in areas of high seismicity, such as San Francisco, the performance-based procedure suggests higher liquefaction hazard than the pseudo-probabilistic procedure. The direct comparison of the Cetin et al. (2009) model is shown in Figure 2-2 and the direct comparison of the Ishihara and Yoshimine (1992) model can be seen in Figure 2-3.

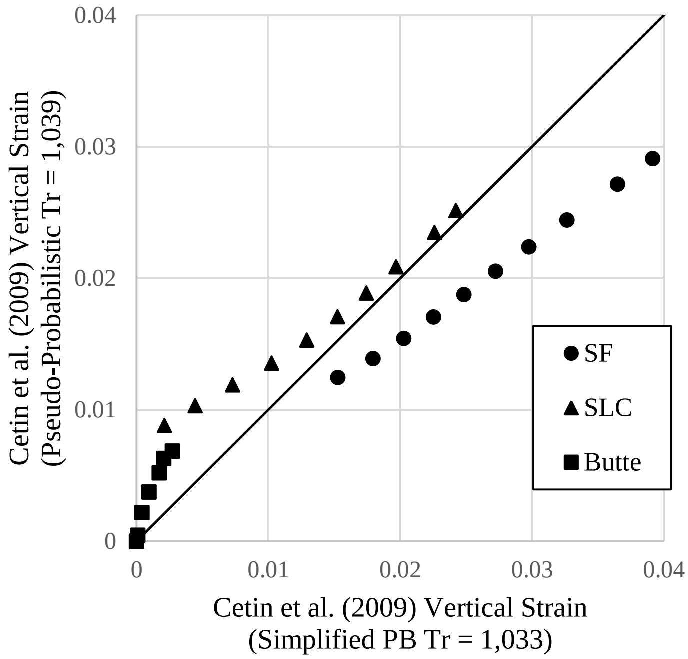


Figure 2-2 Comparison of pseudo-probabilistic and simplified performance-based values of vertical strain using the Cetin et al. (2009) model.

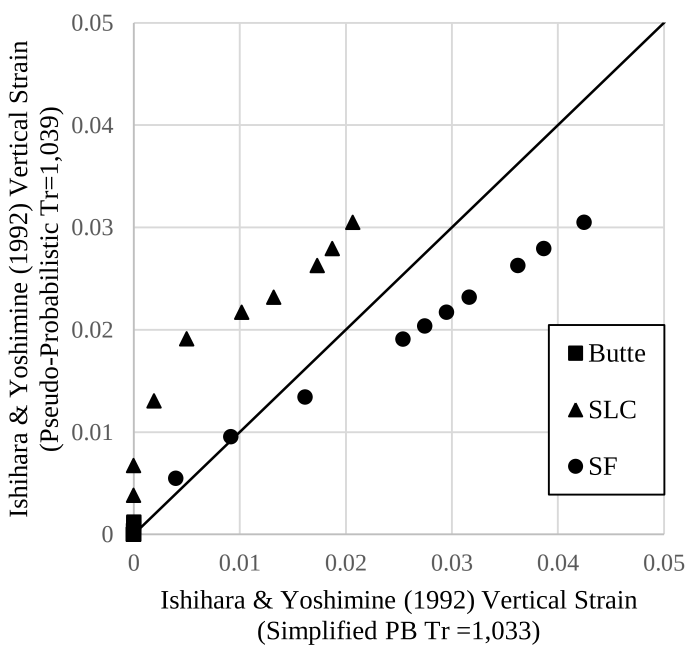


Figure 2-3 Comparison of pseudo-probabilistic and simplified performance-based values of vertical strain using the Ishihara and Yoshimine (1992) model.

2.3.1.2 Deterministic vs. Simplified Performance-based

Direct comparison plots (Figure 2-4 through Figure 2-9) show that the deterministic analyses frequently over-predicted liquefaction hazard in areas of low and medium seismicity. This over-prediction is especially evident in the case of Butte where the simplified performance-based method estimated strain values much lower than the deterministic strains. 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 strains are much lower.

In areas of high seismicity, such as San Francisco, the performance-based procedure closely matches the deterministic hazard at the 475-year return period. In the 1,033 and 2,475-year return periods, the performance-based method over-predicts the deterministic settlement hazard. This is consistent with the expectation that the performance-based method may predict unrealistically high values of liquefaction hazard in areas of high seismicity.

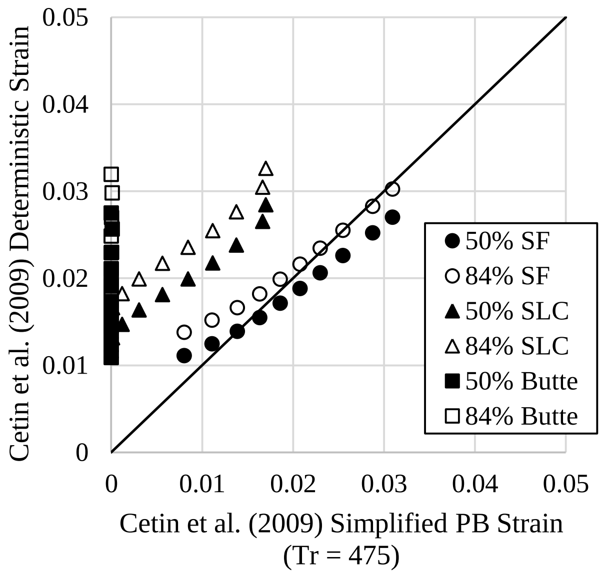


Figure 2-4 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 475 years).

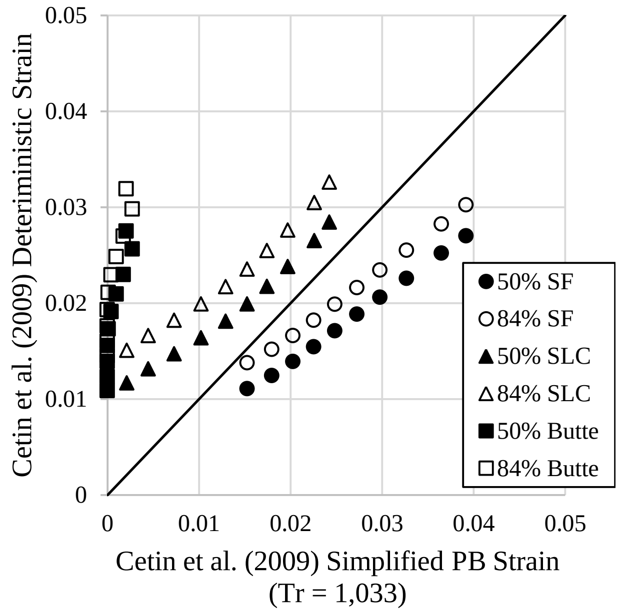


Figure 2-5 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 1,033 years).

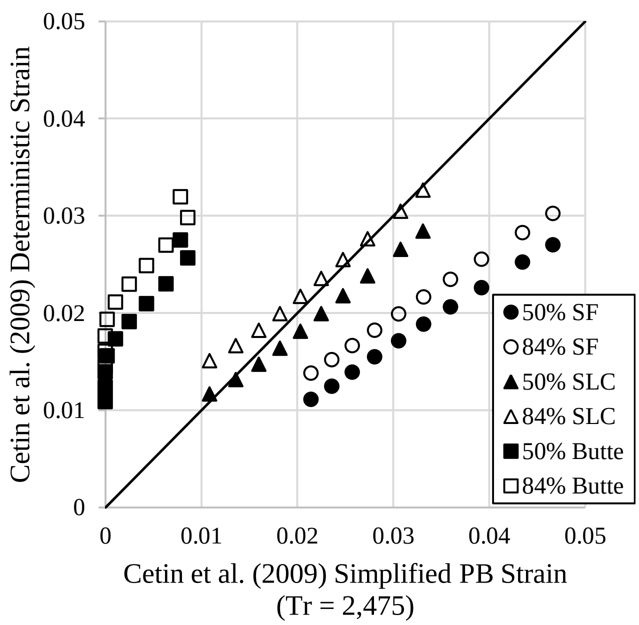


Figure 2-6 Comparison of deterministic and performance-based vertical strains for the Cetin et al. model (PB Return Period = 2,475 years).

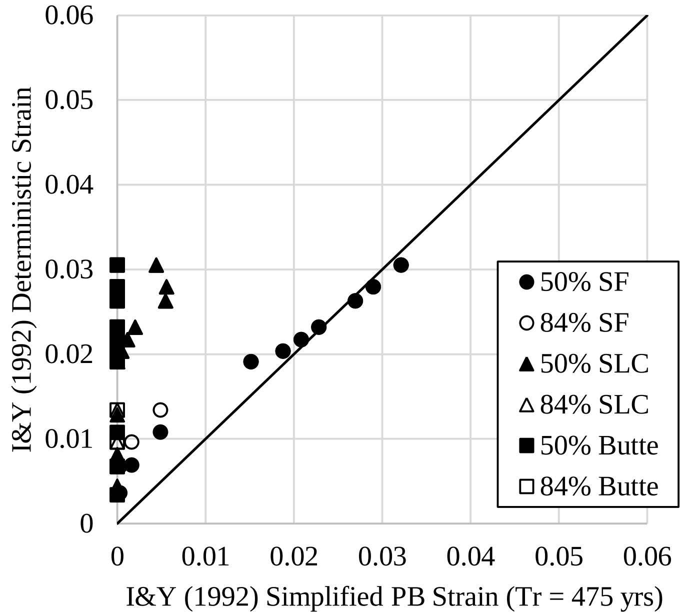


Figure 2-7 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 475 years).

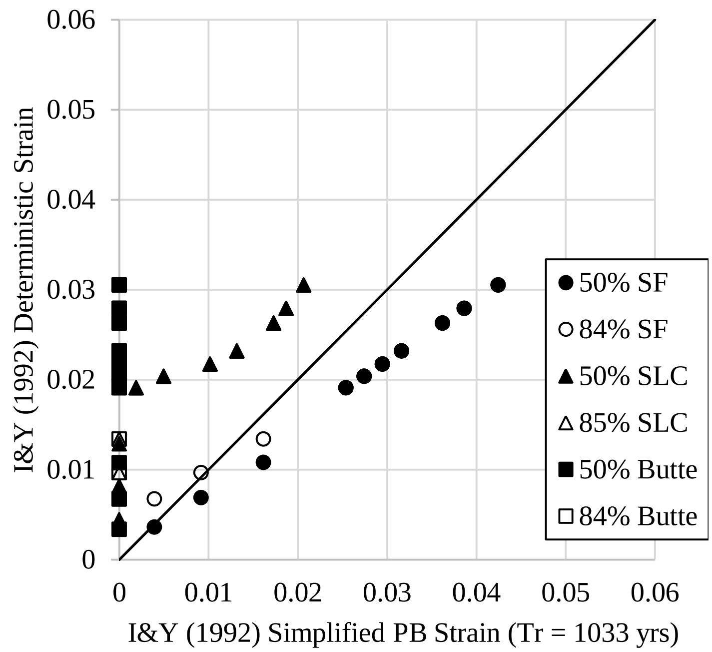


Figure 2-8 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 1,033 years).

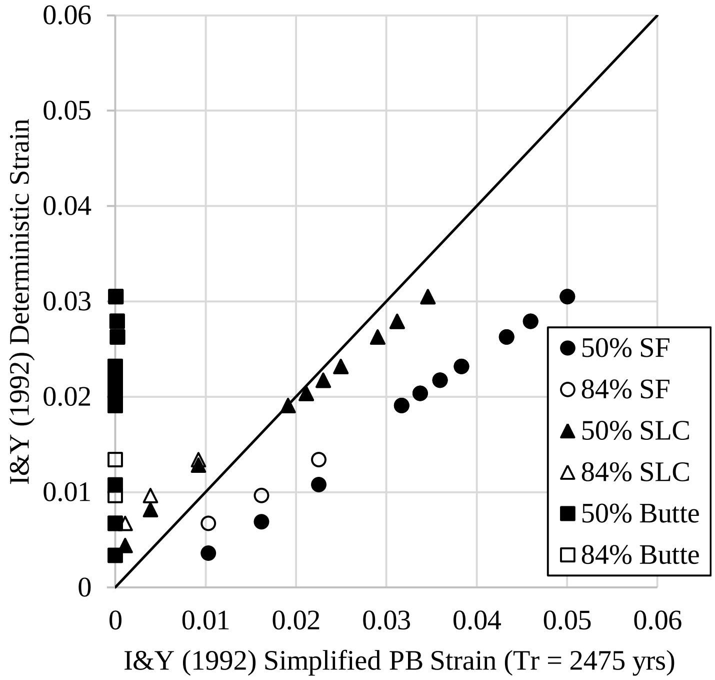


Figure 2-9 Comparison of deterministic and performance-based vertical strains for the Ishihara & Yoshimine (1992) model (PB Return Period = 2,475 years).

2.3.2 Seismic Slope Displacement Model

Once the analysis of the different methods was completed, the data was examined and charts were created for each city. These charts compare, side by side, the results of the simplified, pseudo-probabilistic, and deterministic analyses using both Rathje & Saygili (2009) and Bray & Travasarou (2007) method. These charts can be seen below.

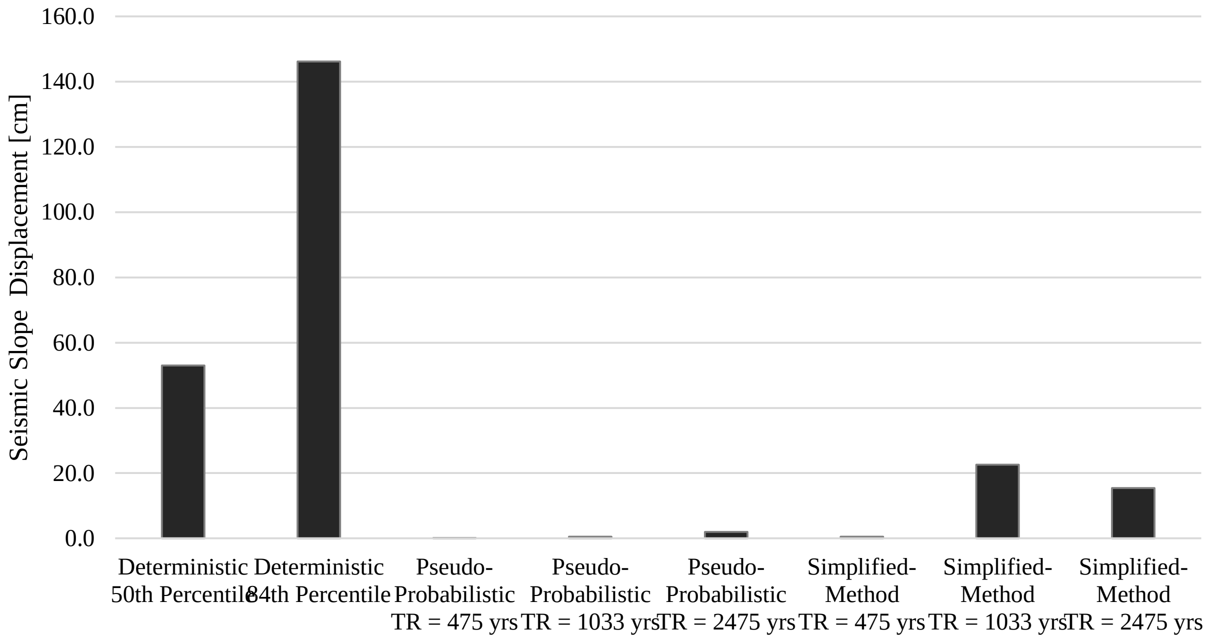


Figure 2-10 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for Butte, MT (Latitude 46.033, Longitude -112.533).

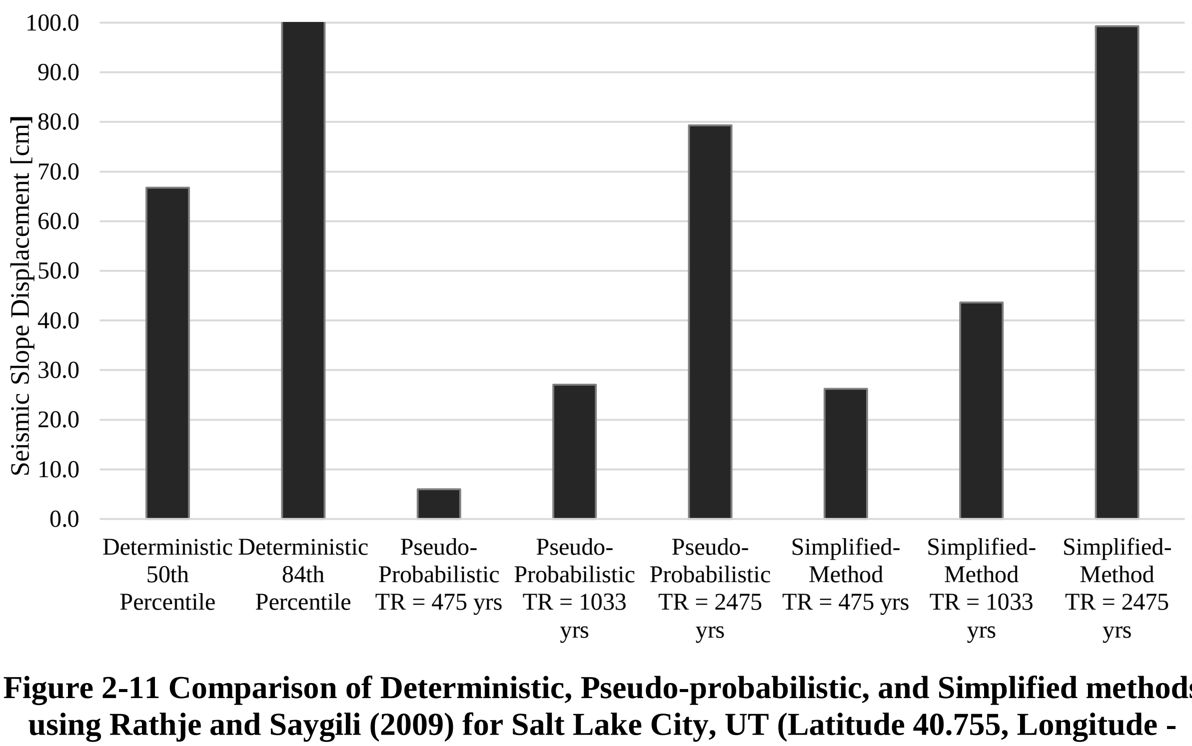


Figure 2-11 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for Salt Lake City, UT (Latitude 40.755, Longitude -111.898).

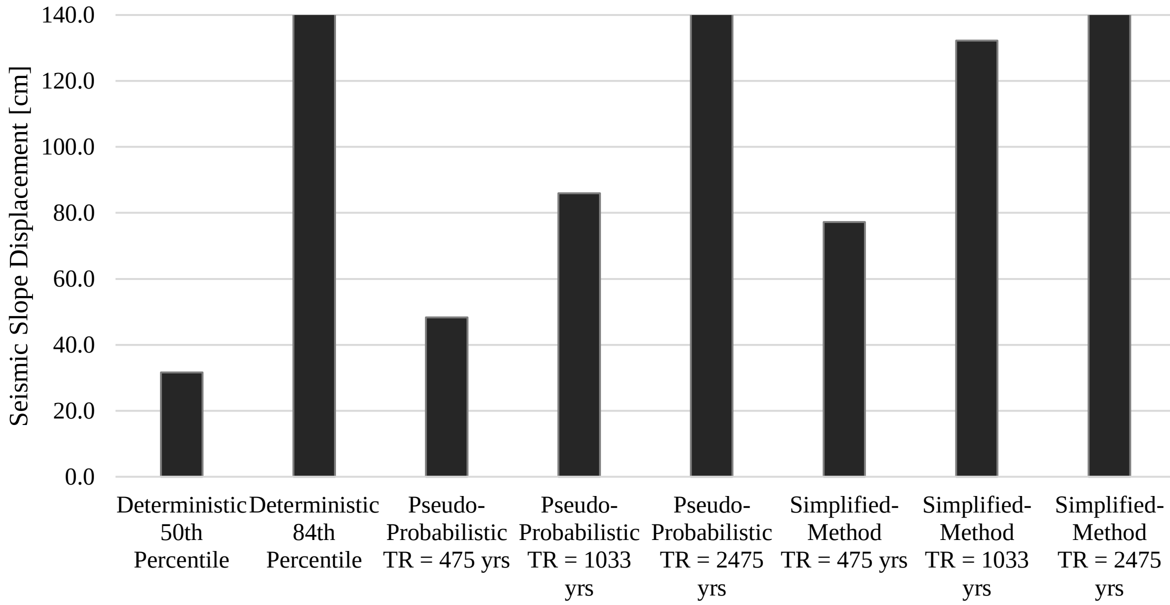


Figure 2-12 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Rathje and Saygili (2009) for San Francisco, CA (Latitude 37.775, Longitude -122.418).

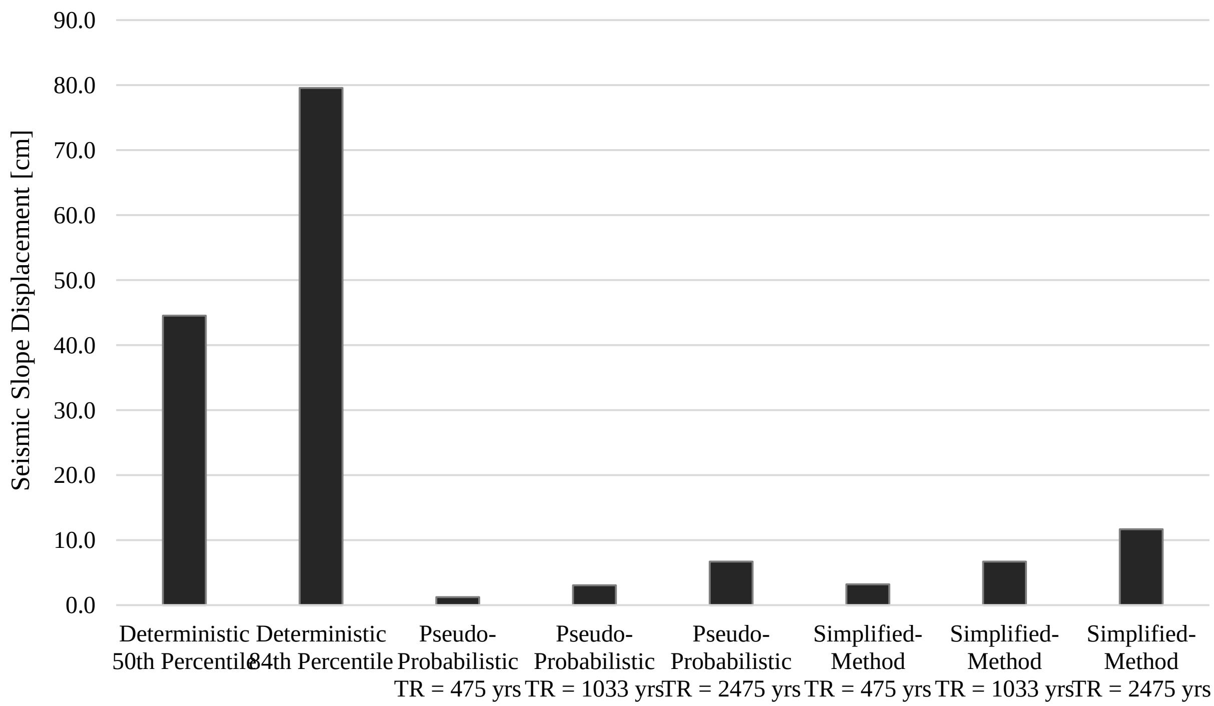


Figure 2-13 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for Butte, MT (Latitude 46.033, Longitude -112.533).

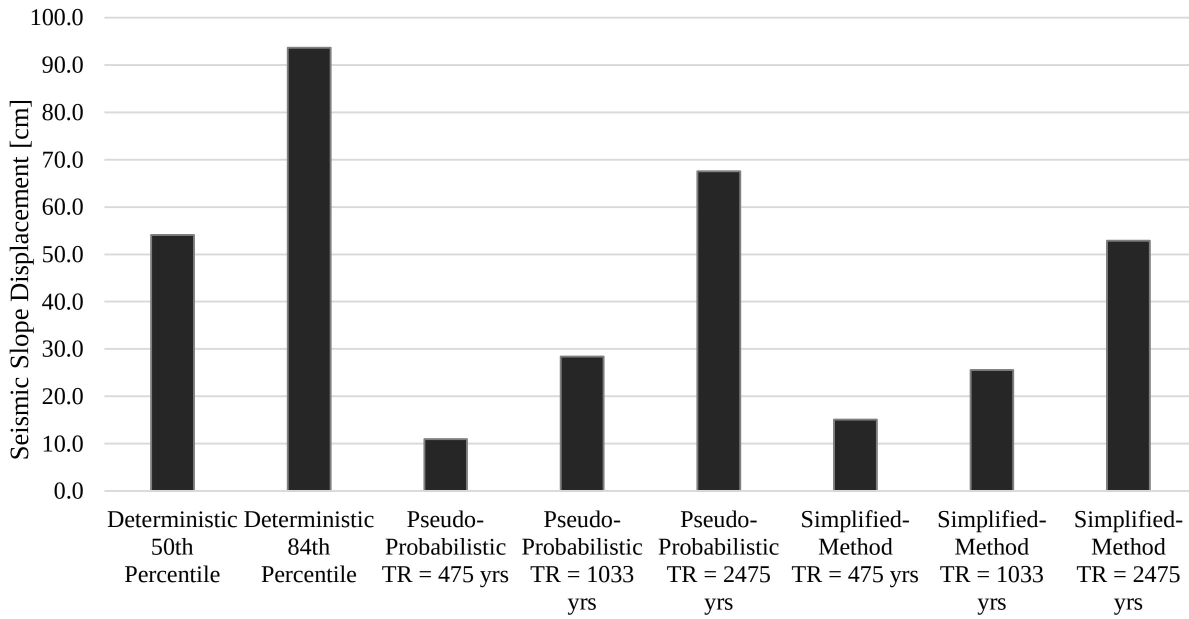


Figure 2-14 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for Salt Lake City, UT (Latitude 40.755, Longitude -111.898).

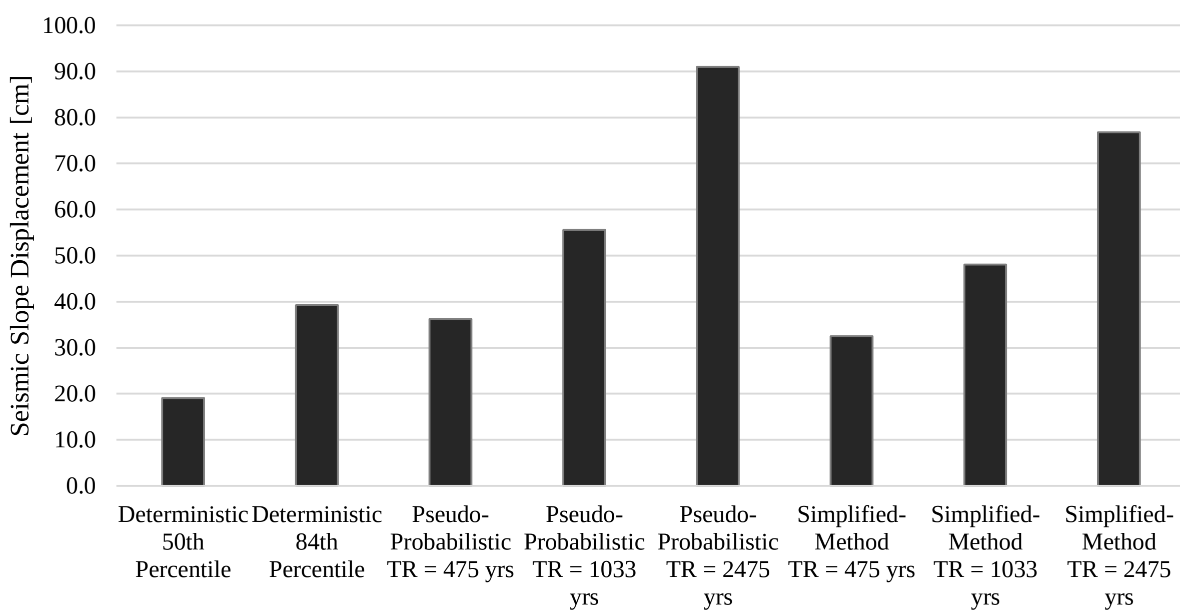


Figure 2-15 Comparison of Deterministic, Pseudo-probabilistic, and Simplified methods using Bray and Travasarou (2007) for San Francisco, CA (Latitude 37.775, Longitude -122.418).

The different seismicity areas represented by the plots shown previously, and the deterministic comparisons with the simplified results show interesting conclusions. Figure 2-10 shows the deterministic method highly over predicts the displacements predicted by the simplified and pseudo-probabilistic methods in areas of low seismicity such as Butte using the Rathje & Saygili method. This result can be attributed to the deterministic procedure not accounting for the likelihood of the Rocker fault rupturing, and predicts a displacement with extremely low probability of occurring. Similar behavior can also be observed in Figure 2-13 when the Bray & Travasarou method is used in Butte.

The medium seismicity city, Salt Lake City seen in Figure 2-11 using the Rathje & Saygili method, shows that the deterministic method predicts displacements higher than the simplified and pseudo-probabilistic procedures at return periods of 475 and 1,033 years. This is not the case for the 2,475 year return period in which the simplified and pseudo-probabilistic procedures slightly over estimate displacements. The Bray & Travasarou method in the same area, as observed in Figure 2-14, showed at all return periods that the 84th percentile of the deterministic procedure over predicted displacements when compared to those computed with the simplified and pseudo-probabilistic procedures.

In San Francisco, the high seismicity city; similar results for deterministic, simplified, and pseudo-probabilistic procedures at the 2,475 return period were calculated, as shown in Figure 2-12 when using the Rathje & Saygili method. When the Bray and Travasarou model is used as shown in Figure 2-15 the simplified and pseudo-probabilistic methods seem to over predict seismic slope displacements.

2.4 Summary

The results of this study, for both the post-liquefaction settlement and seismic slope displacement, show that deterministic methods predicted significantly more earthquake induced hazard than probabilistic methods in Butte—an area of low seismicity. The deterministic results also generally showed more earthquake induced 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 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* should 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 necessary to perform a post-liquefaction settlement and seismic slope displacement analysis and provides some guidance for how the tool should be used. The guidelines for performing a simplified performance-based analysis of liquefaction triggering and lateral spread are included in the Year 1 Quarter 3 report of this study and are not described here.

This section also addresses the addition of the mapped reference parameter database and how an interpolated reference parameter is obtained from this database.

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 (Figure 3-1) and enter the soil profile information (Figure 3-2), mapped or interpolated reference values, and other parameters, which are necessary for the simplified performance-based procedure (Figure 3-3). 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.

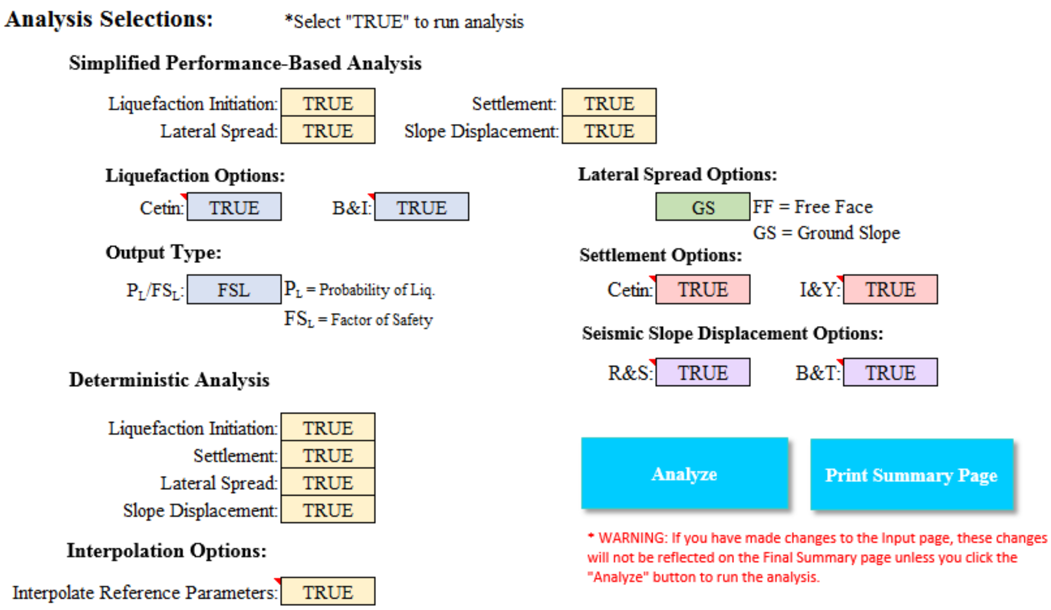
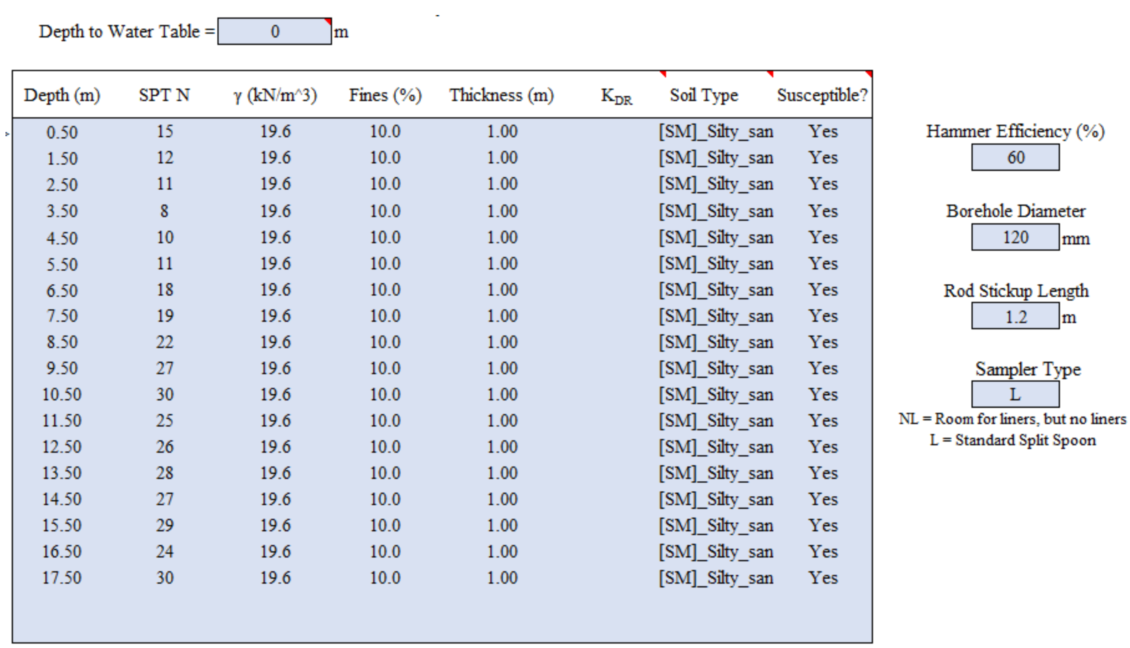


Figure 3-1 Analysis Selections section on the *Inputs* tab.



Depth (m)	SPT N	γ (kN/m^3)	Fines (%)	Thickness (m)	K_{DR}	Soil Type	Susceptible?
0.50	15	19.6	10.0	1.00		[SM]_Silty_san	Yes
1.50	12	19.6	10.0	1.00		[SM]_Silty_san	Yes
2.50	11	19.6	10.0	1.00		[SM]_Silty_san	Yes
3.50	8	19.6	10.0	1.00		[SM]_Silty_san	Yes
4.50	10	19.6	10.0	1.00		[SM]_Silty_san	Yes
5.50	11	19.6	10.0	1.00		[SM]_Silty_san	Yes
6.50	18	19.6	10.0	1.00		[SM]_Silty_san	Yes
7.50	19	19.6	10.0	1.00		[SM]_Silty_san	Yes
8.50	22	19.6	10.0	1.00		[SM]_Silty_san	Yes
9.50	27	19.6	10.0	1.00		[SM]_Silty_san	Yes
10.50	30	19.6	10.0	1.00		[SM]_Silty_san	Yes
11.50	25	19.6	10.0	1.00		[SM]_Silty_san	Yes
12.50	26	19.6	10.0	1.00		[SM]_Silty_san	Yes
13.50	28	19.6	10.0	1.00		[SM]_Silty_san	Yes
14.50	27	19.6	10.0	1.00		[SM]_Silty_san	Yes
15.50	29	19.6	10.0	1.00		[SM]_Silty_san	Yes
16.50	24	19.6	10.0	1.00		[SM]_Silty_san	Yes
17.50	30	19.6	10.0	1.00		[SM]_Silty_san	Yes

Figure 3-2 Soil profile input section.

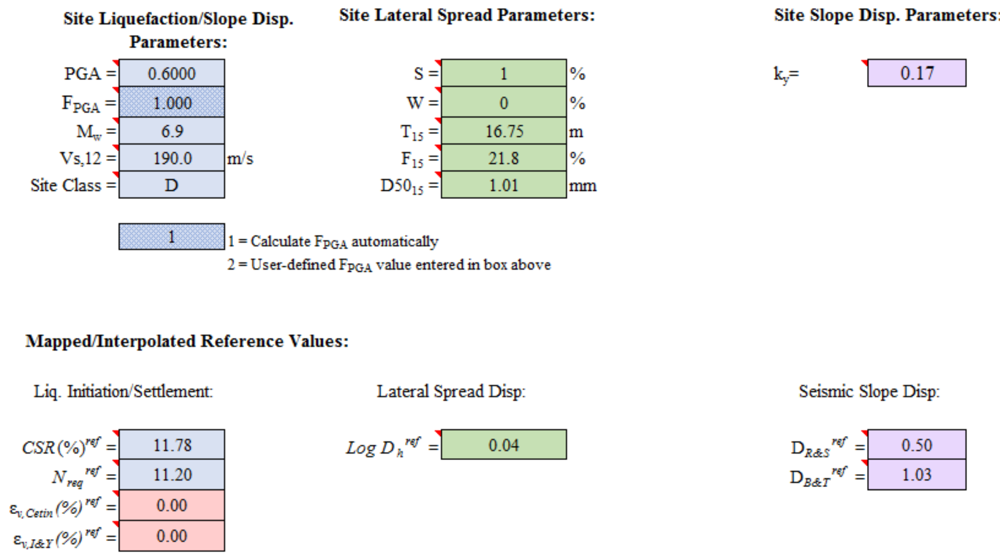


Figure 3-3 Ground motion and reference input parameters.

3.2.2 Map Help

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

3.2.3 Simplified Performance-based Post- Liquefaction Settlement

Simplified performance-based settlement calculations are performed on the *PB Settlement* tab. The *Det Settlement* tab contains calculations to perform a deterministic analysis of liquefaction settlement. Both the performance based and deterministic calculations are based on the Ishihara and Yoshimine (1992) and Cetin et al. (2009) settlement models. The derivation of the simplified model is presented in the Quarter 1 Year 2 report of this study. These sheets are available for review from the user but do not require any input or changes from the user. All calculations are done automatically when the “Analyze” button on the *Inputs* tab is selected.

3.2.4 Simplified Performance-based Seismic Slope Displacement

This section of the spreadsheet computes the simplified and deterministic seismic slope displacements based on the Rathje and Saygili (2009) and the Bray and Travasarou (2007) models. The derivation of the simplified model is explained in Quarter 1 Year 2 report. This sheet is to provide the user information about how the displacements are being computed, but do not require any input or changes from the user. When the user clicks the "Analyze" button in the input page all calculations will be done automatically.

3.2.5 Final Summary

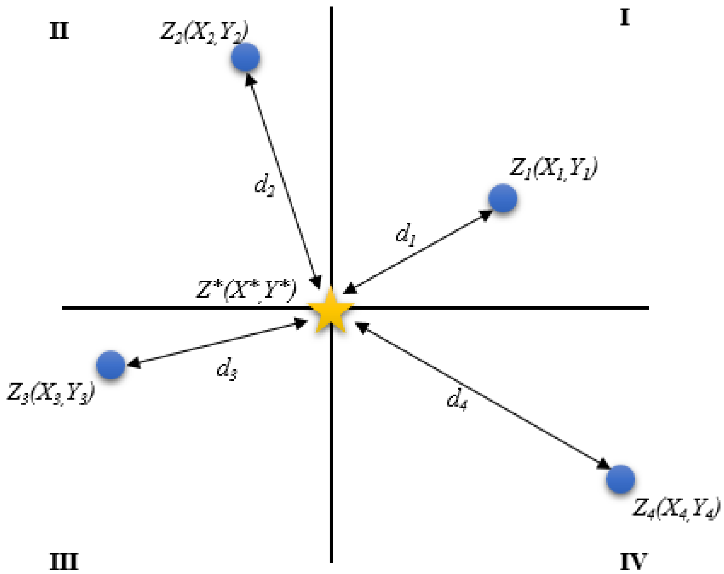
This section shows the final results of the analyses chosen on the *Inputs* tab. The format of this section is already set up for easy printing. The headers of each page are associated with the project information entered on the *Inputs* tab. The first page provides a summary of inputs from the *Inputs* 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. It also provides information on how a reference hazard value is calculated through interpolation.

3.2.7 Interpolation

The included interpolation tool will calculate a liquefaction hazard reference value of a selected location using an inverse distance weighted (IDW) interpolation scheme. Once a location is entered as a longitude and latitude, the tool will find the four nearest surrounding data points and interpolate a reference hazard value from the four points. Figure 3-4 displays a schematic of the interpolation performed by the Simplified Tool. The *Interpolation* tab in the Simplified Tool displays more information and theory behind the IDW interpolation scheme.



$$Z^*(X^*,Y^*) = \frac{\sum \frac{Z_i}{d_i^2}}{\sum \frac{1}{d_i^2}} \qquad d_i = \sqrt{(X_i - X^*)^2 + (Y_i - Y^*)^2}$$

Figure 3-4 Inverse distance weighted interpolation scheme as performed in the Simplified Tool.

The user may enter a location, return period, and choose to automatically interpolate reference parameters on the *Inputs* tab. If the user chooses to opt out of automatic interpolation, the reference hazard parameters must be obtained from an appropriate liquefaction hazard loading map and must be entered manually.

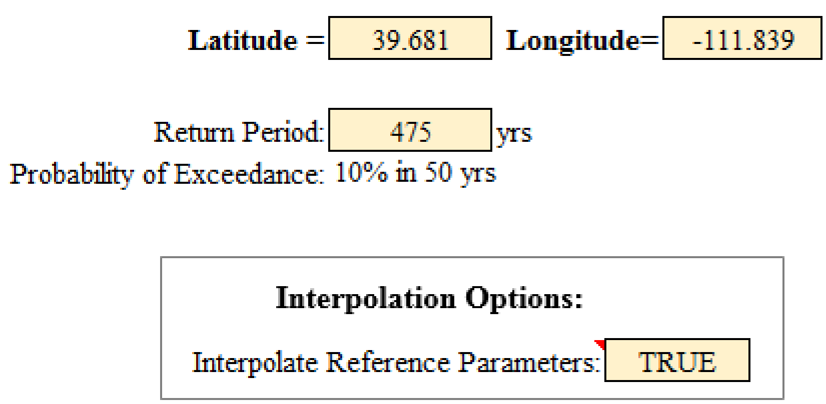


Figure 3-5 Inputs required for the included interpolation tool.

At the time of dissemination of this report, the interpolation tool contains full functionality for all states included in this study for liquefaction initiation and lateral spread analyses. The liquefaction settlement and seismic slope displacement database is not included for Alaska due to the unavailability of deaggregation data from the United States Geological Survey. Once the Alaska deaggregation data becomes available, a new Simplified Tool with an updated Alaska database will be released.

3.3 Suggested Simplified Procedure

The following sections describe the suggested simplified procedure for assessing post-liquefaction settlement and seismic slope displacement.

3.3.1 Simplified Performance-based Post-Liquefaction Settlement

1) All input data and model options are entered and changed on the *Inputs* tab of the simplified tool (Figure 3-1 through Figure 3-3).
2) Enter the latitude, longitude and select the appropriate return period (T_R) from the dropdown menu (Figure 3-5). Options available to select are: 475, 1033, and 2475 year return periods. This step is particularly important if the tool will be interpolating a reference hazard value rather than a manual input received from reference map.
3) Enter the required soil profile information in the appropriate cells. Please note that the simplified tool only allows for 20 soil sub-layers; therefore, divide or combine the soil profile properties accordingly (Figure 3-2).
4) In the "Analysis Selections:" section of the *Inputs* tab, choose the liquefaction hazard analysis to be run (Figure 3-1).
    a. The "Cetin" settlement analysis cannot be run without also performing the "Cetin" liquefaction initiation model; likewise, the "I&Y" (Ishihara and Yoshimine) settlement model cannot be run without also performing the "B&I" (Boulanger and Idriss) initiation procedure.
    b. You may also choose to run a deterministic liquefaction initiation/ settlement analysis in the "Analysis Selections:" section.

c. If you would like the simplified tool to interpolate hazard reference values rather than inputting the values manually, select "TRUE" from the dropdown menu under "Interpolate Reference Parameters:". If you choose "FALSE", the reference hazard values must be entered manually.

5) Enter the required settlement parameters on the "Inputs" tab (Figure 3-3):

   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 (15)	50 (75)
1,039 (1,033)	2 (7)	21 (75)
2,475	2 (3)	50 (75)

   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 chooses to "Calculate F_{pga} automatically" by inputting "1" into the corresponding cell, 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 liquefaction initiation calculations only. If the user is just running the seismic slope displacement analysis he or she does not need to worry about the value that is entered in this box.

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) If "Interpolate Reference Parameters:" was set to "FALSE", enter the applicable mapped reference values for $CSR\ (\%)^{ref}$, N_{req}^{ref}, $\varepsilon_{v,Cetin}(\%)ref$, $\varepsilon_{v,I\&Y}(\%)^{ref}$ obtained from the appropriate liquefaction hazard map (both model and return period).

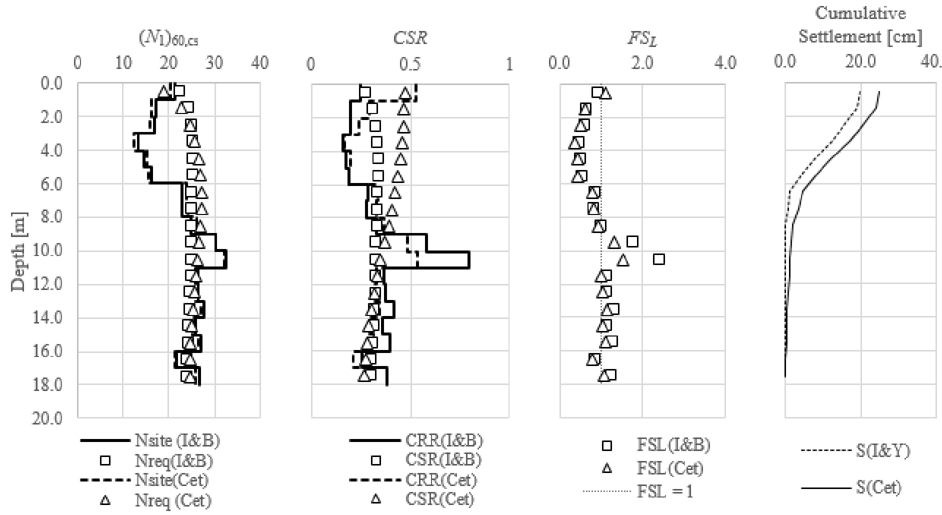
7) The user can also enter in a PGA, F_{PGA}, M_W, and Percentile in the corresponding cells to perform a deterministic analysis.

8) Once everything is correctly entered into the *Inputs* tab, click "Analyze". The calculations will be displayed on the *Final Summary* 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. An example final summary output is seen in

Company:	GEO Company		**Project:**	Trial Run
Drawn by: B. Error		**Checked:** L. Astorga	**Location:**	Salt Lake City, UT
Date:	3/18/2016	**Date:**	**Project #:**	AB-123-4567

Liquefaction Initiation and Settlement Simplified Performance-based Results:



	Idriss and Boulanger (2008, 2012); Ishihara & Yoshimine (1992)					Cetin et al. (2004, 2009)				
Depth (m)	$(N_1)_{60,cs}$	N_{req}^{site}	CSR^{site}	FS_L	$\sum S$ [cm]	$(N_1)_{60,cs}$	N_{req}^{site}	CSR^{site}	FS_L	$\sum S$ [cm]
0.50	21.23	22.48	0.2740	0.922	19.67	20.26	18.79	0.4738	1.112	24.90
1.50	17.21	24.33	0.3131	0.640	19.09	16.32	22.88	0.4701	0.622	24.21
2.50	16.86	24.84	0.3260	0.603	15.69	15.76	24.68	0.4650	0.524	20.77
3.50	13.29	25.26	0.3375	0.480	12.30	12.28	25.77	0.4584	0.376	16.93
4.50	14.70	25.31	0.3389	0.516	7.92	15.10	26.47	0.4497	0.439	12.00
5.50	16.08	25.31	0.3389	0.556	4.30	15.60	26.89	0.4386	0.441	8.19
6.50	23.02	25.13	0.3337	0.853	1.33	23.96	27.09	0.4250	0.796	4.73

Figure 3-6 Example final summary for liquefaction initiation and settlement.

3.3.2 Simplified Performance-based Seismic Slope 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) Open the simplified performance-based liquefaction hazard assessment tool (provided as part of this report). Under "Analysis Selections" choose the analysis to perform.

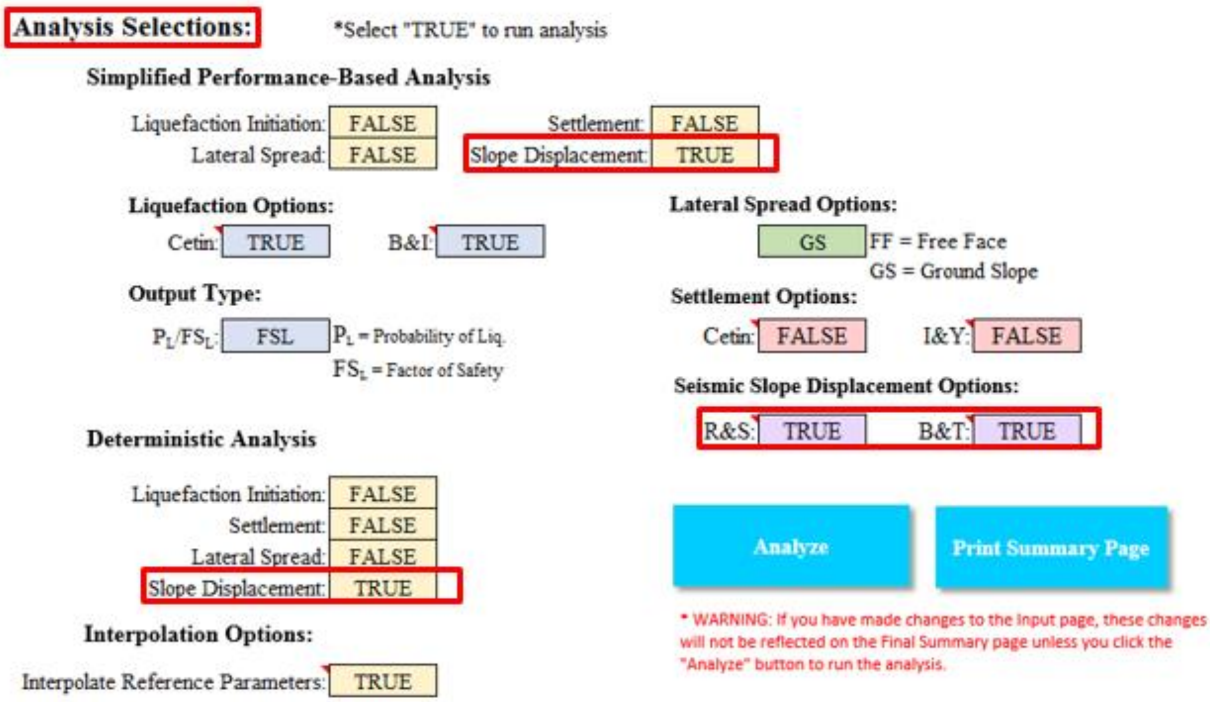


Figure 3-7 Analysis Selections for Slope Displacement

3) Enter the required site slope displacement parameters on the *Inputs* tab. Some of the parameters will be the same as those you will enter for site liquefaction analysis in which case the values need to be filled just once.

   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.

      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 liquefaction initiation calculations only. If the user is just running the seismic slope displacement analysis he or she does not need to worry about the value that is entered in this box.

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.

f. k_y: The yield acceleration represents the horizontal acceleration (in units of g) that results in a factor of safety of 1.0 which initiates sliding in the slope. This value is necessary for computation of seismic slope displacements for both Rathje & Saygili (2009), and Bray & Travasarou (2007) models. See the *References* tab of the spreadsheet for further help in determining k_y.

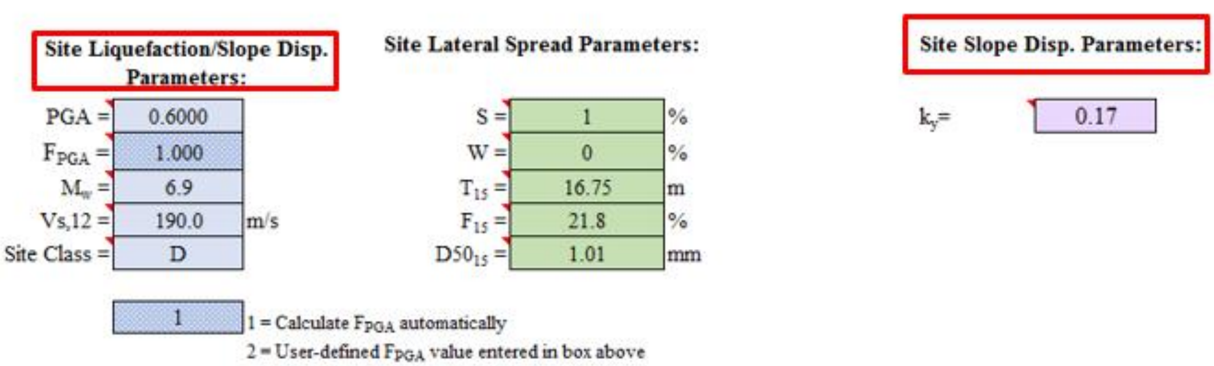


Figure 3-8 Site Slope Displacement Parameter Inputs

4) Retrieve the logged reference seismic slope displacement value (D^{ref}) for both the Rathje & Saygili (2009) and Bray & Travasarou (2007) models from the map with the desired return period or use the automatically interpolated values by the simplified performance-based liquefaction hazard assessment tool.

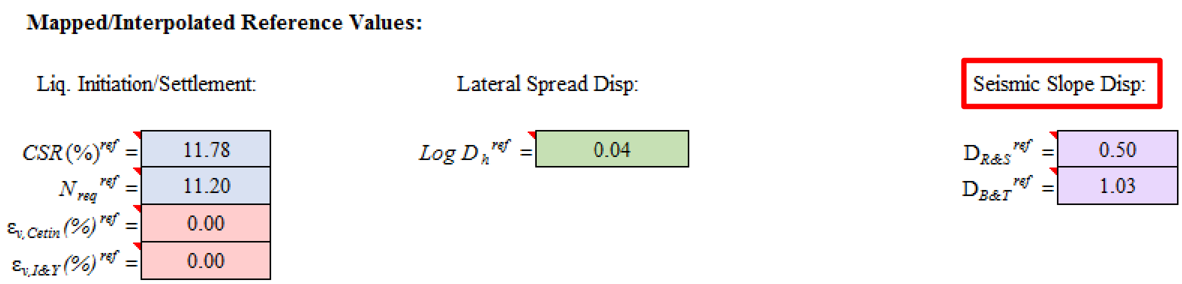


Figure 3-9 Mapped/Interpolated Slope Displacement Values

5) 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.

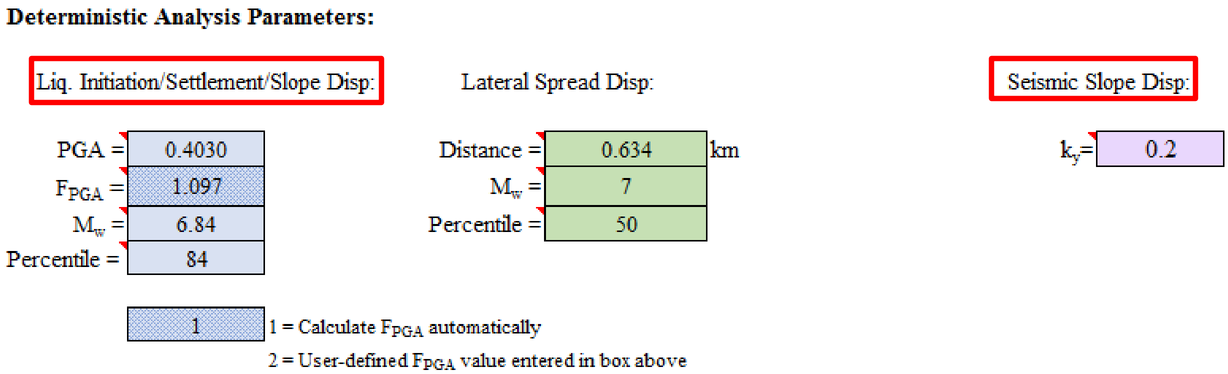


Figure 3-10 Deterministic Analysis Parameters for Slope Displacement

6) Several dropdown menus 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) and models (Rathje & Saygili or Bray & Travasarou), the user would like to consider. Select the desired analyses, models, and options before proceeding to the next step.
7) Once everything is correctly entered into the *Inputs* tab, click "Analyze". The calculations will be displayed on the *Final Summary* tab.

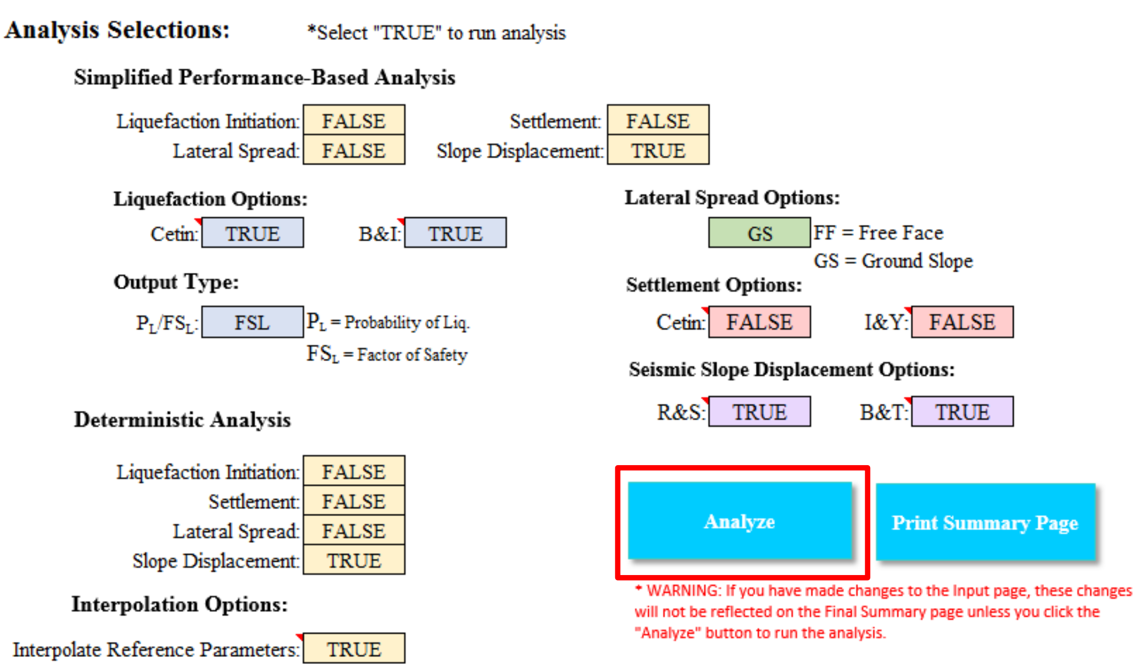


Figure 3-11 Final check of all inputs and "Analyze"

8) 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.

Summary of Inputs for Seismic Slope Displacement Analysis:

Input Parameters		Refence Value		Inputs for Deterministic Analysis	
PGA =	0.6	$D_{R\&S}^{ref}$ =	0.5	PGA =	0.403
F_{PGA} =	1	$D_{B\&T}^{ref}$ =	1.0	k_y=	0.2
M_w =	6.85			M_w =	6.84
k_y=	0.17			Percentile =	84
Site Class =	D				

Seismic Slope Displacement Results:

Simplified PB Results:			Deterministic Results:		
$D_{R\&S}^{site}$ =	**0.040**	cm	$D_{R\&S}$ =	**0.000**	cm
$D_{B\&T}^{site}$ =	**0.552**	cm	$D_{B\&T}$ =	**3.637**	cm

Figure 3-12 Example of Final Summary of Slope Displacement Analysis

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 post-liquefaction settlement and seismic slope 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 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.

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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)