THE OVERPREDICTION OF LIQUEFACTION HAZARD IN CERTAIN AREAS OF LOW TO MODERATE SEISMICITY

Dr. Kevin Franke, Ph.D., P.E., M.ASCE
Dept. of Civil and Environmental Engineering
Brigham Young University
April 20, 2017
Liquefaction Hazard

- Liquefaction can result in significant damage to infrastructure during earthquakes.
- Liquefaction hazard is generally correlated with seismic hazard.
- Some areas of low to moderate seismicity have significant liquefaction hazard, however.

Image: Karl V. Steinbrugge Collection, EERC, Univ of California, Berkeley
Liquefaction is usually evaluated with a factor of safety, $FS_L$

$$FS_L = \frac{\text{Resistance}}{\text{Loading}} = \frac{\text{Cyclic Resistance Ratio}}{\text{Cyclic Stress Ratio}} = \frac{CRR}{CSR}$$

Function of both $a_{\text{max}}$ and $M_w$, which collectively characterize seismic loading

(after Mayfield et al. 2010)
$N_{\text{req}}$: An Alternative to CSR and CRR

$N_{\text{site}} = (N_1)_{60,cs,i}$ = the actual $N$ value for the soil layer of interest

$N_{\text{req}} =$ the SPT resistance required to resist liquefaction at a given CSR (after Mayfield et al. (2010))
Various Approaches for Liquefaction Hazard Analysis

- **Deterministic Approach**
  - Considers *an individual seismic source* and corresponding ground motions individually
  - Usually assumes mean values for the inputs and models

- **Pseudo-Probabilistic Approach**
  - Considers *probabilistic ground motion* from a single return period
  - Usually assumes mean values for the inputs and models

- **Probabilistic (or Performance-Based) Approach**
  - Considers *probabilistic ground motions from ALL return periods*
  - Accounts for parametric and model uncertainties
  - Results depend on desired hazard level or return period
Pseudo-Probabilistic Approach: How do we get $a_{\text{max}}$ and $M_w$?

- Deaggregation Analysis

Downtown San Diego
Conventional (i.e., “pseudo-probabilistic”) Liquefaction Triggering Procedure

1. Perform PSHA with PGA and a deaggregation analysis at the specified return period of PGA (e.g., 2475-year for the MCE)
2. Obtain either the mean or modal $M_w$ from the deaggregation analysis
3. Correct the PGA value for site response using site amplification factors or a site response analysis to compute $a_{\text{max}}$
4. Couple $a_{\text{max}}$ with the mean or modal $M_w$ to perform a scenario liquefaction triggering analysis
5. Typically define liquefaction triggering as $P_L \geq 15\%$ and $FS_L \leq 1.2$
Consider the following site in Cincinnati, Ohio:

Soil Profile

- Sand and Gravel Fill
- Silty Sand (SM)
- Poorly-graded Sand with Silt (SP-SM)

Clean Sand-Equivalent SPT Resistance, $(N_1)_{60, cs}$
Pseudo-Probabilistic Example.....

Here is the corresponding 2,475-yr deaggregation from the USGS:

PGA = 0.067 g

New Madrid Seismic Zone

$M_w = 7.5$ to $8.0$

$R = 454$ km

PSH Deaggregation on NEHRP BC rock
Hypothetical_Ci 84.511° W, 39.096 N.
Peak Horiz. Ground Accel.$>=0.06676$ g
Ann. Exceedance Rate .040E-03. Mean Return Time 2475 years
Mean ($R.M,\varepsilon_0$) 175.3 km, 6.30, 0.50
Modal ($R.M,\varepsilon_0$) = 453.9 km, 7.70, 1.46 (from peak $R,M$ bin)
Modal ($R.M,\varepsilon_0^+$) = 453.7 km, 7.70, 1 to 2 sigma (from peak $R,M,\varepsilon$ bin)
Binning: DeltaR 25. km, deltaM=0.2, Delta$\varepsilon=1.0$
Consider the liquefaction triggering and settlement results for a site in Cincinnati, Ohio:

**Conventional Approach, \( MCE_G \) with Modal Magnitude**

Does this make sense? How likely is it that an M7.5 EQ over 450 km away produces PGA = 0.067g?  
<1% according to Toro et al. (1997)  
<2% according to Atkinson and Boore (2006)
Challenges with the Pseudo-probabilistic Approach

- It can be easy to make an “incompatible” \((a_{max}, M_w)\) pair, especially if using the modal \(M_w\).
- PGA and \(M_w\) typically are taken from a single return period, but other return periods are ignored.
- Does not rigorously account for uncertainty in the liquefaction triggering model or the site response.
- Contributes to inaccurate interpretations of liquefaction hazard (e.g., “I used the 2,475-year PGA in my analysis, so my liquefaction results correspond to the 2,475-year return period.”)
Kramer and Mayfield (2007) introduced a PLHA approach that uses probabilistic ground motions in a probabilistic manner. It accounts for uncertainty in seismic loading AND the liquefaction triggering model. This approach produces liquefaction hazard curves for each sublayer in the soil profile. 

\[
\Lambda_{FSL} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_{amax}} P\left[ FS_L < FS^*_L \mid a_{max_i}, m_j \right] \Delta \lambda_{a_{max_i}, m_j}
\]

\[
\lambda_{N_{req}} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_{amax}} P\left[ N_{req} < N_{req}^* \mid a_{max_i}, m_j \right] \Delta \lambda_{a_{max_i}, m_j}
\]
Back to the Cincinnati Example.....

Let's use the Kramer and Mayfield (2007) PLHA approach with the Boulanger and Idriss (2012) triggering model:

Conventional Approach, $MCE_G$ with Modal Magnitude

PLHA Approach, $Tr=2,475$ years

Only difference: how we considered our seismic loading and uncertainties!
What About Other Cities?

10 cities selected throughout the Central and Eastern U.S.....

(after Franke et al., 2017 [under review] )
6 representative soil profiles with wide range in SPT values...

(after Franke et al., 2017 [under review] )
What About Other Cities?

Results if assuming a Site Class D.....

(after Franke et al., 2017 [under review] )
What About Other Cities?

Results if assuming a Site Class E.....

(after Franke et al., 2017 [under review] )
Existing Tools for PLHA Approach in Practice

**WSLiq** (http://faculty.washington.edu/kramer/WSliq/WSliq.htm)
- Developed by the U. of Washington in 2008 using VB.Net
- Accounts for multiple liquefaction hazards (triggering, lateral spread, settlement, and residual strength)
- Developed only for use in Washington State with 2002 USGS ground motion data, but you can “trick” the program for other locations
- Limited control over the analysis uncertainty options and models

**PBLiquefY v2.0**
- V1.0 developed by BYU in 2013 using Microsoft Excel and VBA
- Liquefaction triggering, settlement, and Newmark slope displacement
- Can be used for any site in the U.S.
- Multiple model options
- Offers lots of control over the analysis uncertainties, including site amplification factors

Neither of these tools has been used widely in design!
Many of us understand how the USGS NSHMP uses PSHA to develop the National Seismic Hazard Maps......
Mayfield et al. (2010) presented a similar idea for liquefaction triggering.

**Simplified Probabilistic Liquefaction Triggering Procedure**

1. **Gridded PB Analysis for Generic Soil Layer**
   - 6 meters Saturated Sand FC < 5%
   - $N_{180} = 18$
   - $\gamma_{sat} = 19.62 \text{ kN/m}^3$
   - $V_{s,12} = 175 \text{ m/s}$

2. **Map Liquefaction Hazard at Targeted Return Periods**

3. **Correct for Site-Specific Soil Conditions and Stresses**

**Liquefaction Parameter Map**
- DIFFERENT FROM a Liquefaction Hazard Map

**Depth Reduction**
- Soil Stresses
- Site Amplification
In 2014, a major multi-state, multi-agency research effort was initiated to develop map-based uniform hazard analysis procedures for various liquefaction effects (settlement, lateral spread, and Newmark slope displacement).
Research was performed at BYU to develop a simplified procedure for the Boulanger and Idriss (2012, 2014) probabilistic triggering model. Similar to the approach introduced by Mayfield et al. (2010), but we incorporated a few changes:

- The quadratic equation format of the Boulanger and Idriss model requires a different and more complex approach.
- Many engineers are still uncomfortable with the $N_{req}$ concept.
- Incorporation of the $(N_1)_{60,cs}$-dependent MSF.
If given a liquefaction triggering model for which CRR is defined as a function of SPT resistance $N$, we can see that $N_{req}$ is just a proxy for the seismic loading (i.e., CSR):

$$CSR = CRR \left( N_{req} \right)$$

From Boulanger and Idriss (2012, 2014):

$$CRR = \exp \left[ \left( \frac{N_1}{14.1} \right) + \left( \frac{N_1}{126} \right)^2 - \left( \frac{N_1}{23.6} \right)^3 + \left( \frac{N_1}{25.4} \right)^4 - 2.67 + \sigma \cdot \Phi^{-1}[P_L] \right]$$

$$CRR_{P_L=50\%} = CRR = \exp \left[ \left( \frac{N_1}{14.1} \right) + \left( \frac{N_1}{126} \right)^2 - \left( \frac{N_1}{23.6} \right)^3 + \left( \frac{N_1}{25.4} \right)^4 - 2.67 \right]$$
By combining equations, we obtain:

$$CSR_{P_L=50\%} = CSR = \exp \left[ \left( \frac{N_{req}}{14.1} \right) + \left( \frac{N_{req}}{126} \right)^2 - \left( \frac{N_{req}}{23.6} \right)^3 + \left( \frac{N_{req}}{25.4} \right)^4 \right] - 2.67$$

So instead of developing liquefaction parameter maps for a reference $N_{req}$, we can develop reference maps for the median CSR to characterize seismic loading. Engineers seem much more comfortable characterizing seismic loading with CSR than they do with $N_{req}$.

We have called these new maps **Liquefaction Loading Parameter Maps**.
BYU has recently developed the following simplified procedure for the Boulanger and Idriss (2014) model (Ulmer and Franke 2016):

**Step 1: Obtain the reference CSR(%) from the appropriate liquefaction loading map**

\[ CSR^{ref} = CSR^{ref} \text{ (\%)} \cdot 100 \]
BYU has recently developed the following simplified procedure for the Boulanger and Idriss (2014) model (Ulmer and Franke 2016):

**Step 2: For every soil sublayer in your profile, compute the appropriate CSR correction factors, \( \Delta CSR \)**

**Site Amplification:**

\[
\Delta CSR_{F_{pga}} = \ln \left( F_{pga} \right)
\]

**Depth Reduction:**

\[
\Delta CSR_{d} = \left( -0.6712 - 1.126 \sin \left( \frac{z}{11.73} + 5.133 \right) \right) + M_{w} \left( 0.0675 + 0.118 \sin \left( \frac{z}{11.28} + 5.142 \right) \right)
\]

**Soil Stress:**

\[
\Delta CSR_{\sigma} = \ln \left[ \frac{\sigma_{v}}{\sigma_{v}'} \right]^{\frac{z}{11.73}}
\]

Mean magnitude from PGA deaggregation at target return period

(z in meters)
BYU has recently developed the following simplified procedure for
the Boulanger and Idriss (2014) model (Ulmer and Franke 2016):

Step 2: For every soil sublayer in your profile, compute the appropriate CSR

correction factors, \( \Delta CSR \)

Duration:

\[
\Delta CSR_{MSF} = -\ln \left( \frac{MSF_{\text{site}}^{\text{MSF}}}{MSF_{\text{ref}}^{\text{ref}}} \right) = -\ln \left\{ \frac{1+\left( MSF_{\text{max}}^{\text{site}} - 1 \right) \left( 8.64 \exp \left( \frac{-M_w}{4} \right) - 1.325 \right)}{1+\left( MSF_{\text{max}}^{\text{ref}} - 1 \right) \left( 8.64 \exp \left( \frac{-M_w}{4} \right) - 1.325 \right)} \right\}
\]

\[
MSF_{\text{max}}^{\text{site}} = 1.09 + \left( \frac{(N_1)_{60,ex}}{31.5} \right)^2 \leq 2.2
\]

\[
MSF_{\text{max}}^{\text{ref}} = 1.09 + \left( \frac{1.237 \left( -\ln (CSR_{\text{ref}}) \right)^4 - 4.918 \left( -\ln (CSR_{\text{ref}}) \right)^3 + 1.762 \left( -\ln (CSR_{\text{ref}}) \right)^2 - 5.473 \left( -\ln (CSR_{\text{ref}}) \right) + 33.65}{31.5} \right)^2 \leq 2.2
\]

**NOTE: if you prefer MSF from Boulanger and Idriss (2012), then \( \Delta CSR_{MSF} = 0 \) ***
BYU has recently developed the following simplified procedure for the Boulanger and Idriss (2014) model (Ulmer and Franke 2016):

**Step 2: For every soil sublayer in your profile, compute the appropriate CSR correction factors, $\Delta CSR$**

\[
\Delta CSR_{k,s} = -\ln \left( \frac{K_{site}}{K_{ref}} \right) = -\ln \left( \frac{1 - C_{site}^{site} \ln \left( \frac{\sigma_v^{site}}{P_a} \right)}{1 - C_{ref}^{ref} \ln \left( \frac{\sigma_v^{ref}}{P_a} \right)} \right)
\]

\[
C_{\sigma}^{site} = \frac{1}{18.9 - 2.55 \sqrt{(N_1)_{60,cs}}} \leq 0.3
\]

\[
C_{\sigma}^{site} = 0 < \frac{1}{18.9 - 2.55 \left[ 1.237 \left( -\ln \left( CSR_{ref} \right) \right)^4 - 4.918 \left( -\ln \left( CSR_{ref} \right) \right)^3 + 1.762 \left( -\ln \left( CSR_{ref} \right) \right)^2 - 5.473 \left( -\ln \left( CSR_{ref} \right) \right) + 33.65 \right]^{0.5}} \leq 0.3
\]
Boulanger and Idriss (2012, 2014)
Simplified PB Liquefaction Model

BYU has recently developed the following simplified procedure for the Boulanger and Idriss (2014) model (Ulmer and Franke 2016):

Step 3: For every soil sublayer in your profile, compute the site-specific CSR corresponding to the targeted return period

Total Correction for layer i:

$$\Delta CSR_i = \Delta CSR_{\sigma,i} + \Delta CSR_{F_{pga},i} + \Delta CSR_{r_d,i} + \Delta CSR_{MSF,i} + \Delta CSR_{K_{\sigma,i}}$$

Site Specific CSR for layer i:

$$CSR_i = \exp\left[\ln\left(CSR_{ref}\right) + \Delta CSR_i\right]$$
Step 4: For each soil sublayer in your profile, characterize liquefaction triggering hazard using whichever metric you prefer.

Factor of Safety: \[
(FS_L)_i = \left( \frac{CRR}{CSR} \right)_i = \exp \left[ (N_{60,cs})_i - 14.1 + \left( (N_{60,cs})_i \right)^2 - \left( (N_{60,cs})_i \right)^3 + \left( (N_{60,cs})_i \right)^4 - 2.67 \right] \]

Probability of Liquefaction: \[
(P_L)_i = \Phi \left[ - \frac{\ln \left( \frac{CRR}{CSR} \right)_i}{0.277} \right] = \Phi \left[ - \frac{\ln \left( (FS_L)_i \right)}{0.277} \right]
\]

*Note that these equations account for both parametric uncertainty (e.g., \((N_1)_{60,cs}\)) and model uncertainty, and are only to be used with the Boulanger and Idriss (2014) procedure.
Does the simplified procedure actually work? Here are some comparisons from 10 different cities, 5 different soil profiles, and 3 different return periods (Ulmer and Franke 2016):
Example Demonstration – San Diego, CA

\[ CSR^{ref} = 0.191 \]

(from Franke et al. 2016)
### Example Demonstration — San Diego, CA

Groundwater at \( z = 2.0 \) meters  
Free-face case, \( W = 10\% \)  
\((D50)_{15} = 0.5 \text{mm}\)

<table>
<thead>
<tr>
<th>Depth, ( z ) (m)</th>
<th>Soil Type</th>
<th>Thickness (m)</th>
<th>( (N_1)_{60} ) (blows/0.3 meter)</th>
<th>Fines (%)</th>
<th>Unit Weight (kN/m(^3))</th>
<th>( (N_1)_{60,cs} ) (blows/0.3 meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Hydraulic Fill</td>
<td>0.5</td>
<td>12</td>
<td>3</td>
<td>18.70</td>
<td>12.0</td>
</tr>
<tr>
<td>0.6</td>
<td>Hydraulic Fill</td>
<td>1.0</td>
<td>20</td>
<td>4</td>
<td>18.70</td>
<td>20.0</td>
</tr>
<tr>
<td>1.5</td>
<td>Poorly Graded Sand with Silt</td>
<td>0.5</td>
<td>28</td>
<td>11</td>
<td>18.85</td>
<td>33.6</td>
</tr>
<tr>
<td>2.1</td>
<td>Poorly Graded Sand with Silt</td>
<td>1.0</td>
<td>35</td>
<td>12</td>
<td>18.85</td>
<td>37.1</td>
</tr>
<tr>
<td>3</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>36</td>
<td>15</td>
<td>19.55</td>
<td>39.3</td>
</tr>
<tr>
<td>4.6</td>
<td>Poorly Graded Sand with Silt</td>
<td>1.5</td>
<td>13</td>
<td>8</td>
<td>18.85</td>
<td>13.4</td>
</tr>
<tr>
<td>6.1</td>
<td>Poorly Graded Sand with Silt</td>
<td>1.5</td>
<td>14</td>
<td>6</td>
<td>18.85</td>
<td>14.0</td>
</tr>
<tr>
<td>7.6</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>36</td>
<td>18</td>
<td>19.55</td>
<td>40.1</td>
</tr>
<tr>
<td>9.1</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>43</td>
<td>20</td>
<td>19.55</td>
<td>47.5</td>
</tr>
<tr>
<td>10.7</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>50+</td>
<td>17</td>
<td>19.55</td>
<td>54+</td>
</tr>
<tr>
<td>12.2</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>50+</td>
<td>23</td>
<td>19.55</td>
<td>55+</td>
</tr>
<tr>
<td>13.7</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>50+</td>
<td>24</td>
<td>19.55</td>
<td>55+</td>
</tr>
<tr>
<td>15.2</td>
<td>Silty Sand</td>
<td>1.5</td>
<td>50+</td>
<td>22</td>
<td>19.55</td>
<td>55+</td>
</tr>
</tbody>
</table>

1 Computed using Idriss and Boulanger [2008, 2010]

(from Franke et al. 2016)
# Example Demonstration – San Diego, CA

## Liquefaction Triggering Results (Ulmer and Franke 2016)

<table>
<thead>
<tr>
<th>Depth, ( z ) (m)</th>
<th>USCS</th>
<th>((N_1)_{60,cs}) (blows/0.3 meter)</th>
<th>( \Delta CSR_\sigma ) (Eqn A2)</th>
<th>( \Delta CSR_{F_{p_{pga}}} ) (Eqn A3)</th>
<th>( \Delta CSR_{r_d} ) (Eqn A4)</th>
<th>( \Delta CSR_{K_\sigma} ) (Eqn A5)</th>
<th>( CSR ) (Eqn A1)</th>
<th>( CRR )</th>
<th>( FS_{Liq} ) (Eqn A7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>SP-SM</td>
<td>33.6</td>
<td>-0.693</td>
<td>0.37 (0.07)</td>
<td>0.08 (0.07)</td>
<td>-0.206</td>
<td>0.121 (0.203)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>2.1</td>
<td>SP-SM</td>
<td>37.1</td>
<td>-0.532</td>
<td>0.37 (0.07)</td>
<td>0.07 (0.06)</td>
<td>-0.219</td>
<td>0.139 (0.233)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>3</td>
<td>SM</td>
<td>39.3</td>
<td>-0.399</td>
<td>0.37 (0.07)</td>
<td>0.05 (0.05)</td>
<td>-0.164</td>
<td>0.166 (0.278)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>4.6</td>
<td>SP-SM</td>
<td>13.4</td>
<td>-0.262</td>
<td>0.37 (0.07)</td>
<td>0.03 (0.03)</td>
<td>0.006</td>
<td>0.219 (0.368)</td>
<td>0.163</td>
<td>0.75 (0.44)</td>
</tr>
<tr>
<td>6.1</td>
<td>SP-SM</td>
<td>14.0</td>
<td>-0.196</td>
<td>0.37 (0.07)</td>
<td>0.00 (0.00)</td>
<td>0.026</td>
<td>0.232 (0.390)</td>
<td>0.168</td>
<td>0.73 (0.43)</td>
</tr>
<tr>
<td>7.6</td>
<td>SM</td>
<td>40.1</td>
<td>-0.174</td>
<td>0.37 (0.07)</td>
<td>-0.03 (-0.03)</td>
<td>0.023</td>
<td>0.229 (0.386)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>9.1</td>
<td>SM</td>
<td>47.5</td>
<td>-0.147</td>
<td>0.37 (0.07)</td>
<td>-0.07 (-0.07)</td>
<td>0.068</td>
<td>0.238 (0.402)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>10.7</td>
<td>SM</td>
<td>54</td>
<td>-0.125</td>
<td>0.37 (0.07)</td>
<td>-0.11 (-0.10)</td>
<td>0.112</td>
<td>0.244 (0.413)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>12.2</td>
<td>SM</td>
<td>54</td>
<td>-0.110</td>
<td>0.37 (0.07)</td>
<td>-0.15 (-0.14)</td>
<td>0.149</td>
<td>0.247 (0.420)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>13.7</td>
<td>SM</td>
<td>54</td>
<td>-0.098</td>
<td>0.37 (0.07)</td>
<td>-0.19 (-0.18)</td>
<td>0.184</td>
<td>0.249 (0.423)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
<tr>
<td>15.2</td>
<td>SM</td>
<td>54</td>
<td>-0.089</td>
<td>0.37 (0.07)</td>
<td>-0.23 (-0.22)</td>
<td>0.216</td>
<td>0.249 (0.425)</td>
<td>&gt;0.6</td>
<td>&gt;2 (&gt;2)</td>
</tr>
</tbody>
</table>

1. Computed with Boulanger and Idriss [58], \( P_L=50\% \)

(from Franke et al. 2016)
Conclusions

• The conventional pseudo-probabilistic approach can overpredict liquefaction hazard in areas of low to moderate seismicity
  • Especially where the selected $M_w \geq 7.5$ and is located more than 200 km away from the site

• Current seismic design provisions (e.g., IBC, ASCE, AASHTO) serve to propagate the overprediction of liquefaction

• Probabilistic approaches can help solve the problem, but are not easy to apply without special tools

• New simplified approximation methods can give you the benefits of the probabilistic approach with the convenience of the conventional approach

• Reference parameter maps and online tools to use them are currently being developed for Utah, Idaho, Oregon, Montana, Alaska, South Carolina, and Connecticut
References


THE OVERPREDICTION OF LIQUEFACTION HAZARD IN CERTAIN AREAS OF LOW TO MODERATE SEISMICITY

Dr. Kevin Franke, Ph.D., P.E., M.ASCE
Dept. of Civil and Environmental Engineering
Brigham Young University
April 20, 2017