SIMPLIFIED PERFORMANCE-BASED LIQUEFACTION HAZARD ANALYSIS

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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
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. Coupla_{\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, $(N_1)_{60,cs}$
Here is the corresponding 2,475-yr deaggregation from the USGS:

PGA = 0.067 g
Consider the liquefaction triggering (B&I 2012) and settlement results (I&Y 1993) 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.

- 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:

- Uses probabilistic ground motions in a probabilistic manner.
- Accounts for uncertainty in seismic loading AND the liquefaction triggering model.
- Produces liquefaction hazard curves for each sublayer in the soil profile.

\[ \Lambda_{FS_L} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_{a_{max}}} P[F_{S_L} < F_{S_L}^* | a_{max_i}, m_j] \Delta \lambda_{a_{max_i}, m_j} \]

\[ \lambda_{N_{req}} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_{a_{max}}} P[N_{req} < N_{req}^* | a_{max_i}, m_j] \Delta \lambda_{a_{max_i}, m_j} \]

(after Kramer and Mayfield 2007)
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!**

The manner in which we account for seismic loading is MUCH more impactful than selecting which triggering model “is best.”
What About Other Cities?

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

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

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.....

What About Other Cities?

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

Existing Tools for PLHA Approach in Practice

- **WSLiq** ([http://faculty.washington.edu/kramer/WSLiq/WSLiq.htm](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**
2. **Map Liq Hazard at Targeted Return Periods**
3. **Correct for Site-Specific Soil Conditions and Stresses**

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**Liquefaction Reference Parameter Map**

- $\gamma_{sat}=19.62 \text{ kN/m}^3$
- $V_{s,12}=175 \text{ m/s}$
- $N_d=18$
- Saturated Sand FC < 5%

**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).
Simplified PB Liquefaction Triggering

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
Simplified PB Liquefaction Triggering

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 reference map**

\[ CSR^{ref} = \frac{CSR^{ref} \text{ (\%)} }{100} \]
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, $\Delta CSR$

\[
\text{Soil Amplification: } \Delta CSR_{F_{pga}} = \ln \left( F_{pga} \right)
\]

\[
\text{Depth Reduction: } \Delta CSR_{r_l} = \left( -0.6712 - 1.126 \sin \left( \frac{z}{11.73} + 5.133 \right) \right) + M_w \left( 0.0675 + 0.118 \sin \left( \frac{z}{11.28} + 5.142 \right) \right)
\]

\[
\text{Soil Stress: } \Delta CSR_{\sigma} = \ln \left( \frac{\sigma_v}{\sigma_v'} \right)^{\frac{z}{z_{ref}}}
\]

Mean magnitude from PGA deaggregation at target return period

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

Duration: 

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

$$MSF_{max}^{site} = 1.09 + \left( \frac{N_1}{31.5} \right)^2 \leq 2.2$$

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

**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, ΔCSR**

Overburden:

\[
\Delta CSR_{K_\sigma} = -\ln \left( \frac{K_{site}^{K_{\sigma}}}{K_{\sigma}^{K_{ref}}} \right) = -\ln \left( \frac{1 - C_{\sigma}^{site} \ln \left( \frac{\sigma'_v^{site}}{P_a} \right)}{1 - C_{\sigma}^{ref} \ln \left( \frac{\sigma'_v^{ref}}{P_a} \right)} \right)
\]

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

\[
C_{\sigma}^{site} = 0 < \frac{1}{18.9 - 2.55 \left[ 1.237 \left( -\ln \left( CSR^{ref} \right) \right)^4 - 4.918 \left( -\ln \left( CSR^{ref} \right) \right)^3 + 1.762 \left( -\ln \left( CSR^{ref} \right) \right)^2 - 5.473 \left( -\ln \left( CSR^{ref} \right) \right) + 33.65 \right]^{0.5}} \leq 0.3
\]
Step 3: For every soil sublayer in your profile, compute the site-specific CSR corresponding to the targeted return period

Total Correction for layer $i$: \[ \Delta CSR_i = \Delta CSR_{\sigma,i} + \Delta CSR_{F,pga,i} + \Delta CSR_{r,i} + \Delta CSR_{MSF,i} + \Delta CSR_{K,\sigma,i} \]

Site-Specific Probabilistic CSR for layer $i$: \[ \overbrace{CSR_i}^\text{Mapped based on uniform reference layer} = \exp\left[ \ln\left( CSR_{ref} \right) + \Delta CSR_i \right] \]

Correction for site-specific conditions
Simplified PB Liquefaction Triggering

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

Step 4: For each soil sublayer in your profile, characterize liquefaction triggering hazard using whichever metric you prefer

Factor of Safety:

\[
(FS_L)_i = \frac{(CRR)_i}{(CSR)_i} = \exp \left[ \frac{((N_1)_{60,cs})_i}{14.1} + \frac{((N_1)_{60,cs})^2}{126} - \frac{((N_1)_{60,cs})^3}{23.6} + \frac{((N_1)_{60,cs})^4}{25.4} - 2.67 \right]
\]

Probability of Liquefaction:

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

*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, showing Boulanger and Idriss (2012, 2014) model results)
What about lateral spread displacement? A similar simplified performance-based approach was developed using the Youd et al. (2002) lateral spread model. (Ekstrom and Franke 2016)
Newmark seismic slope displacement? Lucy Astorga (GeoEngineers, Tacoma, WA) developed a simplified performance-based approach for Bray and Travasarou (2007) and Rathje and Saygili (2009).
Tools to Perform Simplified PB Liquefaction Hazard Analysis

SPLIQ V1.41, released in February 2019
Tools to Perform Simplified PB Liquefaction Hazard Analysis

Online Liquefaction Reference Parameter Database (currently only for 7 states)
What About Areas of High Seismicity?

“But California isn’t ‘low to moderate seismicity.’ What about us here?”

High seismicity area (San Francisco, CA) predicts more liquefaction (i.e., lower FSL) with performance-based methods than moderate seismicity area (Salt Lake City, UT) and low seismicity area (Butte, MT).

Just like with PSHA and ground motions…..Solution? Cap with a deterministic liquefaction hazard analysis!
Overall Recommended Approach

For a given site, perform a (1) simplified performance-based liquefaction assessment, and a (2) deterministic liquefaction assessment. Use the LESSER HAZARD (i.e., higher $F_{SL}$, lower settlements or displacements) for design.

Abandon use of the pseudo-probabilistic approach!
Example Demonstration – Fort Mill, SC
Example Demonstration – Fort Mill, SC

Free-Face Ratio, $W = 18\%$

• Liquefaction Triggering in Native Soil
• Lateral Spread Displacement in Native Soil
• Seismic Slope Displacement in Abutment Fill
<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Thickness (m)</th>
<th>SPT Resistance, N</th>
<th>Fines (%)</th>
<th>Mean Grain Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean Clay</td>
<td>2</td>
<td>17</td>
<td>87</td>
<td>---</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>1.2</td>
<td>13</td>
<td>17</td>
<td>0.05</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>2.3</td>
<td>10</td>
<td>94</td>
<td>---</td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>0.9</td>
<td>11</td>
<td>65</td>
<td>0.01</td>
</tr>
<tr>
<td>Lean Clay</td>
<td>5</td>
<td>5</td>
<td>98</td>
<td>---</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>1.4</td>
<td>8</td>
<td>34</td>
<td>0.03</td>
</tr>
<tr>
<td>Fat Clay</td>
<td>25+</td>
<td>7</td>
<td>90+</td>
<td>---</td>
</tr>
</tbody>
</table>
Between 0 and 6 inches of predicted post-liquefaction settlement.
Example Demonstration – Fort Mill, SC – RESULTS

Probabilistic Lateral Spread Displacement = 0.0 meters

Newmark Seismic Slope Displacement (Tr = 1,033 years):

Bray and Travasarou (2007)
Rathje and Saygili (2009)
So... What Else Can We Do With Map-Based Analysis?
What About Long, Linear Infrastructure?

Traditionally a nightmare to evaluate for lateral spread hazards, particularly in a probabilistic manner.

- Can pass through multiple seismic environments
- Mapping topography is challenging
- Knowing where to perform geotechnical exploration can be daunting, ESPECIALLY if multiple possible routes are planned
- This type of analysis can take years to perform and review
Step #1: Define a “tolerable” lateral spread displacement for each return period of interest. These are the “limit state displacements,” \( D_h^{\text{limit}} \)

Step #2: Obtain reference displacements, \( \log(D_h)^{\text{ref}} \) from the appropriate reference parameter maps along every possible alignment of the infrastructure

Step #3: Determine the required site parameter \( S^{\text{req}} \) to prevent \( D_h^{\text{limit}} \) from occurring at each return period

Step #4: Identify areas along alignment(s) where \( D_h^{\text{ref}} \) exceeds \( D_h^{\text{limit}} \). These are areas where additional geotechnical explorations may be needed for lateral spread

Step #5: Further eliminate areas of geotechnical exploration through evaluation of mapped geology

Step #6: Engineer areas where \( S^{\text{req}} \) needs to be increased
Step #3: Determining $S_{req}$

\[ \log D_H^{\text{actual}} = \log D_H^{\text{ref}} + \Delta D_H \]

\[ \Delta D_H = \left( L - S^{\text{actual}} \right) - \left( L - S^{\text{ref}} \right) = S^{\text{ref}} - S^{\text{actual}} = 9.044 - S^{\text{actual}} \]

Given $D_H^{\text{limit}}$ at return period of interest:

\[ S_{req} = \log D_H^{\text{ref}} + 9.044 - \log D_H^{\text{limit}} \]

$S_{req}$ represents the minimum site parameter value needed to prevent $D_H^{\text{limit}}$ from occurring. Inadequate $S_{req}$ values at a given location can be increased through ground improvement and/or site grading.
Example Application

Consider a hypothetical proposed linear infrastructure extending from Rock Springs, WY to North Salt Lake, Utah.
Use of EZ-FRISK Software with the simplified performance-based model, assuming $D_H^{\text{limit}} = 0.5 \text{ meter}$ yields the following:

Tr = 2,475 years

Tr = 475 years
We will not worry about locations where $D_H^{\text{ref}} \leq D_H^{\text{limit}}$. However, locations where $D_H^{\text{ref}} > D_H^{\text{limit}}$ will require additional geological filtering and may need additional geotechnical exploration for lateral spread assessment.

Example Application

Limitation for $D_H^{\text{ref}}$ is $\leq 2,475$ years.

Tr = 2,475 years

Limitation for $D_H^{\text{ref}}$ is $> 475$ years.

Tr = 475 years
Can quickly develop reference displacements for the entire alignment
- Took an undergraduate student ≤ 2 hours to analyze all 325km of both pipeline alignments

Can accommodate multiple potential alignments

Site-specific lateral spread estimates can be computed as geotechnical data is collected without additional probabilistic analyses

Use of the procedure with $D_H^{limit}$ allows the engineer to rapidly screen for areas that may need additional site investigation for lateral spread
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; very handy for long, linear projects

• Reference parameter maps and online tools to use them have been developed for Utah, Idaho, Oregon, Montana, Alaska, South Carolina, and Connecticut
Related References


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