Improved Liquefaction Hazard Evaluation through PLHA

Steven L. Kramer
University of Washington
Soil Liquefaction

Three primary questions to answer:

Is the soil susceptible to liquefaction?

If so, is the anticipated loading strong enough to initiate liquefaction?

If so, what will be the effects of liquefaction?

Susceptibility

- Yes: Initiation
  - Yes: Effects
    - Lateral spreading
    - Flow sliding
    - Settlement
  - No: No hazard
- No: No hazard

Initiation

- Yes: Effects
  - Lateral spreading
  - Flow sliding
  - Settlement
- No: No hazard

Effects

- Yes: Lateral spreading
  - Flow sliding
  - Settlement
- No: No hazard

Susceptibility

- Yes: Initiation
  - Yes: Effects
    - Lateral spreading
    - Flow sliding
    - Settlement
  - No: No hazard
- No: No hazard
Three primary questions to answer:

Is the soil susceptible to liquefaction?

If so, is the anticipated loading strong enough to initiate liquefaction?

If so, what will be the effects of liquefaction?

Evaluation of liquefaction potential
Current procedures produce inconsistent liquefaction potential

Inferred damage levels are inconsistent

Inferred loss levels are inconsistent

Inferred risk is inconsistent

Probabilistic performance-based approach can solve this problem

Full-blown probabilistic analyses (PLHA) are time-consuming

Approximate procedures are available

Using mapped parameters, engineers can obtain benefits of fully probabilistic approach using conventional calculations
Evaluation of Liquefaction Potential

Simplified Method

$$FS = \frac{CRR}{CSR} = \frac{\text{Resistance}}{\text{Loading}} = \frac{\text{Capacity}}{\text{Demand}}$$

Youd et al.

Cetin-Seed
Evaluation of Liquefaction Potential

Simplified Method

\[ FS = \frac{CRR}{CSR} \left( \frac{\text{Resistance}}{\text{Loading}} = \frac{\text{Capacity}}{\text{Demand}} \right) \]

Intensity Measure (IM):

- \( PGA \)  \( \leftarrow \) Measure of amplitude of motion
- \( M \)  \( \leftarrow \) Measure of duration (number of loading cycles)
Conventional Evaluation of Liquefaction Potential

1. Determine 475-yr (or 2,475-yr) PGA
   - One PGA

2. Determine corresponding $M_w$ from deaggregation
   - One $M_w$

3. Compute $CSR = 0.65 \frac{PGA}{g} \frac{\sigma_{vo}}{\sigma_v'_{o}} r_d \frac{1}{MSF}$
   - One CSR

4. Based on $(N_1)_{60}$, compute CRR

5. Compute $FS_L = CRR / CSR$

Conventional criterion:

$$FS_{min} = 1.1 - 1.3$$

Probabilistic representation of ground motion hazard is combined with deterministic representation of liquefaction resistance
Football Defense

11 players
Different sizes
Different speeds
Different consequences
Football Defense

Free safety
Small
Really fast
Makes tackles all over field
Football Defense

Middle linebacker
Big
Fast
Makes tackles in middle of field
Defensive tackle

- Huge
- Slow
- Little range, but hits really hard
Different Liquefaction Procedures

- Smaller, more frequent
- Bigger, more rare

Only block one player
proved Liquefaction Procedure

Probabilistic Liquefaction Hazard Analysis (PLHA)

Coupled probabilistic liquefaction potential procedure with PSHA

Return Period of Soil Liquefaction

Steven L. Kramer, M.ASCE1; and Roy T. Mayfield2

Abstract: The paper describes a performance-based approach to the evaluation of liquefaction potential, and shows how it can be used to account for the entire range of potential ground shaking. The result is a direct estimate of the return period of liquefaction, rather than a factor of safety or probability of liquefaction conditional upon ground shaking with some specified return period. As such, the performance-based approach can be considered to produce a more complete and consistent indication of the actual likelihood of liquefaction at a given location than conventional procedures. In this paper, the performance-based procedure is introduced and used to compare likelihoods of the initiation of liquefaction at identical sites located in areas of different seismicity. The results indicate that the likelihood of liquefaction depends on the position and slope of the peak acceleration hazard curve, and on the distribution of earthquake magnitudes contributing to the ground motion hazard. The results also show that the consistent use of conventional procedures for the evaluation of liquefaction potential produces inconsistent actual likelihoods of liquefaction.

DOI: 10.1061/(ASCE)1090-0241(2007)133:7(802)

CE Database subject headings: Earthquakes; Liquefaction; Sand; Penetration tests; Hazards.

Introduction

Liquefaction of soil has been a topic of considerable interest to geotechnical engineers since its devastating effects were widely observed following 1964 earthquakes in Niigata, Japan and
proved Liquefaction Procedure

Probabilistic Liquefaction Hazard Analysis (PLHA)

Coupled probabilistic liquefaction potential procedure with PSHA

Application of PEER PBEE framework

Mean annual rate of non-exceedance of $FS_L^*$

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

Sum over all peak accelerations

Sum over all magnitudes
proved Liquefaction Procedure

Probabilistic Liquefaction Hazard Analysis (PLHA)

Coupled probabilistic liquefaction potential procedure with PSHA

Application of PEER PBEE framework

![Graph showing relationship between log $\Delta_{FS}$ and $T_R$]

- Short $T_R$
  - Weak motions
  - High $F_{SL}$
- Long $T_R$
  - Strong motions
  - Low $F_{SL}$
proved Liquefaction Procedure

Probabilistic Liquefaction Hazard Analysis (PLHA)

Coupled probabilistic liquefaction potential procedure with PSHA

Application of PEER PBEE framework
Performance-Based Liquefaction Evaluation

Illustration of procedure

Idealized soil profile

![Diagram showing clean sand and liquefied soil layers with depth and $(N_1)_{60}$ value.]
Performance-Based Liquefaction Evaluation

Seismic environments

But we also need $M_w$ to evaluate liquefaction potential.
Performance-Based Liquefaction Evaluation

Selection of magnitude

- Multiple magnitudes contribute to PGA at a given return period

Prob. Seismic Hazard Deaggregation
Seattle 122.300° W, 47.530 N.
Peak Horiz. Ground Accel.>=0.3349 g
Mean Return Time 475 years
Mean $\langle R, M, r, \epsilon \rangle$ = 36.0 km, 6.57, 0.56
Modal $\langle R, M, r, \epsilon \rangle$ = 4.0 km, 6.64, -1.28 (from peak R,M bin)
Modal $\langle R, M, r, \epsilon \rangle$ = 4.1 km, 6.63, 0 to 1 sigma (from peak R,M bin)
Binning: DeltaR 10.0 km, deltam=0.2, Delta=1.0
Selection of magnitude

- Multiple magnitudes contribute to PGA at a given return period
- Contributions are different at different return periods
Performance-Based Liquefaction Evaluation

Selection of magnitude

- Multiple magnitudes contribute to PGA at a given return period
- Contributions are different at different return periods
Performance-Based Liquefaction Evaluation

Assume idealized site is located in 10 different U.S. cities

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat. (N)</th>
<th>Long. (W)</th>
<th>475-yr $a_{\text{max}}$</th>
<th>2,475-yr $a_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butte, MT</td>
<td>46.003</td>
<td>112.533</td>
<td>0.120</td>
<td>0.225</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>32.776</td>
<td>79.931</td>
<td>0.189</td>
<td>0.734</td>
</tr>
<tr>
<td>Eureka, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memphis, TN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland, OR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Lake City, UT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Jose, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Monica, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seattle, WA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Performance-Based Liquefaction Evaluation

Deterministic analysis – using mean magnitudes

Higher $PGA_{475}$ leads to:
- Lower $FS_L$
- Higher $N_{req}$
Performance-Based Liquefaction Evaluation

Performance-based analysis

Hazard curves for $FS_L$, $N_{req}$ for element at 6 m depth

(a) $FS_L$

(b) $N_{req}$
Performance-Based Liquefaction Evaluation

Performance-based analysis

Hazard curves for $FS_L$, $N_{req}$ for element at 6 m depth
Performance-Based Liquefaction Evaluation

Performance-based analysis

Hazard curves for $FS_L$, $N_{req}$ for element at 6 m depth
Performance-Based Liquefaction Evaluation

Performance-based analysis

Hazard curves for $F_{S_L}$, $N_{req}$ for element at 6 m depth
Performance-Based Liquefaction Evaluation

Performance-based analysis

To compute deterministic \( N_{\text{req}} \) values associated with conventional criterion for adequate liquefaction resistance (\( FS_L > 1.2 \) using \( PGA_{475} \) and mean magnitude)

Then we use liquefaction hazard curves for \( N_{\text{req}} \) to compute return period for liquefaction (\( N < N_{\text{req}} \))

Level of agreement will provide insight into consistency of liquefaction hazards as evaluated using conventional approach
Performance-Based Liquefaction Evaluation

Performance-based analysis

- Compute deterministic \( N_{\text{req}} \) values associated with conventional criterion for adequate liquefaction resistance \((F_{S_L} > 1.2)\) using \( PGA_{475} \) and mean magnitude.
- Then use liquefaction hazard curves for \( N_{\text{req}} \) to compute return period for liquefaction \((N < N_{\text{req}})\).
- Level of agreement will provide insight into consistency of liquefaction hazards as evaluated using conventional approach.

Consistent application of conventional procedures for evaluation of liquefaction.
Performance-Based Liquefaction Evaluation

Assume idealized site is located in 10 different U.S. cities

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat. (N)</th>
<th>Long. (W)</th>
<th>475-yr $a_{max}$</th>
<th>2,475-yr $a_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butte, MT</td>
<td>46.003</td>
<td>112.533</td>
<td>0.120</td>
<td>0.225</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>32.776</td>
<td>79.931</td>
<td>0.189</td>
<td>0.734</td>
</tr>
<tr>
<td>Eureka, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Memphis, TN</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Portland, OR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Lake City, UT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Francisco, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>San Jose, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santa Monica, CA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seattle, WA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph](image-url)
Performance-Based Liquefaction Evaluation

Assume idealized site is located in 10 different U.S. cities

Deterministic analysis – using mean magnitudes
In this chapter, we present a performance-based liquefaction evaluation approach. The method is designed to compute deterministic $N_{\text{req}}$ values associated with conventional criterion for adequate liquefaction resistance ($F_{S_L} > 1.2$) using $PGA_{475}$ and mean magnitude. We then use liquefaction hazard curves for $N_{\text{req}}$ to compute return periods for liquefaction ($N < N_{\text{req}}$). The level of agreement will provide insight into consistency of liquefaction hazards as evaluated using conventional approach. The consistent application of conventional procedures for evaluation of liquefaction
Performance-Based Liquefaction Evaluation

Relative factors of safety

<table>
<thead>
<tr>
<th>Location</th>
<th>$N_{\text{req}}^{\text{det}}$</th>
<th>$N_{\text{req}}^{PB}$</th>
<th>$\frac{CRR(N_{\text{req}}^{\text{det}})}{CRR(N_{\text{req}}^{PB})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butte, MT</td>
<td>6.6</td>
<td>7.3</td>
<td>0.95</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>15.9</td>
<td>12.1</td>
<td>1.32</td>
</tr>
<tr>
<td>Eureka, CA</td>
<td>34.9</td>
<td>34.8</td>
<td>1.01</td>
</tr>
<tr>
<td>Memphis, TN</td>
<td>19.4</td>
<td>15.7</td>
<td>1.31</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>17.9</td>
<td>18.8</td>
<td>0.94</td>
</tr>
<tr>
<td>Salt Lk. City, UT</td>
<td>22.5</td>
<td>21.1</td>
<td>1.11</td>
</tr>
<tr>
<td>San Fran., CA</td>
<td>31.8</td>
<td>31.5</td>
<td>1.02</td>
</tr>
<tr>
<td>San Jose, CA</td>
<td>28.3</td>
<td>29.6</td>
<td>0.91</td>
</tr>
<tr>
<td>Santa Mon., CA</td>
<td>27.3</td>
<td>27.5</td>
<td>0.99</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>23.5</td>
<td>24.2</td>
<td>0.95</td>
</tr>
</tbody>
</table>
## Performance-Based Liquefaction Evaluation

Relative factors of safety

< 1.0 = unconservative  
> 1.0 = conservative

<table>
<thead>
<tr>
<th>Location</th>
<th>$N^\text{det}_{\text{req}}$</th>
<th>$N^\text{PB}_{\text{req}}$</th>
<th>$\frac{CRR(N^\text{det}<em>{\text{req}})}{CRR(N^\text{PB}</em>{\text{req}})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butte, MT</td>
<td>6.6</td>
<td>7.3</td>
<td>0.95</td>
</tr>
<tr>
<td>Charleston, SC</td>
<td>15.9</td>
<td>12.1</td>
<td>1.32</td>
</tr>
<tr>
<td>Eureka, CA</td>
<td>34.9</td>
<td>34.8</td>
<td>1.01</td>
</tr>
<tr>
<td>Memphis, TN</td>
<td>19.4</td>
<td>15.7</td>
<td>1.31</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>17.9</td>
<td>18.8</td>
<td>0.94</td>
</tr>
<tr>
<td>Salt Lk. City, UT</td>
<td>22.5</td>
<td>21.1</td>
<td>1.11</td>
</tr>
<tr>
<td>San Fran., CA</td>
<td>31.8</td>
<td>31.5</td>
<td>1.02</td>
</tr>
<tr>
<td>San Jose, CA</td>
<td>28.3</td>
<td>29.6</td>
<td>0.91</td>
</tr>
<tr>
<td>Santa Mon., CA</td>
<td>27.3</td>
<td>27.5</td>
<td>0.99</td>
</tr>
<tr>
<td>Seattle, WA</td>
<td>23.5</td>
<td>24.2</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Relative $FS$ in Charleston is 45% higher than in San Jose
Performance-Based Liquefaction Evaluation

Relative factors of safety

These are big differences

Geotechs spend a lot of time tweaking various components

- Magnitude scaling factor, MSF
- Depth reduction factor, $r_d$
- Overburden stress factor, $K_\sigma$
- Fines content correction

Effects of tweaks have much smaller effect than those shown here
So what can we do to improve consistency?

Base liquefaction criteria on return period of liquefaction

Consistent return period will lead to consistent probability of liquefaction

Can handle liquefaction potential in different ways
Performance-Based Liquefaction Evaluation

So what can we do to improve consistency?

Base liquefaction criteria on return period

Consistent return period will lead to consistent probability of liquefaction

Can be expressed in terms of $N_{\text{req}}$ for a specified return period

Simulations performed on a cross state (247 pts)
At each point, PB calcs ordered 100 PGA levels of 10 magnitudes of 247 deterministic 94,000 probabilistic
Performance-Based Liquefaction Evaluation

Contours of $N_{\text{req}}$ for $FS_L = 1.2$ in 6-m-deep element based on conventional analysis with 475-yr PGA and mean $M_w$

$N_{\text{req}} \sim 22$ for Seattle
Performance-Based Liquefaction Evaluation

Contours of $N_{req}$ for $FS_L = 1.2$ in 6-m-deep element based on conventional analysis with 475-yr PGA and mean $M_w$

$N_{req} \approx 22$ for Seattle
From $N_{req}$ hazard curve, corresponding return period is 400 yrs.
Performance-Based Liquefaction Evaluation

Contours of $N_{req}$ for $FS_L = 1.2$ in 6-m-deep element based on conventional analysis with 475-yr $PGA$ and mean $M_w$

$N_{req} \sim 22$ for Seattle

From $N_{req}$ hazard curve, corresponding return period is 400 yrs

To obtain uniform hazard across state, use hazard curves to determine 400-yr $N_{req}$ values everywhere
Performance-Based Liquefaction Evaluation

Contours of $N_{\text{req}}$ based on performance-based analysis with 400-yr return period

$N_{\text{req}} \approx 22$ for Seattle
Performance-Based Liquefaction Evaluation

Contours of $N_{\text{req}}$ based on performance-based analysis with 400-yr return period

$N_{\text{req}} \approx 22$ for Seattle

$N_{\text{req}}$ values east of Seattle are very nearly the same as deterministic values.
Contours of $N_{\text{req}}$ based on performance-based analysis with 400-yr return period

- $N_{\text{req}} \approx 22$ for Seattle
- $N_{\text{req}}$ values east of Seattle are very nearly the same as deterministic values
- $N_{\text{req}}$ values west of Seattle are lower
Performance-Based Liquefaction Evaluation

Contours of difference in $N_{\text{req}}$ for conventional and performance-based analyses
Performance-Based Liquefaction Evaluation

Contours of relative factor of safety inherent in use of conventional analyses

Coastal sites are effectively being required to design for 40% - 50% higher $FS$ than required to obtain same hazard as Seattle.
Performance-Based Liquefaction Evaluation

Contours of relative factor of safety inherent in use of conventional analyses

Coastal sites are effectively being required to design for 40% - 50% higher FS than required to obtain same hazard as Seattle.

Risk-consistent design using conventional analyses should use
Performance-Based Liquefaction Evaluation

Contours of $N_{req}$ based on performance-based analysis with 400-yr return period

Results correspond to 6 m deep element in reference profile. How can they be used for different depths in different profiles, i.e., for site-specific liquefaction hazard evaluations?
Performance-Based Liquefaction Evaluation

Site-specific correction

Cetin equation

$$CRR = \exp \left[ \frac{N_{1,60}(1 + 0.004 FC) - 29.53 \ln M_w - 3.70 \ln \left( \frac{\sigma'_{vo}}{p_a} \right) + 0.05 FC - 16.85 + \beta \cdot \Phi^{-1}(P_L)}{13.32} \right]$$

Letting

we can write

$$N_{1,60,cs} = 13.32 \ln CSR + 29.53 \ln M_w + 3.70 \ln \left( \frac{\sigma'_{vo}}{p_a} \right) - 16.85 - \beta \cdot \Phi^{-1}(P_L)$$

Substituting for CSR and using $$P_L = 0.6$$ (equivalent to standard curve)

$$N_{1,60,cs} = 13.32 \ln \left( 0.65 \frac{a_{max}}{g} \frac{\sigma_{vo}}{\sigma'_{vo}} r_d \right) + 29.53 \ln M_w + 3.70 \ln \left( \frac{\sigma'_{vo}}{p_a} \right) - 16.85 - 0.253 \beta$$
Performance-Based Liquefaction Evaluation

Site-specific correction

Defining these terms for a reference site condition,

\[ N_{1,60,cs,\text{ref}} = 13.32 \ln \left( 0.65 \frac{a_{\text{max}}}{g} \left( \frac{\sigma_{vo}}{\sigma'_{vo}} \right)_{\text{ref}} (r_d)_{\text{ref}} \right) + 29.53 \ln M_w + 3.70 \ln \left( \frac{\sigma'_{vo}}{p_a} \right)_{\text{ref}} - 16.85 - 0.253 \beta \]

Then the site-specific required penetration resistance can be defined as

\[ N_{1,60,cs,\text{req}} = N_{1,60,cs,\text{ref}} + \Delta N \]

So \[ \Delta N = N_{1,60,cs,\text{req}} - N_{1,60,cs,\text{ref}} \]

\[ = 13.32 \ln \left( 0.65 \frac{a_{\text{max}}}{g} \left( \frac{\sigma_{vo}}{\sigma'_{vo}} \right) \left( r_d \right) \right) + 29.53 \ln M_w + 3.70 \ln \left( \frac{\sigma'_{vo}}{p_a} \right)_{\text{ref}} - 16.85 - 0.253 \beta \]

**Initial stress-related terms**

**Response-related term**

**Site- and profile-specific blowcount adjustment**
Performance-Based Liquefaction Evaluation

Then

$$\Delta N = \Delta N_\sigma + \Delta N_{rd} = 13.32 \ln \left[ \frac{\sigma_{vo}}{(\sigma_{vo})_{ref}} \right] + 3.70 \ln \left[ \frac{\sigma'_{vo}}{(\sigma'_{vo})_{ref}} \right] + 13.32 \ln \left[ \frac{r_d}{(r_d)_{ref}} \right]$$

Function of:
- density
- groundwater level
- depth

Function of:
- depth
- shear wave velocity
- peak acceleration
- earthquake magnitude
Performance-Based Liquefaction Evaluation

Then

$$\Delta N = \frac{13.32 \ln \left( \frac{\sigma_{vo} \sigma_{vo}}{\sigma_{vo} \sigma_{vo}} \right)_{ref} + 3.70 \ln \left( \frac{\sigma_{vo} \sigma_{vo}}{\sigma_{vo} \sigma_{vo}} \right)_{ref} + 13.32 \ln \left( \frac{r_d}{r_d} \right)_{ref}}{\Delta N}$$

Function of:
- density
- groundwater level
- depth

Function of:
- depth
- shear wave velocity
- peak acceleration
- earthquake magnitude
Performance-Based Liquefaction Evaluation

Correction of stress-related terms
Performance-Based Liquefaction Evaluation

Correction of $r_d$-related terms

\[ \Delta N_{r_d} \text{ (blows/ft)} \]

\[ V_{s,12} \text{ (m/sec)} \]

Depth, $z$ (m)
Performance-Based Liquefaction Evaluation

Comparison of $N_{\text{req}}$ values – chart-based approximate procedure vs. full PB analysis
Performance-Based Liquefaction Evaluation

Comparison of $N_{\text{req}}$ values – chart-based approximate procedure vs. full PB analysis
Performance-Based Liquefaction Evaluation

Comparison of $N_{\text{req}}$ values – chart-based approximate procedure vs. full PB analysis

Example, chart-based adjustment procedure appears to be useful.
Performance-Based Liquefaction Evaluation

Comparison of $N_{\text{req}}$ values – chart-based approximate procedure vs. full PB analysis

Example, chart-based adjustment procedure appears to be useful benefits of performance-based calculations embodied in mapped $N_{\text{req}}$ value for reference element in reference profile.
Performance-Based Liquefaction Evaluation

Comparison of $N_{\text{req}}$ values – chart-based approximate procedure vs. full PB analysis

Example, chart-based adjustment procedure is useful – agrees with full PLHA

Benefits of performance-based calculations embodied in mapped $N_{\text{req}}$ value for reference element in reference profile.

Accounts for site-specific conditions through adjustment procedure.
Performance-Based Liquefaction Evaluation

Can map $N_{req}$ values for reference element in reference soil profile.
Performance-Based Liquefaction Evaluation

Alternative approaches

Map reference CSR value – for given return period

Use CSR-based adjustments
Performance-Based Liquefaction Evaluation

Alternative approaches

Map reference CSR value – for given return period
Use CSR-based adjustments

Approximated $N_{req}$ vs. Site-specific $N_{req}$

- $Tr=1,033$ yrs: $y = 0.9626x$, $R^2 = 0.9777$
- $Tr=475$ yrs: $y = 0.9676x$, $R^2 = 0.9832$
- $Tr=2,475$ yrs: $y = 0.9591x$, $R^2 = 0.9693$
Performance-Based Liquefaction Evaluation

Alternative approaches

Map reference CSR value – for given return period
Use CSR-based adjustments

\[ T_R = 475 \text{ yrs} \]
Performance-Based Liquefaction Evaluation

Alternative approaches

- Map reference CSR value — for given return period
- Use CSR-based adjustments

\[ T_R = 1,033 \text{ yrs} \]
Performance-Based Liquefaction Evaluation

Alternative approaches

Map reference CSR value – for given return period

Use CSR-based adjustments

$T_R = 2,475 \text{ yrs}$
Performance-Based Liquefaction Evaluation

Alternative approaches

Map magnitude-corrected PGA value

\[ CSR = 0.65 \frac{PGA}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot \frac{r_d}{MSF} \]

\[ = 0.65 \frac{PGA}{MSF} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \]

\[ = 0.65 PGA_M \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \]

\[ PGA_M = \frac{PGA}{MSF} \]

Could create program to run USGS PSHA analysis, extract hazard curve and deaggregation data, and compute PGA\(_M\) at different return periods. Program could be used to create PGA\(_M\) maps or could be made
Performance-Based Liquefaction Evaluation

Result:

User goes to map or website, computes $\text{PGA}_M$ for return period of interest

User computes liquefaction potential ($F_{SL}$) in same way he/she does now

Issues:

Requires selection of liquefaction potential "model(s)"

In short term (next 5 yrs), Idriss and Boulanger procedure most common

In longer term, NGL relationships will be available

Multiple relationships by different modelers

Epistemic uncertainty characterized
Performance-Based Liquefaction Evaluation

Benefits:

• More complete evaluation of liquefaction potential
  ▪ Considers all levels of shaking
    ✓ All PGAs
    ✓ All magnitudes

• Provides consistent actual liquefaction hazards at sites in different seismo-tectonic environments
  ▪ Equal hazards across U.S.
  ▪ Equal retrofit / soil improvement requirements across U.S.

• Would allow realization of full benefits of NGL models