Simplified Performance-Based Assessment of Liquefaction Triggering

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Liquefaction Hazard

- Liquefaction can result in significant damage to infrastructure during earthquakes
- Such damage was observed following the 1964 Niigata earthquake, as shown in these images

Image: Karl V. Steinbrugge Collection, EERC, Univ of California, Berkeley

Existing Liquefaction Analysis Methods

- Since 1970's several liquefaction analysis methods have been developed
  - Laboratory and Field Methods
  - Numerical Methods
  - Empirical Methods
- Simplified Empirical Methods:
  - Seed and Idriss (1971) was first
  - Youd et al. (2001) (NCEER)
  - Cetin et al. (2004)
  - Idriss and Boulanger (2006, 2008,2014)

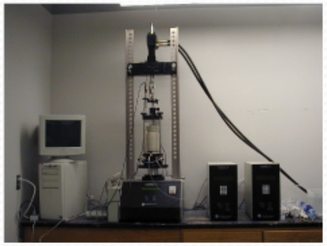
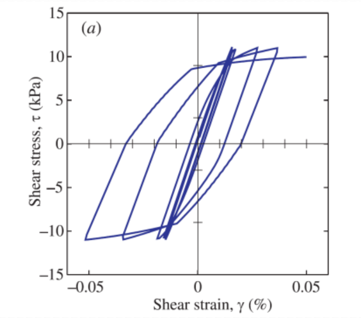
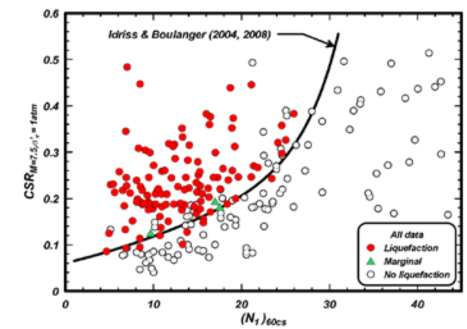


Image: Drexel University CE Facilities webpage
http://www.cae.drexel.edu/facilities.asp



After Byrne et al. (2004)

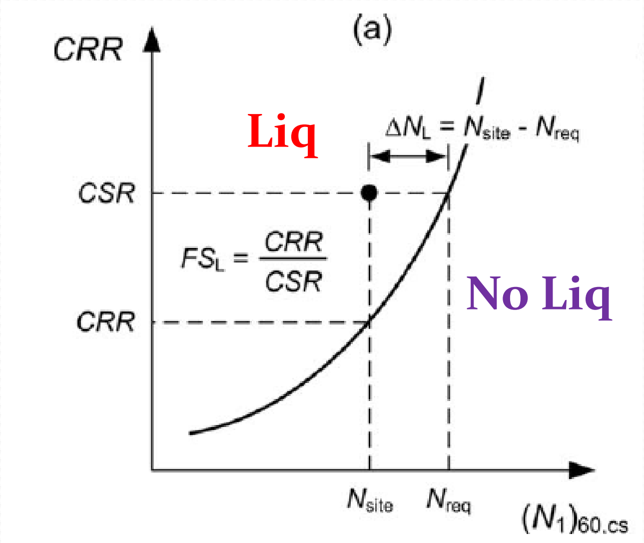


After Idriss and Boulanger (2010)

Overview of Simplified Empirical Method

- Liquefaction is usually evaluated with a factor of safety, FS_L

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



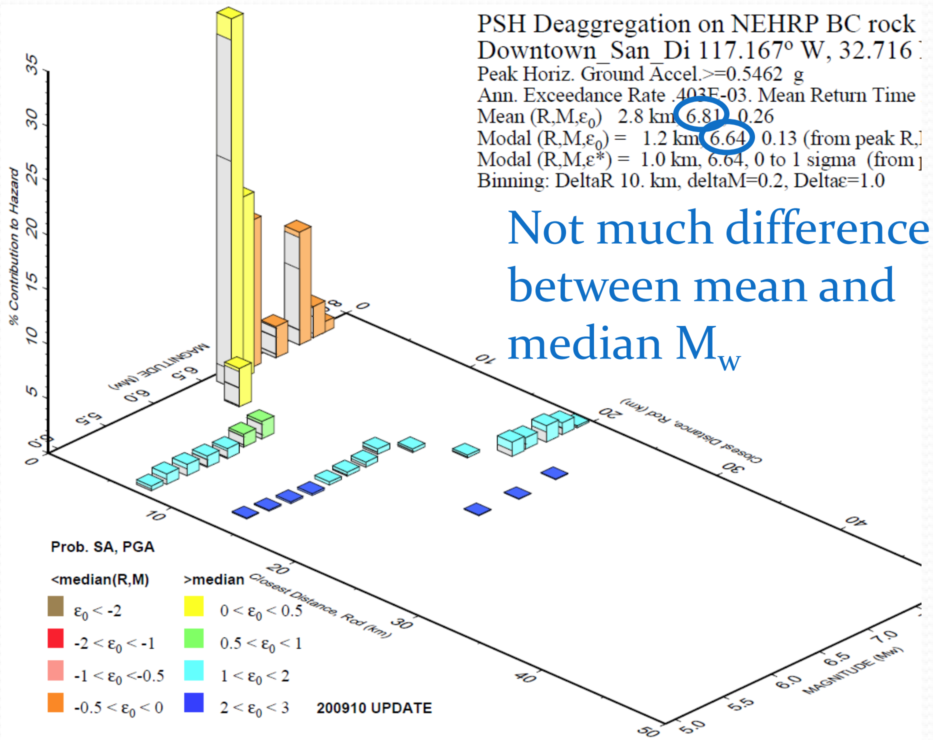
(after Mayfield et al. 2010)

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

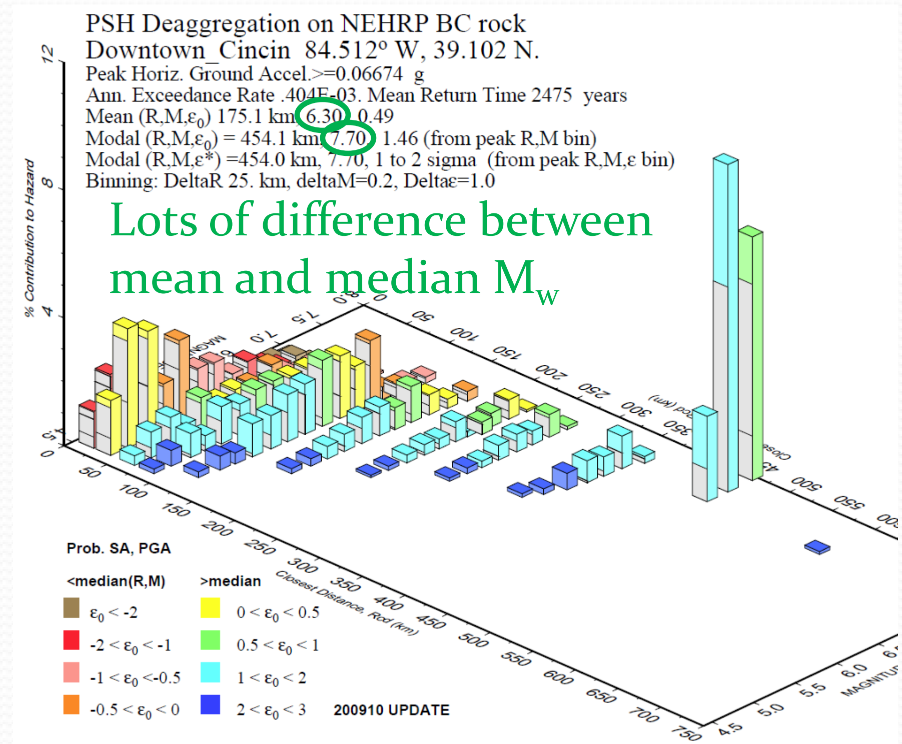
How do we get a_{max} and M_w?

- Deaggregation Analysis

Downtown San Diego



Downtown Cincinnati



Conventional (i.e., "pseudoprobabilistic") 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 median 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_{max}
4. Couple a_{max} with the mean or median M_w to perform a *deterministic* liquefaction triggering analysis
5. Typically define liquefaction triggering as P_L=15% and FS_L=1.2-1.3

Deficiencies of the Pseudoprobabilistic Approach

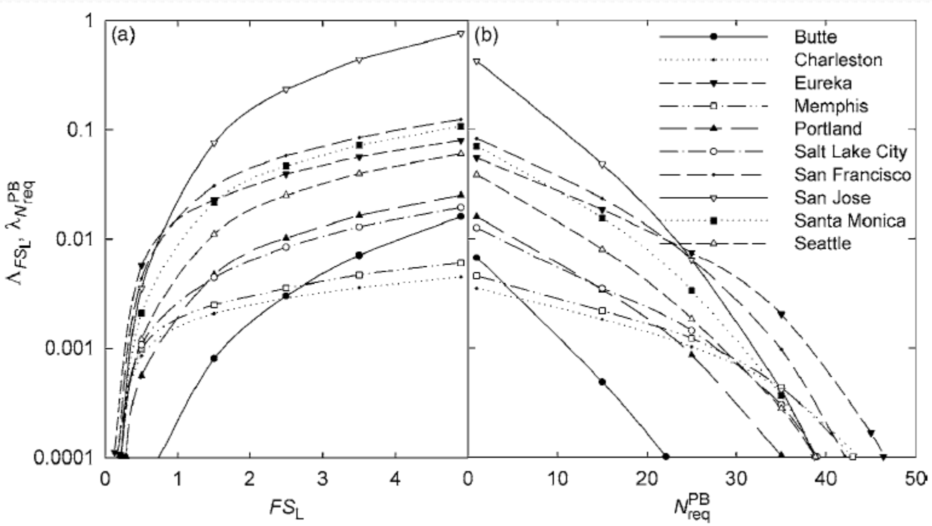
- If using PSHA to define seismic hazard, can be difficult to select the "appropriate" PGA and M_w to use
- PGA and M_w typically are taken from a single return period, but other return periods are ignored
- Does not rigorously account for uncertainty in the liquefaction triggering model
- Contributes to inaccurate interpretations of liquefaction hazard

Performance-Based Liquefaction Assessment – A Uniform Hazard Approach

- Kramer and Mayfield (2007) introduced a performance-based 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

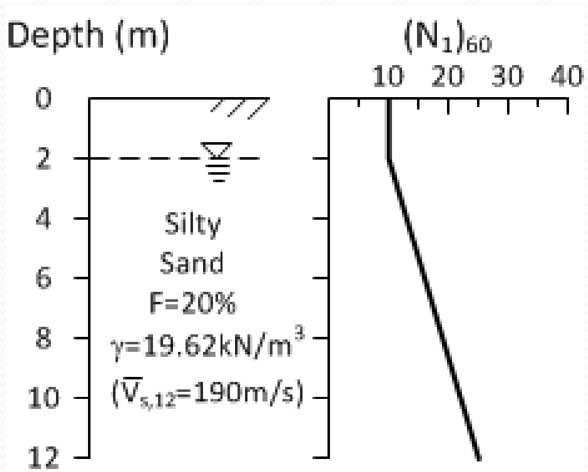
$$\Lambda_{FS_L} = \sum_{j=1}^{N_M} \sum_{i=1}^{N_{a_{max}}} P\left[FS_L < FS_L^* \mid a_{\max_i}, m_j\right] \Delta\lambda_{a_{\max_i}, m_j}$$

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

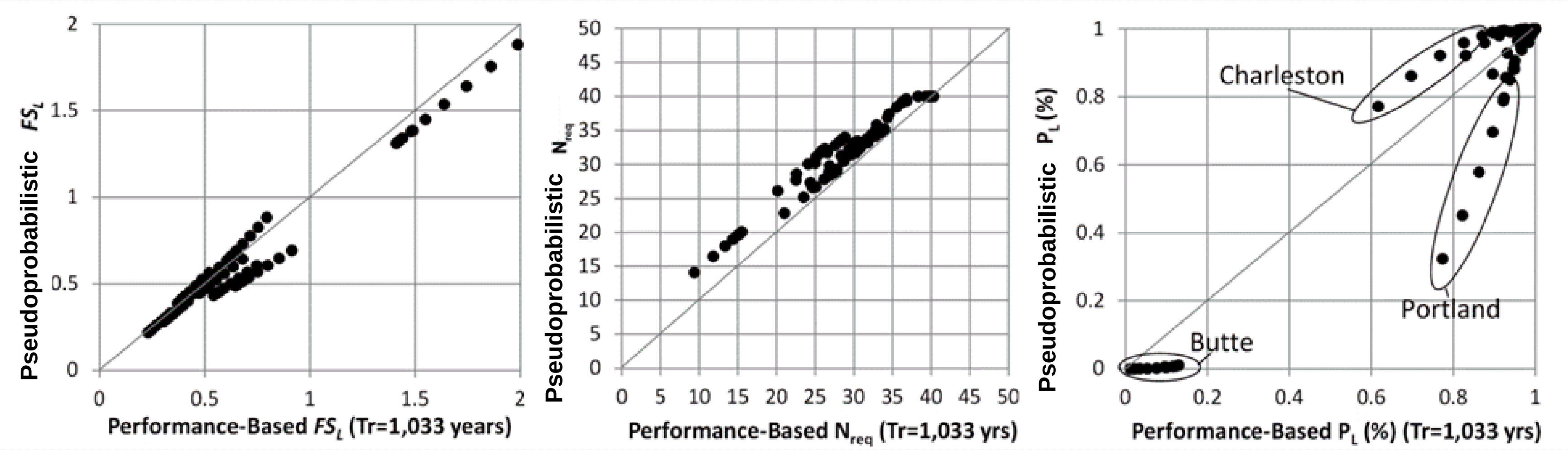


Comparison Between Pseudoprobabilistic and Performance-based Procedures

- Using a generic soil profile, liquefaction potential evaluated in 10 different cities across the US
- Targeted hazard level from PB model is 7% probability of exceedance in 75 years (T_R = 1,033 years)



Comparison Between Pseudoprobabilistic and Performance-based Procedures



after Franke et al. (2014). Plots based on the Cetin et al. (2004) model, but similar trends would occur with any of the current probabilistic triggering models

Conclusion for the pseudoprobabilistic approach: "The liquefaction triggering hazard is rarely equal to the hazard associated with the input ground motions."

So Here is What We Know……

- Pseudoprobabilistic approaches are biased and inconsistent
- Selection of "appropriate" ground motion parameters can be difficult
- Performance-based implementation of existing liquefaction triggering models can solve these problems

But Here are the Problems……

- Few engineers have the tools or training to implement performance-based models in everyday practice
- Which return period should be used for liquefaction analysis?

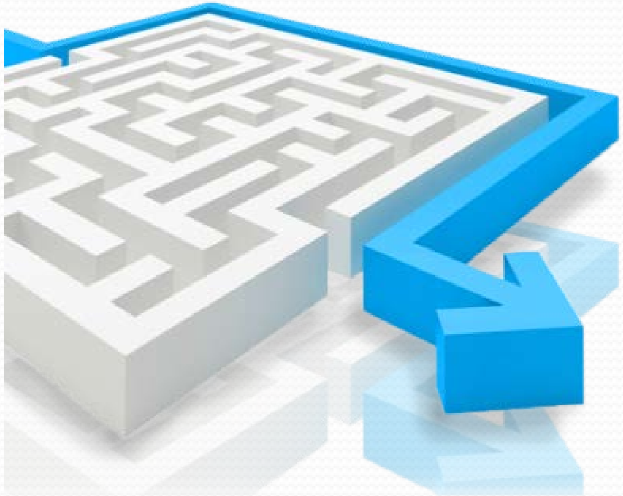
Existing Tools for Performance-Based Liquefaction Triggering Assessment

- 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
  - Developed only for use in Washington State with 2002 USGS ground motion data, but you can "trick" the program for other locations
  - Only utilizes the Cetin et al. (2004) model and offers little control over the analysis uncertainties

- PBLiquefY beta (http://ceen.et.byu.edu/content/kevin-franke)
  - Developed by BYU in 2013 using Microsoft Excel and VBA
  - Currently only assesses liquefaction triggering
  - Compatible with USGS 1996, 2002, or 2008 ground motions. Offers an auto-download feature for these ground motions
  - Can be used for any site in the U.S.
  - Can analyze multiple probabilistic liquefaction triggering models
  - Offers lots of control over the analysis uncertainties, including site amplification factors

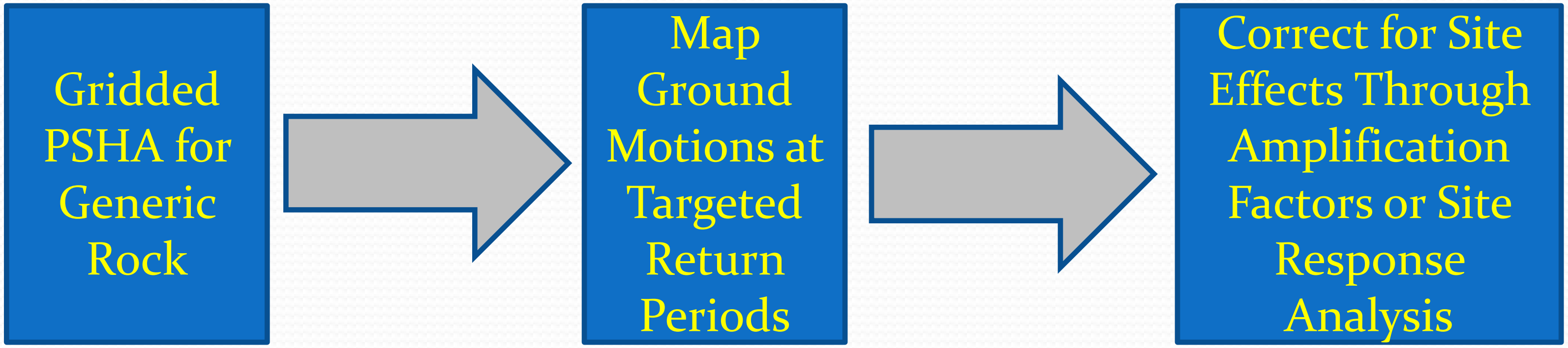
Simplified Uniform Hazard Liquefaction Procedure

- Despite its advantages, the performance-based procedure is currently uncommon for most engineers to perform
- Mayfield et al. (2010) presented a simplified map-based procedure for N_{req} and FS_L that targets a single hazard level of interest
- This procedure mimics the approach we use with PSHA to produce site-specific hazard-targeted liquefaction triggering results



Simplified Uniform Hazard Liquefaction Procedure

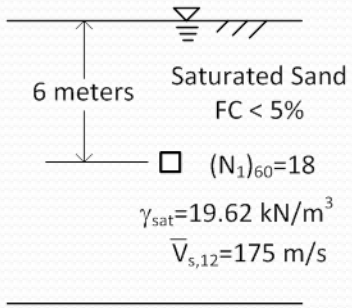
Many of us understand how the USGS NSHMP uses PSHA to develop the National Seismic Hazard Maps……



Simplified Uniform Hazard Liquefaction Procedure

Mayfield et al. (2010) presented a similar idea for liquefaction triggering….

Gridded PB Analysis for Generic Soil Layer → Map Liq Hazard at Targeted Return Periods → Correct for Site-Specific Soil Conditions and Stresses



Liquefaction Parameter Map

DIFFERENT FROM a Liquefaction Hazard Map

Depth Reduction

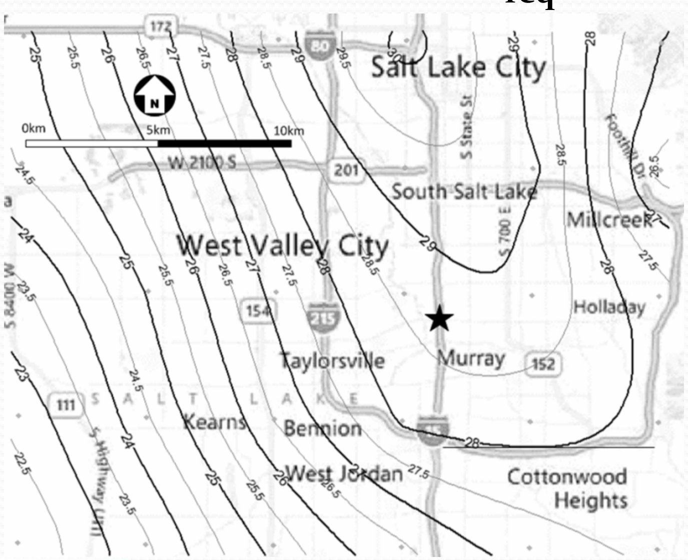
Soil Stresses

Site Amplification

Cetin et al. (2004) Simplified Model

Franke et al. (2014) updated the Mayfield et al. (2010) simplified procedure for the Cetin et al. (2004) probabilistic model.

Step 1: Obtain the reference N_{req} from the appropriate liquefaction parameter map



$$\rightarrow \quad N_{req}^{ref}$$

Cetin et al. (2004) Simplified Model

Franke et al. (2014) updated the Mayfield et al. (2010) simplified procedure for the Cetin et al. (2004) probabilistic model.

Step 2: For every soil sublayer in your profile, compute the appropriate N_{req} correction factors, ΔN

Site Amplification: $\Delta N_F = 13.79 \cdot \ln\left(F_{pga}\right)$

Depth Reduction:

$$\Delta N_{r_d} = 13.79 \cdot \left[\ln\left(\frac{\dfrac{-1.412 + 0.0525\overline{V}_{s,12} + 2.671\exp\left(0.0268\overline{V}_{s,12} - 0.341z\right)}{-1.412 + 0.0525\overline{V}_{s,12} + 2.671\exp\left(0.0268\overline{V}_{s,12}\right)}}{\dfrac{14.079 + 2.313\exp\left(0.0268\overline{V}_{s,12} - 0.341z\right)}{16.258 + 2.671\exp\left(0.0268\overline{V}_{s,12}\right)}} \right) \right]$$

Soil Stress:

$$\Delta N_\sigma = 13.79 \cdot \ln\left[\frac{1 - 0.2 z_w/z}{1 + 0.6 z_w/z}\right] + 3.82 \cdot \ln\left[\frac{z}{6}\left(1 + 0.6 z_w/z\right)\right]$$

z, z_w in meters
$V_{s,12}$ in m/sec

Cetin et al. (2004) Simplified Model

Franke et al. (2014) updated the Mayfield et al. (2010) simplified procedure for the Cetin et al. (2004) probabilistic model.

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

Total Correction: $\Delta N_{req} = \Delta N_{\sigma} + \Delta N_{F} + \Delta N_{r_d}$

Site Specific N_{req}: $N_{req}^{site} = N_{req}^{ref} + \Delta N_{req}$

N_{req}^{site} represents the amount of clean-sand SPT resistance that a particular soil sublayer needs to resist liquefaction triggering at a targeted return period.

Cetin et al. (2004) Simplified Model

Franke et al. (2014) updated the Mayfield et al. (2010) simplified procedure for the Cetin et al. (2004) probabilistic model.

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

Factor of Safety:

$$FS_L = \exp\left[\frac{(N_1)_{60,cs} - N_{req}^{site}}{13.79}\right]$$

Probability of Liquefaction:

$$P_L = \Phi\left[-\frac{(N_1)_{60,cs} - N_{req}^{site}}{4.21}\right]$$

*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 Cetin et al. (2004) procedure.

Boulanger and Idriss (2012, 2014) Simplified Model

Research is underway at BYU to develop a simplified procedure for the Boulanger and Idriss (2012, 2014) probabilistic triggering model. However, we are incorporating a few changes from the Mayfield et al. (2010) and Franke et al. (2014) procedures:

- 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

Boulanger and Idriss (2012, 2014) Simplified Model

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):

$$CSR = CRR\left(N_{req}\right) \qquad \text{(eqn 1)}$$

From Boulanger and Idriss (2012, 2014):

$$CRR = \exp\left[\left(\frac{(N_1)_{60,cs}}{14.1}\right) + \left(\frac{(N_1)_{60,cs}}{126}\right)^2 - \left(\frac{(N_1)_{60,cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60,cs}}{25.4}\right)^4 - 2.67 + \sigma \cdot \Phi^{-1}\left[P_L\right]\right]$$

$$CRR_{P_L=50\%} = \widehat{CRR} = \exp\left[\left(\frac{(N_1)_{60,cs}}{14.1}\right) + \left(\frac{(N_1)_{60,cs}}{126}\right)^2 - \left(\frac{(N_1)_{60,cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60,cs}}{25.4}\right)^4 - 2.67\right] \qquad \text{(eqn 2)}$$

Boulanger and Idriss (2012, 2014) Simplified Model

By combing Eqn 1 with Eqn 3, we obtain:

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

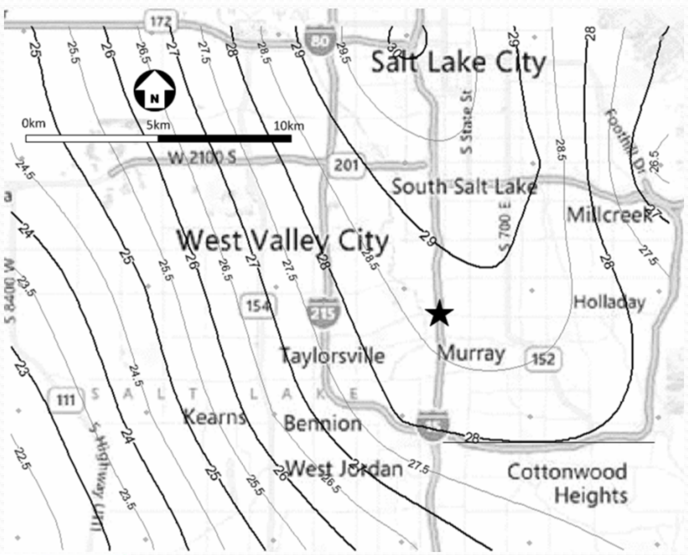
So instead of developing liquefaction parameter maps for a reference N_{req}, we can develop reference maps for the median CSR to characterize seismic loading. Engineers seem much more comfortable characterizing seismic loading with CSR than they do with N_{req}.

We have called these new maps **Liquefaction Loading Maps** to distinguish them from liquefaction parameter maps.

Boulanger and Idriss (2014) Simplified Model

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

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



$$CSR^{ref} = CSR^{ref}(\%) \cdot 100$$

Boulanger and Idriss (2014) Simplified Model

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

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

Mean magnitude from PGA deaggregation

Site Amplification: $\Delta CSR_{F_{pga}} = \ln\left(F_{pga}\right)$

Depth Reduction: $\Delta CSR_{r_d} = \left(-0.6712 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right)\right) + \overline{M_w}\left(0.0675 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right)\right)$

Duration: $$\Delta CSR_{MSF} = -\ln\left[\frac{1 + \left(0.09 + MIN\begin{cases}\left(\frac{(N_1)_{60,cs}}{31.5}\right)^2 \\ 1.2\end{cases}\right)\cdot\left(8.64\exp\left(\frac{-\overline{M_w}}{4}\right) - 1.325\right)}{3.603\exp\left(\frac{-\overline{M_w}}{4}\right) + 0.447}\right]$$

(z in meters)

Boulanger and Idriss (2014) Simplified Model

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

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

Soil Stress:

$$\Delta CSR_{\sigma} = \ln\left[\frac{\left(\sigma_v / \sigma_v'\right)^{sie}}{2}\right]$$

Overburden:

$$\Delta CSR_{K_{\sigma}} = -\ln\left(\frac{1 - \left(MIN\begin{cases}0.3 \\ \dfrac{1}{18.9 - 2.55\sqrt{\left(N_1\right)_{60,cs}}}\end{cases}\right) \cdot \ln\left(\dfrac{\sigma_v'}{p_a}\right)}{1.0682}\right)$$

Boulanger and Idriss (2014) Simplified Model

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

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

Total Correction: $\Delta CSR = \Delta CSR_{\sigma} + \Delta CSR_{F_{pga}} + \Delta CSR_{r_d} + \Delta CSR_{MSF} + \Delta CSR_{K_{\sigma}}$

Site Specific CSR: $\ln\left(CSR^{site}\right) = \ln\left(CSR^{ref}\right) + \Delta CSR$

CSR^{site} represents the level of seismic loading for liquefaction at the targeted return period for each sublayer in the soil profile.

Boulanger and Idriss (2014) Simplified Model

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

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

Factor of Safety:

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

Probability of Liquefaction:

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

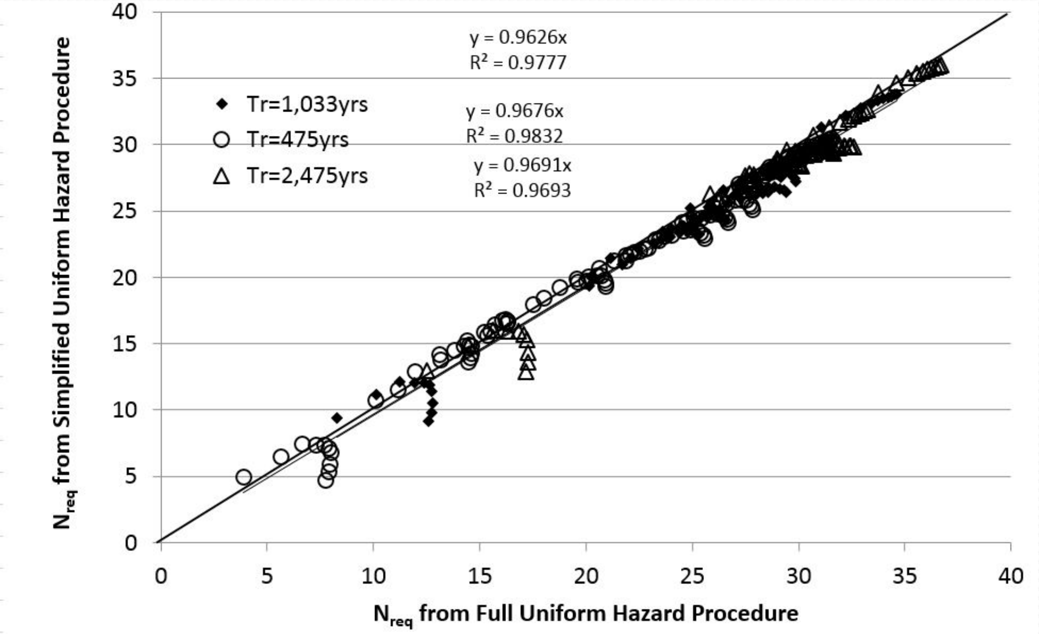
*Note that these equations account for both parametric uncertainty (e.g., $(N_1)_{60,cs}$) and model uncertainty, and are only to be used with the Boulanger and Idriss (2014) procedure.

Boulanger and Idriss (2014) Simplified Model

The simplified model correlates quite well with the full performance-based model. Analysis was performed with the same 10 cities at return periods of 475, 1033, and 2475 years:

$R^2 = 0.97$

(was R^2=0.99 with 2012 model, but some bias was introduced with the new 2014 MSF update)



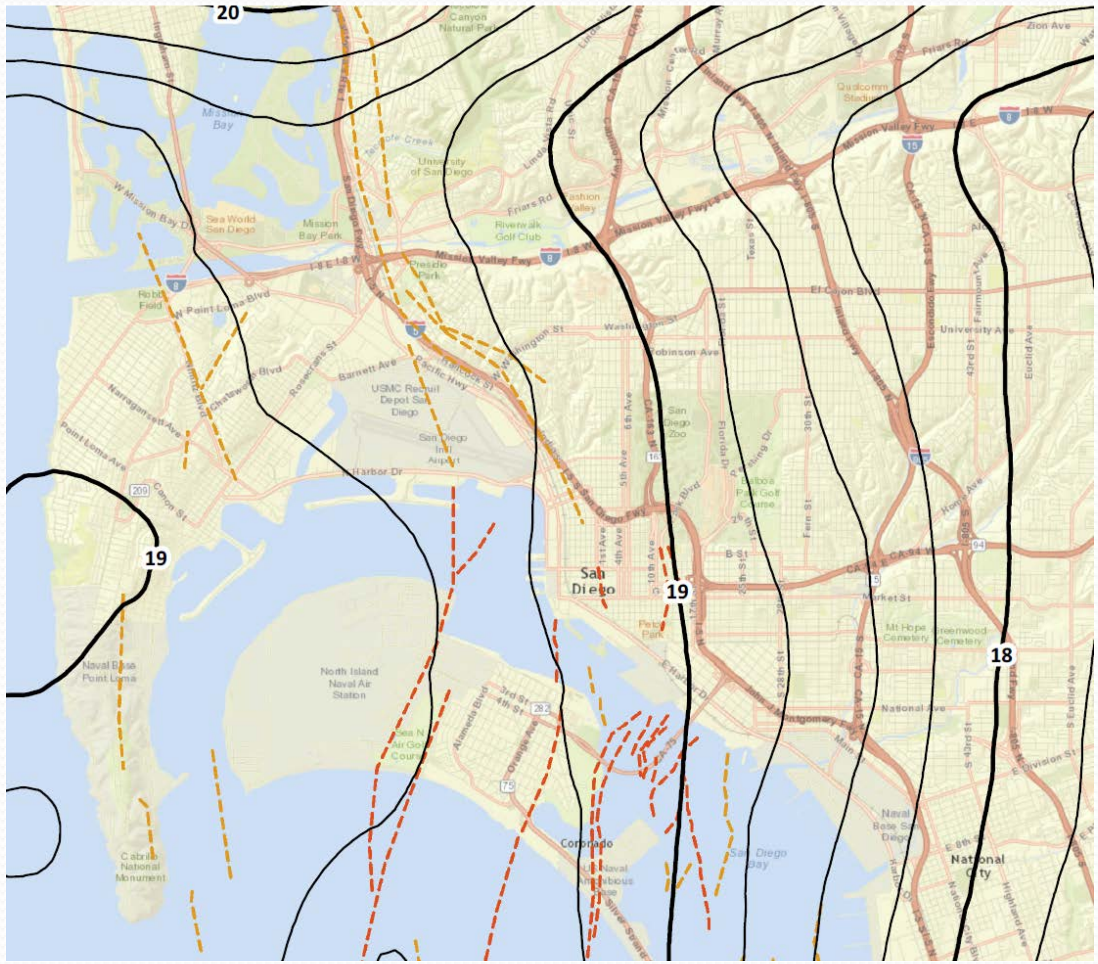
Liquefaction Parameter and Loading Maps for San Diego

- Developed in summer 2014
- Built with PBliquefY and 2008 USGS deaggregation data
- Journal manuscripts are currently being written to present the new simplified performance-based liquefaction procedure and the new maps for San Diego to the engineering public
- Maps developed for three return periods: 475 years (10%PE in 50 years), 1033 years (7%PE in 75 years), and 2475 years (2%PE in 50 years).

Liquefaction Parameter Maps (for use with Cetin et al. 2004)

N_{req}^{ref}

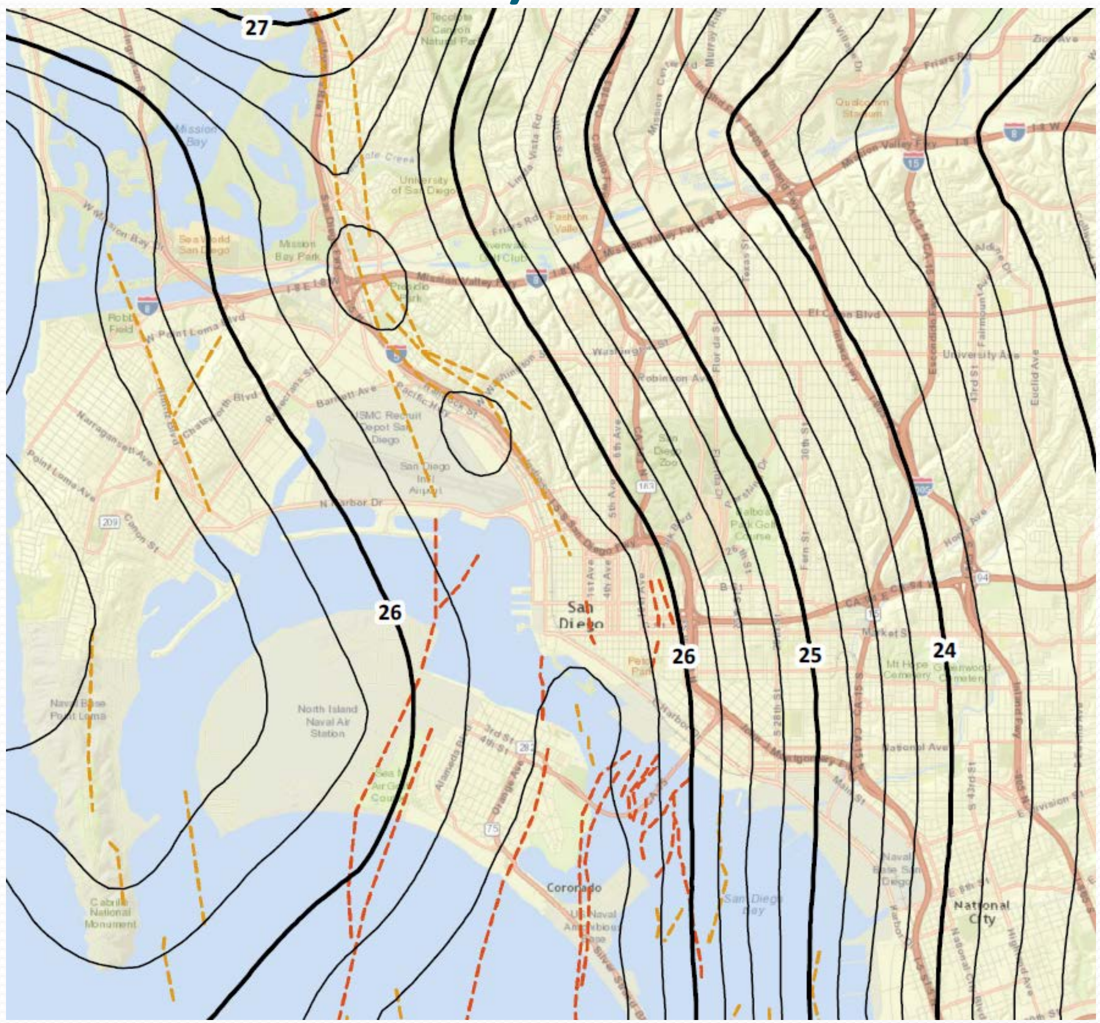
Tr = 475 years
(10%PE in 50 years)



Liquefaction Parameter Maps (for use with Cetin et al. 2004)

N_{req}^{ref}

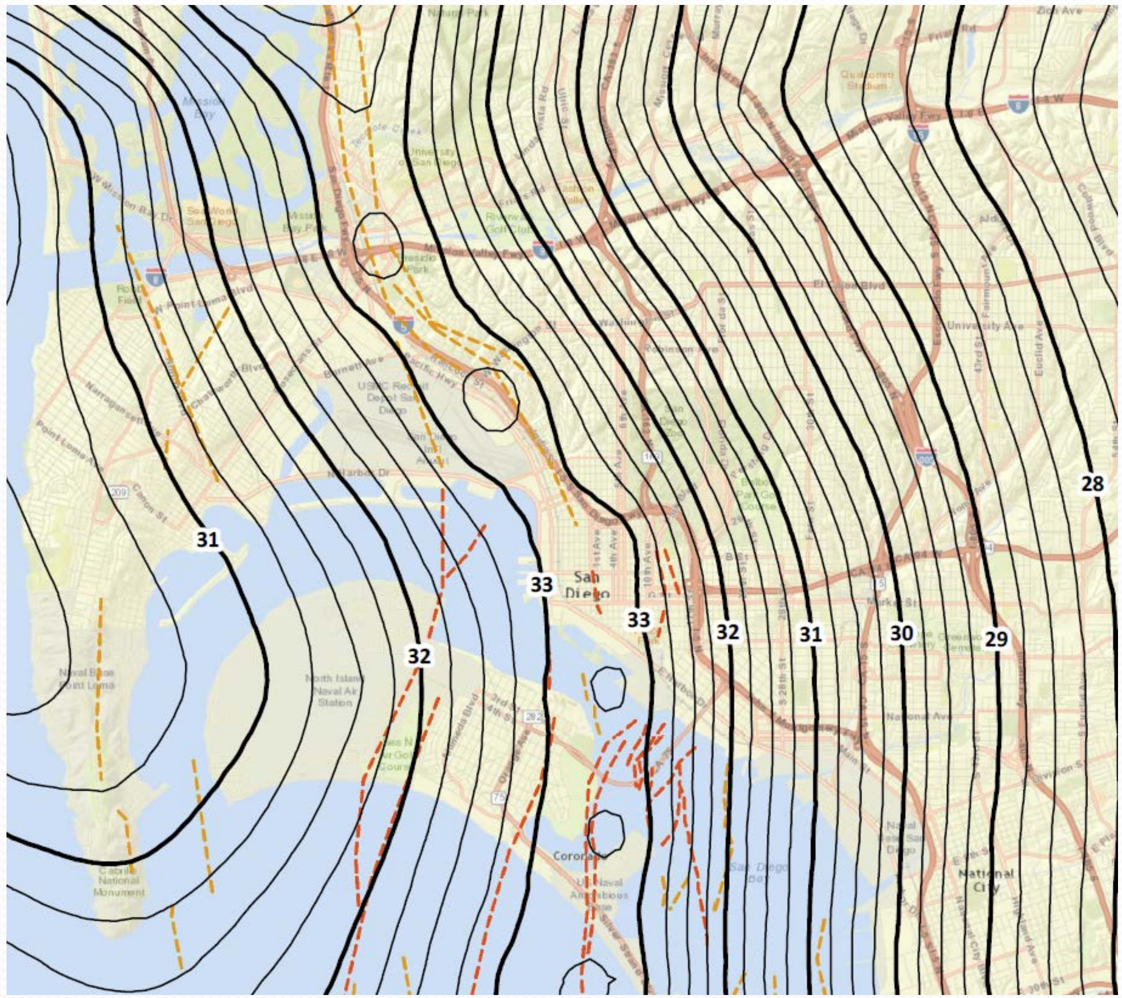
Tr = 1033 years
(7%PE in 75 years)



Liquefaction Parameter Maps (for use with Cetin et al. 2004)

$$N_{req}^{ref}$$

Tr = 2475 years
(2%PE in 50 years)

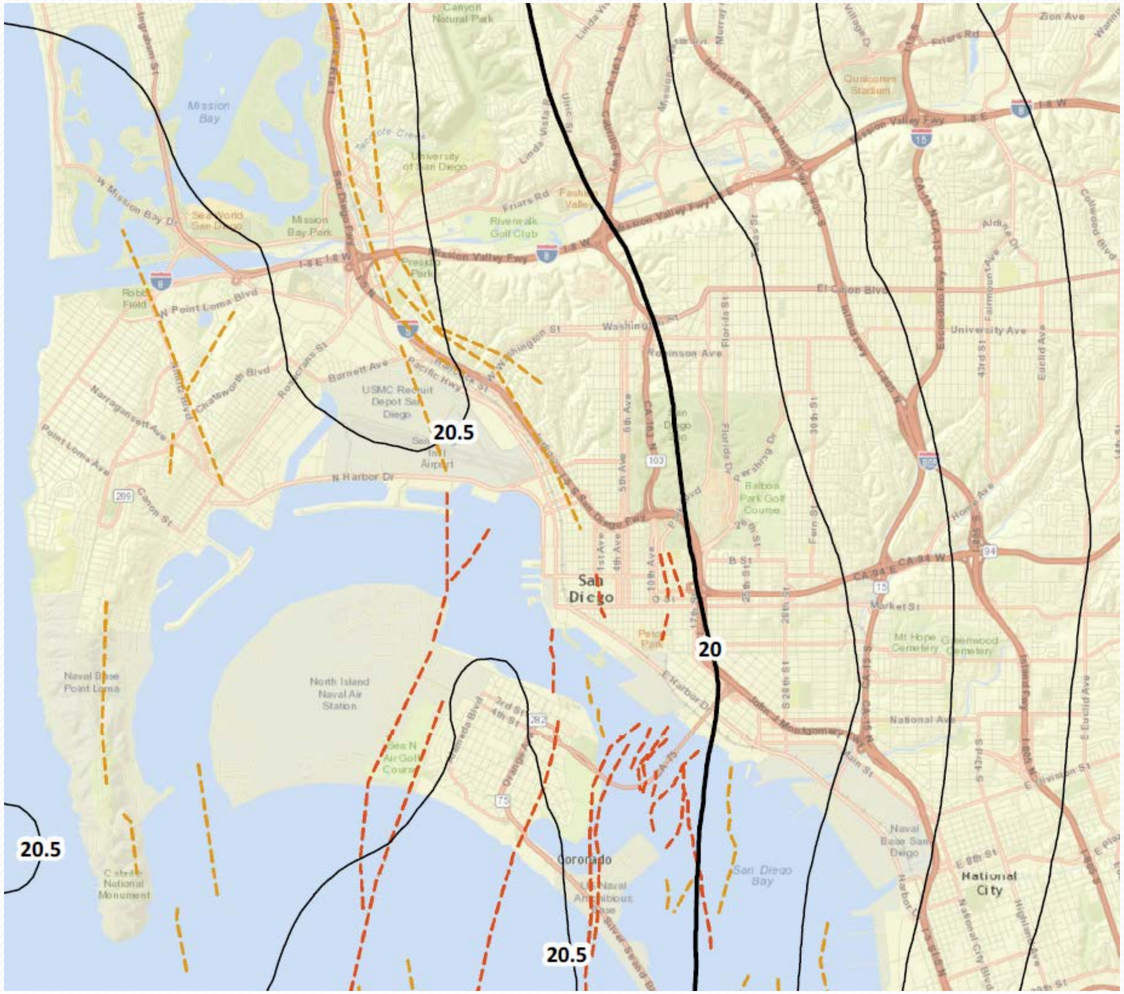


Liquefaction Loading Maps (for use with Boulanger and Idriss 2014)

CSR^{ref} (%)

(unlabeled minor contours represent 1% interval)

Tr = 475 years
(10%PE in 50 years)

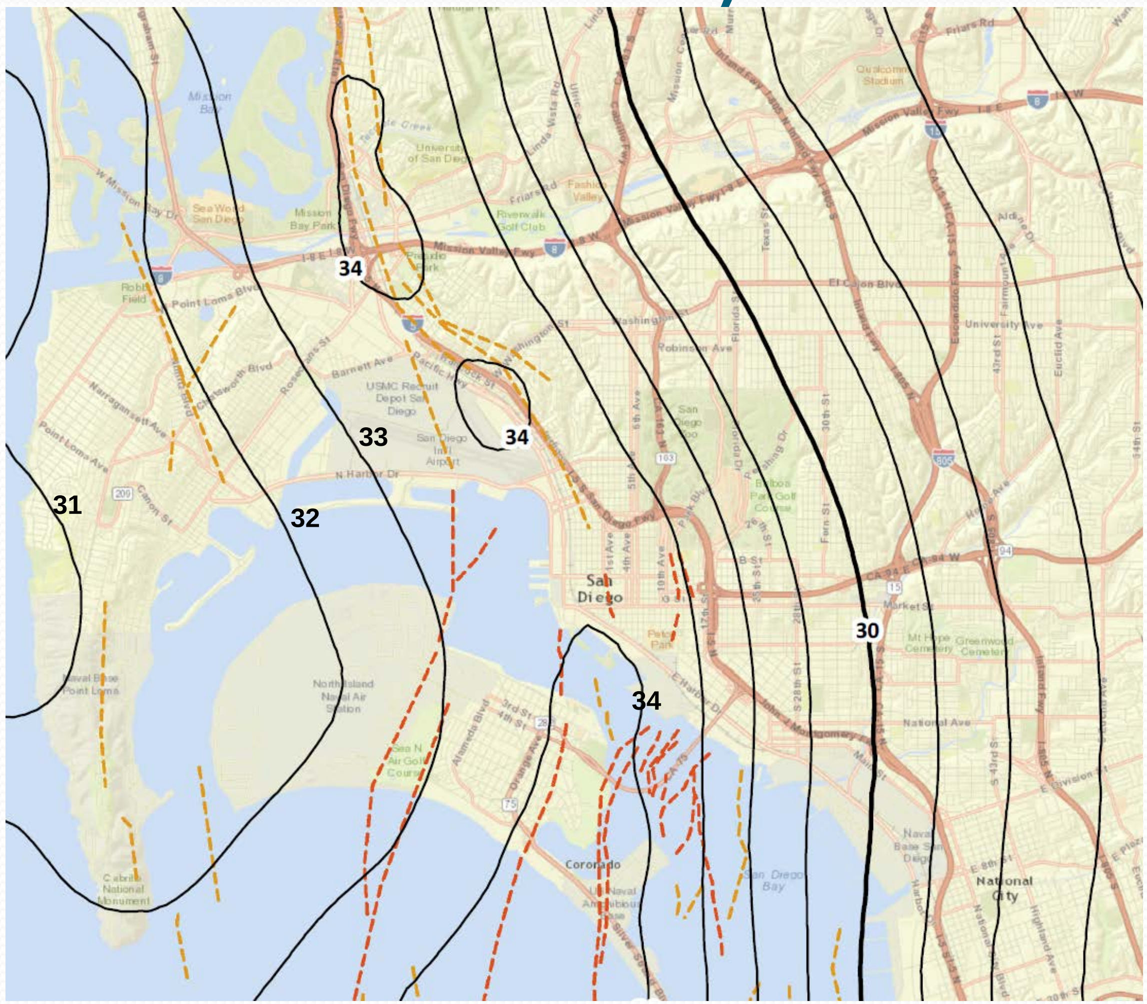


Liquefaction Loading Maps (for use with Boulanger and Idriss 2014)

CSR^{ref} (%)

(unlabeled minor contours represent 1% interval)

Tr = 1033 years
(7%PE in 75 years)

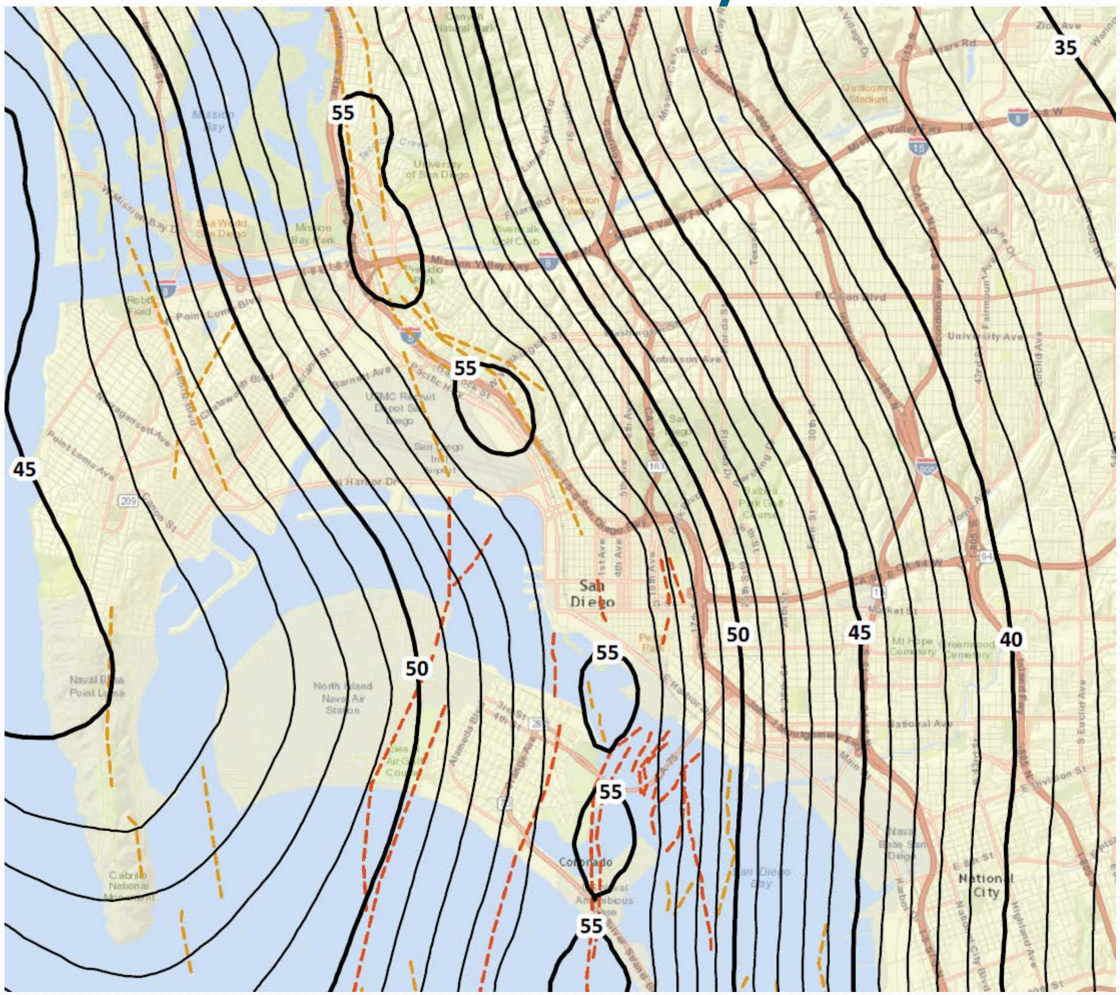


Liquefaction Loading Maps (for use with Boulanger and Idriss 2014)

CSR^{ref} (%)

(unlabeled minor contours represent 1% interval)

Tr = 2475 years
(2%PE in 50 years)



Future Work

- Develop simplified map-based performance-based procedures for various effects:
  - Lateral spread displacement
  - Post-liquefaction free-field settlement
  - Seismic slope displacement
- Update maps with new 2014 USGS deaggregation data, when available
- Develop performance-based and simplified PB procedures for the CPT (w/Dr. Peter Robertson)
- Collaborate with the USGS to investigate the feasibility of developing parameter and loading maps for the entire country as part of the NSHMP

Acknowledgments

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