Ridgecrest Earthquake Sequence: Preliminary Reconnaissance Observations

Scott J. Brandenberg
July 18, 2019
• GEER Report:
  http://geerassociation.org/component/geer_reports/?view=geerreports&id=91&layout=build
Super 8 Security Video

https://youtu.be/-wGWfnZUMKY
Effects of Earthquakes on California’s Water Distribution System

Scott J. Brandenberg

July 18, 2019
Outline

• Sacramento / San Joaquin Delta Background
• Post-cyclic settlement of Sherman Island peat, including nonlinear consolidation analysis.
• Field testing of model levee on Sherman Island
• Centrifuge modeling of non-liquefiable and liquefiable levees.
• Levee system reliability analysis using fragility functions and assessment of spatial correlation of capacity and demand.
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The Delta

Photo courtesy of Roy Tennant.

http://sanjoaquinbasin.com/images/joaquin_dec.png

http://pubs.usgs.gov/fs/2010/3032/images/map01.png
Land Subsidence

- Mount and Twiss (2005)
Land Subsidence

DRMS (2008)
Land Subsidence
Slide courtesy of Les Harder
Seismic Hazard

Deverel et al. (2016)
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Testing of Sherman Island Peat
Sampling Sherman Island Peat

https://youtu.be/aCRfohGjq8w
Consolidation Testing

(a) Stage 2

\[ C_u = 0.25 \]
\[ t_p = 2300s, \ e_p = 6.17 \]

(b) Stage 8

\[ C_u = 0.25 \]
\[ t_p = 10,500s, \ e_p = 4.47 \]
Secondary Compression Behavior

(a) $\log \tau$ vs. $e$

(b) $\log \sigma_v'$ vs. $e$

- $t_p$
- $C_a$
- $C_r$
- $NCL (t=t_{ref})$
- $(e_{ref}, \sigma_v'_{ref})$
- $10t_{ref}$
- $100t_{ref}$
- $1000t_{ref}$
- $C_c$
- $\sigma_p'$
Secondary Compression Behavior

\[
\begin{align*}
\left( \frac{\partial e}{\partial \tau} \right)_{\sigma_v'} &= -\frac{\alpha}{t_{\text{ref}}} \exp \left[ \frac{e - e_{\text{ref}}}{\alpha} + \frac{C_c}{\alpha} \log \left( \frac{\sigma_v'}{\sigma_{v'\text{ref}}} \right) \right] \\
\alpha &= C_{\alpha}/\ln(10)
\end{align*}
\]
• iConsol.js is an nonlinear consolidation code publicly accessible online at [www.uclageo.com/Consolidation/](http://www.uclageo.com/Consolidation/) and described by Brandenberg (2017).

• “Uniform” layer of soil has constant compressibility and permeability constitutive relationship.
Calibration of Peat Properties

(a) Stage 2
(b) Stage 3
(c) Stage 4
(d) Stage 5
(e) Stage 6
(f) Stage 7
(g) Stage 8
(h) Stage 9
(i) Stage 10

Settlement (mm)

τ (s)
Calibration of Peat Properties

(a) Calibration curve for Stage 2:
- \( \sigma_{v,ref} = 9.3 \) kPa,
- \( e_{\sigma,ref} = 7.4 \)
- \( C_c = 3.6 \)

(b) Calibration curve for Stage 8:
- \( k_{ref} = 1.5 \times 10^{-9} \) m/s,
- \( e_{k,ref} = 4.7 \)
- \( C_k = 1.7 \)
Properties of Sherman Island Peat

- Water Content (%)
- Organic Content (%)
- $C_c$
- $C_r$
- $C_\alpha$
Peat Settlement Potential

Cyclic Simple Shear Laboratory Testing Device

Vertical Stress

Strain = Disp/Height
Stress = Force/Area

Shafiee et al. (2015)
Peat Settlement Potential

Shafiee et al. (2015)
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Vibration Level
1. Acceptable for modern buildings
2. Acceptable for historic buildings
3. Acceptable for fragile structures
4. Car driving over levee crest
5. Barely perceptible
6. Ambient vibrations during quiet time

Reinert et al. (2014)
MK-15 Mobile Field Shaker

Reinert et al. (2014)  
https://youtu.be/yuaMA-OYOy4oly
Sample Data

\[ r_{ur} = \frac{\Delta u}{\sigma_{v'_0}} \]

Reinert et al. (2014)
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Levee Centrifuge Models

Clay Levee Model (Non-Liquefiable)

Sand Levee Model (Liquefiable)

Cappa et al. (2017)
Shaking Sandy Levee

https://youtu.be/aCRfohGjq8w
Shaking Sandy Levee

https://youtu.be/aCRfohGjq8w
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# Fragility Functions

![Images of damaged levees](image1.jpg)

<table>
<thead>
<tr>
<th>Damage Level</th>
<th>Crack depth (cm)</th>
<th>Crack width (cm)</th>
<th>Subsidence (cm)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>No damage reported</td>
</tr>
<tr>
<td>1</td>
<td>0~100</td>
<td>0~10</td>
<td>0~10</td>
<td>Slight damage, small cracks</td>
</tr>
<tr>
<td>2</td>
<td>100~200</td>
<td>10~50</td>
<td>10~30</td>
<td>Moderate damage, cracks or small lateral spreading</td>
</tr>
<tr>
<td>3</td>
<td>200~300</td>
<td>50~100</td>
<td>30~100</td>
<td>Severe damage, lateral spreading</td>
</tr>
<tr>
<td>4</td>
<td>&gt; 300</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
<td>Levee collapse</td>
</tr>
</tbody>
</table>

Kwak et al. (2016a)
Fragility Functions

Kwak et al. (2016a)
System Analysis

Capacity = C is a spatially correlated random field with mean, $\mu_C$, standard deviation, $\sigma_C$, and correlation length, $x_C$. Demand = D is a spatially correlated random field with mean, $\mu_D$, standard deviation, $\sigma_D$, and correlation length, $x_D$.

$$\rho_C = \exp \left[ -\left( \frac{3\Delta x}{x_C} \right)^2 \right]$$
System Analysis

- Segment = Elemental length. This is what you would analyze in a 2-D slope stability analysis.
- Reach = A length of levee with uniform statistics for capacity and demand. Capacity and demand vary within a reach, but the random fields are stationary.
- Reach = A length of levee based on an arbitrary jurisdictional boundary.
- System = A length of levee that protects a region from flooding.
- Characteristic Length = A specific length for which the probability of system failure may be computed based on the assumption of statistical independence of each characteristic length.

Kwak et al. (2016b), Zimmaro et al. (2018)
System Analysis

Random realization for:
\( \mu_C = 40, \sigma_C = 10, \rho_C = 3 \)
\( \mu_D = 27, \sigma_D = 3, \rho_D = 8 \)

Factor of safety and margin of safety:
\( FS = \frac{\mu_C}{\mu_D} = 1.5 \)
\( Z = C - D \)
Using level crossing statistics, we can define the probability of failure for a reach of length $L$ as follows:

$$
P(F_R|E) = 1 - \left(1 - P(F_{seg}|E)\right) \exp\left(-\frac{L}{2\pi} \sqrt{-\frac{d^2 \rho_z(0)}{dx^2}} \times \exp\left(-\frac{\beta_z^2}{2}\right)\right)
$$

$$\beta_z = \frac{\sigma_z}{\mu_z} \quad \text{Reliability Index.}
$$

$\rho_z$ = spatial correlation function for margin of safety

must solve for $\beta_z$ and $\rho_z$ using FORM
System Analysis

Graph showing the relationship between a variable labeled $P.f\_system$ and $L$ on a scale from 0 to 100. The graph plots points on the Y-axis at 0.027, 0.967, and 1.0, with corresponding values on the X-axis indicating the range of $L$ from 0 to 100.
Conclusions

• UCLA has performed a wide range of research in the past decade on the seismic response of levees.
• Earthquakes pose a particularly onerous hazard to the Delta due to the potential for multiple simultaneous levee breaches and intrusion of saline water.
• Laboratory, field, and centrifuge testing has helped us characterize the seismic response of levees.
• Fragility curves have been developed from field observations of levee damage in Japan for levees resting on inorganic soils in Niigata, and on organic soils in Hokkaido.
• A new system reliability analysis procedure was developed to compute the probability of system failure given levee capacity and demand as spatially correlated random fields.
Conclusions

• So what does this mean for the Delta?
  – We need to find a permanent solution.
  – Ensuring that no single levee within a system will fail is extremely difficult, and will require a very high factor of safety given the uncertainties in capacity and demand.
  – We are just beginning a study of a Delta island that will utilize the concepts herein.

• What about more traditional flood control levees that do not continuously impound water?
  – These are much more robust because the joint probability of a flood and an earthquake is very low.
  – Damaged levees can be repaired soon after an earthquake, but we must be prepared to move quickly.
  – Key question is what is the design water level we should use for post-earthquake stability assessment. Depends on how rapidly repairs can occur.
References


