Delta ISB Meeting
7/14/2016

Delta Stewardship Council

Seismic Risk Assessment of Levee Systems

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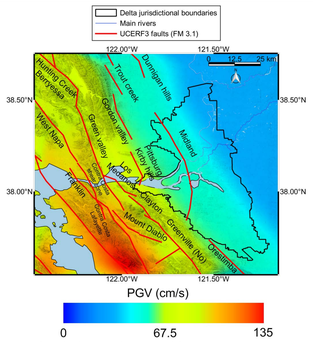
Introduction

- Levees comprise series systems, meaning that failure at any point along the levee constitutes loss of flood control function and failure of the system.
- The probability of failure of a levee system is equal to the probability that the demand exceeds the capacity at any point within the system.
- Levee systems are spatially distributed, and the capacity and demand vary spatially throughout the system. For example, the seismic hazard map below shows peak ground velocity with a 475 year return period within the Sacramento – San Joaquin Delta.
- Levee capacity is spatially correlated because levees that are near each other are often formed of the same materials and rest on similar foundation soils.
- Seismic demand is spatially correlated because distance to the fault rupture varies within the system, and path effects and site conditions tend to be similar at short separation distances.
- Spatial correlation of capacity and demand is a crucial part of seismic risk analysis for levee systems.



PGV seismic hazard map with T_R = 475 years
- Source models: UCERF3 (Field et al., 2014)
- Ground motion models: NGA-West2 (Bozorgnia et al., 2014)
- Target site condition: V_{S30} = 300 m/s
- USGS seismic hazards mapping team: Nico Luco, Peter Powers, and Allison Shumway (personal communication, 4/2016)

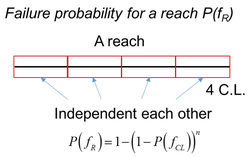
Terminology

- **Levee System:** A length of levee providing flood protection to a specific region.
- **Reach:** A continuous length of levee of homogeneous construction, cross-section geometry, statistical distribution of geotechnical properties, hydrological demand, consequences of failure, and potentially other parameters relevant to risk assessment.
- **Characteristic Length:** A specific length of levee for which the probability of system failure computed by assuming the lengths are statistically independent is identical to the probability of system failure computed in a more robust manner involving explicit consideration of correlation.
- **Segment:** A short length of levee for which the capacity and demand can essentially be considered uniform, and is approximately equal to the width of the levee base (tens of meters).

Existing Approaches

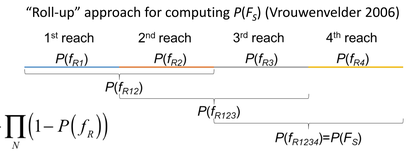
- Reach-based (USACE, 2011; Vrouwenvelder, 2006, DRMS 2008): Levees are divided into reaches, and the reaches are assumed to be statistically independent. Probability of failure of the reach explicitly considers spatial correlation of capacity and demand. Probability of system failure $P(F_S)$ is computed based on the probability of failure of each reach $P(F_R)$, where N is the number of reaches. Vrouwenvelder (2006) rigorously account for spatial correlation of segments within a reach in computing $P(F_R)$. USACE (2011) divide reaches into characteristic lengths, where the characteristic length is assumed based on judgment. DRMS (2008) assumed that the fragility functions apply directly to reaches without considering within-reach correlation or length effects.

Failure probability for a reach $P(f_R)$



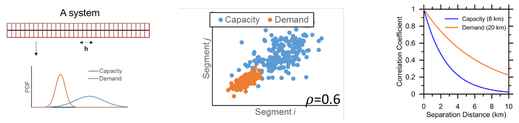
$$P(f_R) = 1 - \left(1 - P(f_{CL})\right)^n$$

"Roll-up" approach for computing $P(F_S)$ (Vrouwenvelder 2006)



$$P(F_s) = 1 - \prod_N \left(1 - P(f_R)\right)$$

- Segment-based (Kwak et al., 2016) (This poster): Levee system is divided into segments rather than reaches, and Monte-Carlo simulation is used to compute $P(F_S)$.



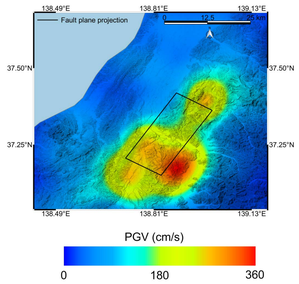
$$F_k = \begin{cases} 0 & \text{if all } C > D \\ 1 & \text{if any } C \le D \end{cases}$$

$$P(F_s) = \frac{1}{N}\sum_{k=1}^{N} F_k$$

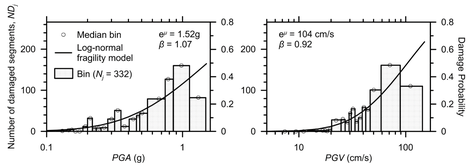
Fragility Functions

- Fragility functions define probability of failure conditioned on shaking intensity and possibly other variables such as surface geology, and groundwater level.
- Fragility functions are typically derived from engineering analysis and expert opinion.
- In this study, fragility functions were derived from empirical observations of a levee system in Niigata, Japan that was shaken by the **M**6.8 Chuetsu earthquake in 2004 and the **M**6.6 Chuetsu-oki earthquake in 2007.
- The Ministry of Land, Infrastructure, Transport, and Tourism conducted detailed post-earthquake damage reports.
- We divided the levee system into 50m long segments, and estimated ground shaking intensity at each levee segment.

Damage State	Crack depth (cm)	Crack width (cm)	Crest Subsidence (cm)	Description
0	0	0	0	No damage reported
1	0~100	0~10	0~10	Slight damage, small cracks
2	100~200	10~50	10~30	Moderate damage, cracks or small lateral spreading
3	200~300	50~100	30~100	Severe damage, lateral spreading
4	> 300	> 100	> 100	Levee collapse



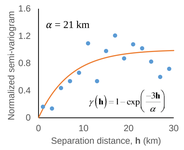
Map of peak ground velocity (PGV) for 2004 Niigata Chuetsu earthquake (above), and fragility functions for 2004 Chuetsu-oki earthquake (left).



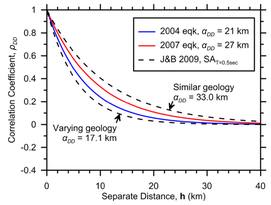
Correlation of Demand and Capacity

Demand Correlation

- Correlation of seismic demand, ρ_{DD}, at two points separated by a distance ***h*** was defined by constructing a variogram of the ground motion data recorded during the earthquakes in Niigata, and subsequently computing correlation versus separation distance.



$$\gamma(\mathbf{h}) = 1 - \exp\left(\frac{-3\mathbf{h}}{\alpha}\right) \Rightarrow \rho_{DD} = \exp\left(\frac{-3\mathbf{h}}{\alpha_{DD}}\right)$$

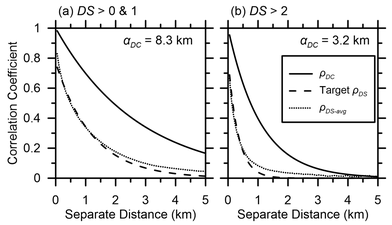


Capacity Correlation

- Correlation of levee capacity to resist seismic shaking was computed by first using the auto-correlation method to define the spatial correlation of damage, ρ_{DS}, observed during each earthquake, and subsequently back-calculating the spatial correlation of capacity, ρ_{DC}, that produces the observed damage correlation. The capacity correlation decreases over much shorter distances than demand correlation.

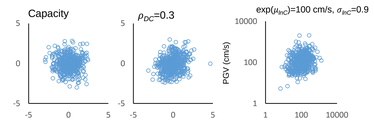
Auto-correlation of damage states
- 1 for damage, 0 for no damage

$$\rho_{ac} = \frac{\mathrm{cov}\left(f_i f_{i+h}\right)}{\sqrt{\mathrm{var}\left(f_i\right)\mathrm{var}\left(f_{i+h}\right)}} = \frac{P\left(f_i \cup f_{i+h}\right) - P\left(f_i\right)P\left(f_{i+h}\right)}{\sqrt{P\left(f_i\right)\left(1-P\left(f_i\right)\right)P\left(f_{i+h}\right)\left(1-P\left(f_{i+h}\right)\right)}}$$

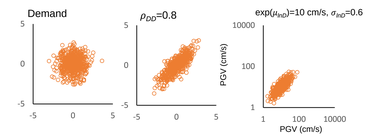


System Analysis Framework

The steps for computing probability of system failure using the proposed system analysis framework involves the following steps:
1. Divide the system into segments.
2. Assign a fragility function to each segment, and a spatial correlation function. Each fragility function is a cumulative distribution function, and the derivative of a fragility function is a probability density function.
3. Randomly generate *MC* number of spatially-correlated random variables from the probability density functions associated with the fragility functions. Cholesky decomposition can be used to generate vectors of correlated random variables. *MC* is the number of Monte Carlo realizations.



4. Select a scenario earthquake event (i.e., a fault rupture plane, magnitude), and compute *MC* number of spatially-correlated seismic demand realizations at each segment location.

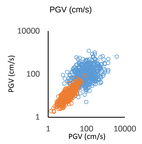


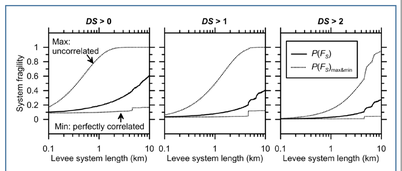
5. Compute the number of cases for which the demand is larger than the capacity for any segment in the system. The probability of system damage is equal to the number of damaged cases divided by *MC*. The probability of system damage increases as the length of the system increases.

$$f_{ik} = \begin{cases} 0 & \text{if } c_{ik} - d_{ik} > 0 \\ 1 & \text{if } c_{ik} - d_{ik} \le 0 \end{cases}$$

$$F_k = \max\left(f_{ik}\right)$$

$$P(F_s) = \frac{1}{N}\sum_{k=1}^{N} F_k$$





Probability of levee system failure for a scenario event (2004 Niigata EQ)

Conclusion

- The proposed system analysis procedure robustly accounts for spatially varying seismic demands and capacity of the levees to resist those demands.
- Correlation of demand and capacity are presented based on observations of earthquakes in Niigata, Japan.
- Probability of system failure is sensitive to spatial correlation of capacity and of demand, and correlation must be considered to accurately compute system reliability.

Acknowledgment

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Seismic Deformation Potential of Sherman Island Peat, and Fragility Functions for Levees on Peat Soil

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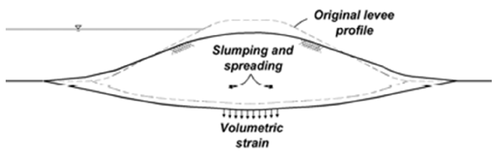
Introduction – Part I: Seismic Response of Peat

- The Sacramento / San Joaquin Delta lies in a region of moderate seismicity.
- Previous seismic risk assessments have found that liquefaction of loose saturated sandy soil is the driver of seismic risk.
- Many Delta levees rest on peat soil. The seismic response of peat is not as well understood as other soils. The extent to which peat soils may contribute to earthquake-induced levee failures is currently unclear.
- This study presents cyclic laboratory testing of peat, and identified a fundamentally new mechanism of earthquake-induced levee deformation caused by post-cyclic reduction in the volume of peat.



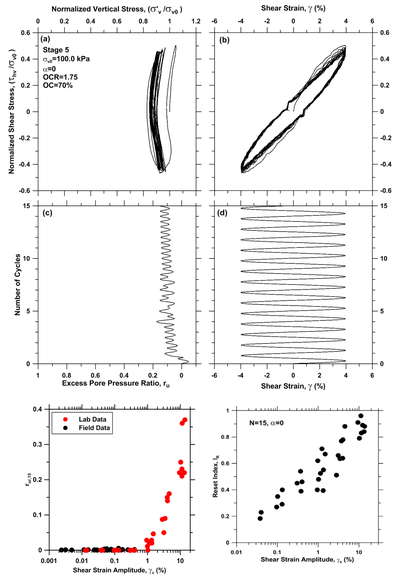
Schematic illustration of a levee settling due to volumetric strain in underlying peat soil.

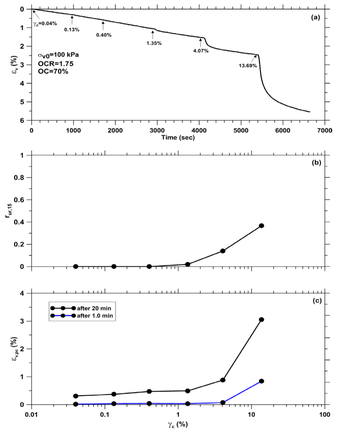
Introduction–Part II: Fragility Functions for Levees on Peat

- Fragility functions quantify the probability of levee failure conditioned on the level of ground shaking, geological, and hydrological conditions. Fragility functions are often based on engineering analysis combined with expert opinion.
- Kwak et al. (2015) developed fragility functions based on observations of damage for levee systems in Niigata, Japan. Those levees rest on inorganic soils, and are therefore not directly applicable Delta levees.
- This study presents preliminary findings for a levee system in Hokkaido, Japan, in which levees resting on peat were shaken by strong earthquake shaking.

Part I: Seismic Response of Sherman Island Peat

- Cyclic loading causes a reduction in the volume of the peat as water is expelled.
- Volume change is due to (1) buildup of excess pore pressure in the peat, and (2) reset of secondary compression.
- Excess pore pressure builds up at strains larger than about 1% in highly organic peat, whereas secondary compression reset begins at smaller strains.

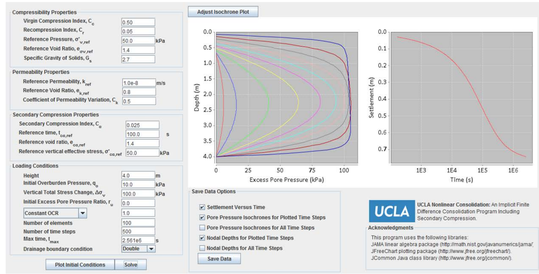




Example laboratory test result showing development of excess pore pressure during cyclic loading (upper left four plots), excess pore pressure and secondary compression versus shear strain amplitude (lower left plots), and post-cyclic volume change response for one sample (right plots).

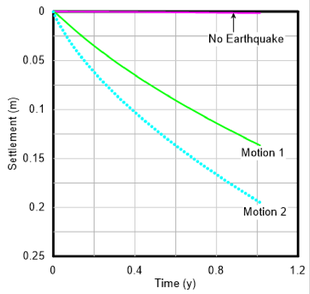
Part I: Estimation of post-earthquake settlement

- A non-linear consolidation code was developed to model reset of secondary compression due to cyclic straining (www.uclageo.com).
- An example problem consisting of a 4m levee atop 11m of peat subjected to two ground motions is shown below.



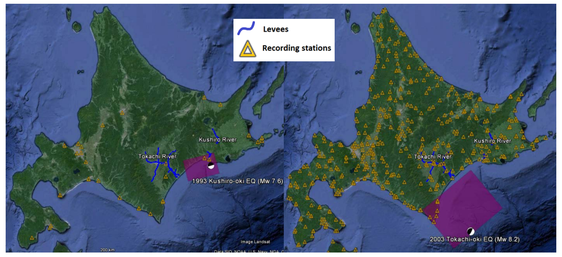
Example problem in which shear strains are predicted in the peat for two earthquake ground motions, and post-cyclic settlement is subsequently predicted considering the effects of pore pressure build-up and secondary compression reset. The levee is predicted to settle by as much as 0.2m after shaking. This would be in addition to any co-seismic settlement that occurs.

	Motion 1	Motion2
Earthquake	1994 Northridge	1995 Kobe
Station	Downey County Maintenance Building	Abeno
M_w	6.7	6.9
R_{jb} (km)	53.2	24.85
V_{s30} (m/s)	272	256
Component	968_180	1100_90
D_{5-95} (s)	17.2	56.4
PGA (g)	0.23	0.23



Part II: Hokkaido Levee Systems

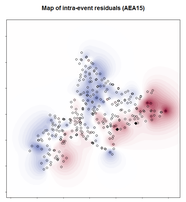
- Two earthquakes, the 1993 **M** 7.6 Kushiro-oki and the 2003 **M** 8.2 Tokachi-oki earthquakes, strongly shook levee systems in Kushiro and Tokachi in Japan's northern-most island, Hokkaido.
- The Ministry of Land, Infrastructure, Transport, and Tourism (MLIT) owns and maintains the levees, and they produced detailed damage reports following each earthquake.
- Available information relevant to this study includes damage measures such as subsidence, crack width and depth, levee geometry, geotechnical boring logs, surface geology maps, stream gauge data, and ground motion recordings



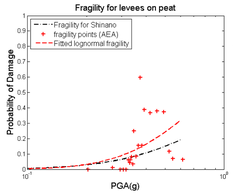
Map showing fault planes and focal mechanisms for the 1993 Kushiro-Oki earthquake (left) and 2003 Tokachi-Oki earthquake (right), ground motion recording station locations, and the Tokachi and Kushiro levee systems.

Part II: Preliminary Fragility Functions

- Fragility functions are computed by dividing the levee system into 50m long segments, assigning a damage state to each segment, and estimating the ground motion at each segment location.
- Rather than directly interpolating measured ground motions, the residuals (i.e., measured minus predicted ground motion) are interpolated instead. This permits consideration of site conditions because levees are typically on softer soils than strong motion recording stations.
- The percent of damage levee segments within a particular ground motion interval are then plotted versus ground motion, and a cumulative distribution function is fit to the data.
- Research is ongoing, particularly with respect to nonlinear site response and its influence on ground motions. Preliminary results indicate that levees on peat are more susceptible to damage compared to levees on inorganic soils.



Mapped ground motion residuals for the 2003 earthquake using the Abrahamson et al. ground motion prediction equation



Preliminary fragility functions indicate that levees resting on peat soil in Hokkaido are more susceptible to damage than levees resting on inorganic soils in Niigata

Conclusions

- Cyclic loading causes peat soil to shrink following cyclic loading. This previously unidentified mechanism can cause levees to settle following earthquakes, and should be considered in addition to other failure mechanisms like liquefaction.
- An example problem illustrates that settlement rate increases significantly following earthquake shaking, reaching 0.15 to 0.20m (6 to 8 inches) one year after shaking.
- Fragility functions are being developed for two levee systems in Hokkaido, Japan that were shaken by two different earthquakes. These levees rest on foundations consisting of peat soil.
- Although this study is not yet complete, preliminary observations indicate that levees founded on peat soil are more fragile during earthquake shaking than levees founded on more traditional inorganic soils.

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