Examples of Accommodating Liquefaction Induced Failure Modes In the Risk Assessment of Dams

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Utah State University
Introduction

- Focus today on Risk Assessment for Failure Modes associated with Earthquake Induced Liquefaction
- Risk Assessment Process
- Risk Assessment Criteria
- Examples involving liquefaction
- Conclusions
Risk Assessment Process

- Loading Conditions – Consider a Full Range of Loading
  - Flood
  - Earthquake
  - Normal operating (may be included with Flood Loading)
- Potential Failure Modes Analysis
  - Identify Credible and Significant PFMs
  - Must understand the Failure Mode
  - Detailed description
- Event Tree Risk Model
- Probability and Consequences of Failure
- Evaluate against criteria
- Repeat for all Risk Reduction Measures
USACE Tolerable Risk Guidelines
- Existing Dams

A) **LIMIT GUIDELINES** that should not be exceeded regardless of cost except in exceptional circumstances:

1) **Annual Probability of Failure (APF)** < 1 in 10,000 per yr

2) **Individual Risk (IR)** - Probability of life loss for the most exposed individual = APF if assume 24x7 presence below dam

3) **Societal Risk (SR)** - A probability distribution (F-N chart) of the number of fatalities from entire PAR

4) **Annualized Life Loss (ALL)** – Av. annual life loss < 0.001 lives/yr

B) **ALARP** (As Low As Reasonably Practicable) considerations:

1) Level of risk compared with Limit Guidelines; 2&3) Cost effectiveness of further risk reduction below the Limit Guidelines (BCR, CSSL, Disproportionality); 4) Essential USACE guidelines; and 5) Consultation.
Portfolio Risk Assessment
Earthquake event tree represent the events and probabilities of those events.
Seismic Loading

- Consider two magnitude ranges
  - M 5.75 (background)
  - M 8.0 (San Andreas & others)
Earthquake Event Tree

Legend
Expanded Chance Node
Collapsed Chance Node
Consequences Node

Liquefaction
No Deformation
No Failure

Deformation (Newmark type)
No Overtopping
No Failure
SEC Failure
Overtopping Failure

Liquefaction
No Stability Failure
No Deformation
No Failure
SEC Failure
Overtopping Failure

Slope
No Breach
Breach

Earthquake event tree
Swaisgood


CSR = \( \left( \frac{\tau_{av}}{\sigma'_o} \right) = 0.65 \left( \frac{a_{max}}{g} \right) \left( \frac{\sigma_{vo}}{\sigma'_{vo}} \right) r_d \)

FS = \( \left( \frac{CRR_{7.5}}{CSR} \right) MSF \)

**FIG. 2.** SPT Clean-Sand Base Curve for Magnitude 7.5 Earthquakes with Data from Liquefaction Case Histories (Modified from Seed et al. 1985)
Probability of Liquefaction

- Youd and Noble (1998)
- Seed, et al. (2001)
- Sequence leading to breach
  - Liquefaction
  - Stability
  - Breach
Liquefaction Models

Fig. 5: Comparison of Best Available Probabilistic Correlations for Evaluation of Liquefaction Potential
(All Plotted for $M_o=7.5$, $\sigma'_v=1300$ psf, and Fines Content $\leq 5\%$)
### Liquefaction Spread Sheet

#### Annual Probability of Liquefaction Calculations

CSR parameters:
- $f_a = 0.3$
- Stress Ratio = 1.35
- $(N_{1s0}) = 33.1$  
  For Silty Sand $(N_{1s0})$ must be corrected
- $M_w = 6.5$  
  Magnitude is only directly considered in the equation by Youd and Noble
- $MCF = 1.19$  
  Magnitude Correction Factor applied to CSR for Liao method $MCF = 1.0$ for M7.5, 1.19 for M6.5

#### Youd and Noble (1998) Equation

<table>
<thead>
<tr>
<th>Loading (pga)</th>
<th>Return Period</th>
<th>Annual Exceedance Prob</th>
<th>Probability Interval</th>
<th>Average pga</th>
<th>CSR</th>
<th>$In[PL/(1-PL)]$</th>
<th>PL/(1-PL)</th>
<th>$F_L$</th>
<th>$F_L$ per year</th>
<th>Modified CSR</th>
<th>QL</th>
<th>$P_L$</th>
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#### Delaware Lake

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<th>AEP</th>
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<th>AEP</th>
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Sum $P_L$ Youd = 8.74E-08  
Sum $P_L$ Liao = 1.53E-09

Parameters Used:
- $(N_{1s0}) = 33.1$
- $M_w = 6.5$
- $MCF = 1.19$
Earthquake Event Tree

Legend
- Expanded Chance Node
- Collapsed Chance Node
- Consequences Node

- No Liquefaction
- No Deformation
- No Failure
- Deformation (Newmark type)
- No Overtopping
- No Failure

- Liquefaction
- No Stability Failure
- No Deformation
- No Failure
- Deformation (Newmark type)
- No Overtopping
- No Failure

- Slope Stability failure
- No Breach
- Breach

Swaisgood
Earthquake event tree

1. Annual Probability for a given PGA range
2. Given the PGA range the conditional probability of liquefaction can be determined
3. Given Liquefaction determine the conditional probability of a slope failure
4. Given the slope failure determine the conditional probability of a breach
5. Repeat for all PGA ranges
Risk Assessment of Success Dam, California

- Evaluation of Operating Restrictions as an Interim Measure to Mitigate Earthquake Risk
- Flood Related Potential Failure Modes
- Earthquake Induced Potential Failure Modes

David Bowles
Loren Anderson
Michael Beaty
Michael Ruthford
Vlad Perlea
David Serafini
Jack Montgomery
SUCCESS DAM
CALIFORNIA

Embankment dam 144 feet (44 m) high
Central clayey core, pervious shells
Founded on alluvial deposit
Cross-Valley Geologic Profile

Problem Zone

35+50 URS
28+50 SPK
Tower Beaty

Typical Embankment Cross Section
Context: Impact Cost of Operating Restrictions in 2004$

1) Agricultural losses associated with reductions in irrigation water

2) Increased flood damages in an historic terminal lake, Tulare Lake agricultural area.

3) Net recreational losses, allowing for shifts to other lakes in the region

$2.1 \text{ m for OR.630 and OR.640}
$2.8 \text{ m for OR.580, OR.600 and OR.620}$
Seepage and Piping Failure Modes

1. Piping into Terrace Deposits Left Abutment Failure
2. Piping into Rock Right Abutment Failure
3. Piping through Rock Foundation Failure
4. Piping through Embankment Failure
5. Piping through Foundation in Older Alluvium Failure
6. Embankment Piping along Outlet Works Failure
Earthquake Failure Modes

- Liquefaction in Recent Alluvium and Upstream Shell

Diagram:
- Upstream:
  - Gross Pool Elevation 652.5'
  - U/S Drill Bench el. 635'
- Downstream:
  - D/S Drill Bench el. 650'
  - D/S Drill Bench el. 595'

Layers:
- Pervious Shell
- Transition Impervious Core
- Pervious Shell
- Recent Alluvium (Qal), 10'-20'
- Older Alluvium (Qog), 0'-140'
- Bedrock
Earthquake Failure Modes

1) Liquefaction leading to vertical crest deformation and failure by Above-Core Erosion (ACE) of the dam.

2) Liquefaction leading to embankment deformation and failure by Seepage Erosion through Cracks (SEC).

3) Liquefaction leading to embankment and tower deformation resulting in failure by piping into a rupture in the control tower - outlet works system, referred to as a Tower-induced Piping (TIP) failure.

*Delayed failure from loss of outlet works*
Results of Probabilistic Seismic Hazard Analysis

![Graph showing annual probability of exceedance vs. peak ground acceleration.](image)
Method of Analysis

Fast Lagrangian Analysis of Continua

Models used in the dynamic shaking simulation
Selected parameter to represent earthquake damage:
Seismic settlement at crest
as a function of: PGA, M, and pool elevation
Smoothed Seismic settlement at crest as a function of: PGA, M, and pool elevation

RAC Adjusted Values (2/24/09)
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Annual Exceedance Probability
Peak Ground Acceleration (g)

Total Hazard
Sum for Mw > 7
Sum for Mw 6.5 to 7
Remaining faults and Fault Zones Mw < 6.5
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Loadings

Deformation
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

- Level 1: Earthquake Magnitude
- Level 2: PGA
- Level 3: Peak El Stage Duration
- Level 4: Emb Vest Def

Loading → Deformation

Settlement in Dam Axis (feet)
Peak Acceleration (g)

RAC Adjusted Values (2/24/09)
Above-Core Erosion (ACE) Failure Mode

Failure Path:
• The embankment deforms due to strength loss of the foundation due to liquefaction.
• The top of the core is lowered below the pool elevation leading to saturation of the downstream shell.
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7
Seepage Erosion through Cracks (SEC) and Tower-induced Piping (TIP) Failure Modes

- Used Event Tree Method Guided by the USACE Piping and Seepage Toolbox
- All estimates made by Engineering Team
- Loss of Outlet control
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Loading
Deformation

Initial Failure Modes

Initial SBC Failure
Initial TIP Failure
Initial AOE Failure
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Initial Failure Modes

Loading
Deformation

SEC SRP values considering Reservoir Elevation

Initial SEC Failure
Initial TIP Failure
Initial ACE Failure
Event Tree for Estimating Individual Conditional Probabilities of a SEC Failure

- Initiation – Flaw exists
- Initiation – Erosion starts
  - Continuation – Unfiltered exit exists (consider: no erosion/some erosion/excessive erosion/continuing erosion)
    - Progression – Roof forms to support a pipe
      - Progression – Upstream zone fails to fill crack
        - Progression – Upstream zone fails to limit flows
          - Intervention fails
            - Dam breaches (consider all likely breach mechanisms)
              - Consequences occur

(1) For Backward Erosion Piping failure modes, no flaw is required. In the case of BEP, initiation assesses the soil type, gradient and heave potential.
Earthquake Event Tree
For \(< M6.5\), M6.5 \(- 7 \) \& \( > M7\)
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Level 1
- Earthquake Magnitude
- PGA

Level 2
- Pool El Stage
- Duration

Level 3
- Emb Vest Def

Level 4
- No Failure

Level 5
- No Failure

Level 6
- Initial Failure Modes

Level 7
- Time from EQ to Breach Initiation

Level 8
- Time to ACE Failure after EQ (hr)

Level 9
- Non-Exceedance Probability
  - Pool El. 652.5
  - Pool El. 635

Level 10
- Time to SEC Failure after EQ (hr)

- Pool El. 652.5
- Pool El. 635
- Pool El. 620

Initial Failure Modes
- Initial ACE Failure
- Initial TIP Failure
- Initial SEC Failure

Time From EQ
- Time From EQ
- Time From EQ
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Loading
Deformation

Loss of Reservoir Control

Initial Failure Modes
Time From EQ to Breach Initiation
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Loading

Deformation

Loss of Reservoir Control

Initial Failure Modes

Time From EQ to Breach Initiation

System Response Probability
Vertical Displacement (ft)
Outlet Works Non-
recoverable
Outlet Works
Functional
Outlet Works Non-
functional But 
Recoverable
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Non-exceedance Probability For Maximum Reservoir Pool Elevation in Three-week Period Following Earthquake

Mid-point Pool Elevation at Time of Earthquake (feet msl)

Maximum Mid-point Reservoir Pool Elevation in Three-week Period Following Earthquake (feet msl)

Initial Failure Modes

Time From EQ to Breach Initiation
Earthquake Event Tree
For < M6.5, M6.5 – 7 & > M7

Delayed Failure Modes

Loading

Deformation

Loss of Reservoir Control

Initial Failure Modes

Time From EQ to Breach Initiation

Delayed SBC Failure

Delayed TIP Failure

Delayed ACE Failure

Initial SBC Failure

Initial TIP Failure

Initial ACE Failure

No Failure

Outlet Functional

Outlet Non-functional

Emb Vent Def

No Failure

No Failure

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ

EQ Time From EQ
## Estimated Life Loss

### Earthquake Failure Modes

<table>
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<tr>
<th>Breach-Inundation Case</th>
<th>Failure Modes</th>
<th>Exposure Case</th>
<th>Warning Time Adjustment (ΔWT) (mins)</th>
<th>PAR</th>
<th>Life Loss</th>
<th>Average Fatality Rate</th>
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<tbody>
<tr>
<td>E.590</td>
<td>SEC, TIP and ACE</td>
<td>Day &gt; 200</td>
<td>48,508</td>
<td>9.4</td>
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### Flood and Flood-internal Failure Modes and Flood No Failure

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<tr>
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<th>Exposure Case</th>
<th>Warning Time Adjustment (ΔWT) (mins)</th>
<th>Total</th>
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Economic Consequences of Dam Failure

Estimated flood damages to agricultural lands in Tulare Lakebed

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<th>Breach Case</th>
<th>Breach Run</th>
<th>Flood Damages ($M)</th>
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Estimated economic damages ($M) to agriculture and structures

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<th>3) Western Porterville Area</th>
<th>4) Tulare County</th>
<th>5) Corcoran</th>
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<td>3.2</td>
</tr>
<tr>
<td>F.PMF NF</td>
<td>421</td>
<td>91</td>
<td>529</td>
<td>0.8</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Other Recent Applications

- Ash Piles at a TVA Power Plant
  - EQ Induced Liquefaction
  - Static Liquefaction
- Mine Closure in the Yukon
  - Tailings Dams
  - Containment Dikes
Important lingering questions

- Importance of establishing a Threshold Earthquake Load
- Mean strength values are used for probabilistic slope stability analysis
- Selection of (N₁)₆₀ values for probabilistic liquefaction analysis
- Thickness of the liquefiable layer – Keaton and Anderson