PBEE evaluation of a bridge with liquefaction hazards

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Introduction (earthquake bridge damage)
Introduction (earthquake bridge damage)
Objective

• Estimate **bridge performance hazards** considering several sources of **uncertainties** using the **PEER PBEE** framework
Outline

- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss
Outline

- **PEER PBEE framework**
  - Target bridge structure and modeling
  - Input Motions
  - Bridge response
  - Uncertainty in EDP
  - Foundation Damage and loss
  - Bridge damage and loss
PEER Performance-Based Earthquake Engineering

Intensity Measure (IM)
- Peak accel = 0.4g

Engineering Demand Parameter (EDP)
- Column drift = 3%

Damage Measure (DM)
- Damage = spalling

Decision Variable (DV)
- Repair cost = $3k

Probabilistic Seismic Hazard Analysis (PSHA)
- Ground motion parameter: PGA, PGV, Ia, CAV5, Sa(T)
PEER Performance-Based Earthquake Engineering

Intensity Measure (IM) → Engineering Demand Parameter (EDP) → Damage Measure (DM) → Decision Variable (DV)

Peak accel = 0.4g
Column drift = 3%
Damage = spalling
Repair cost = $3k

IM = PGA
DV = Repair Cost

IM Hazard curve → ? → DV Hazard curve

total probability theorem

\[ \lambda_{dv|l} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{cdp}} \sum_{i=1}^{N_{im}} P[DV > dv_l | dm_k] P[DM = dm_k | cdp_j] P[EDP = cdp_j | im_i] \Delta \lambda_{im_l} \]
\[ \lambda_{dv_i} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{edp}} \sum_{i=1}^{N_{im}} P[DV > dv_i | dm_k] P[DM = dm_k | edp_j] P[EDP = edp_j | im_i] \Delta \lambda_{im_i} \]
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Target Structure = Bridge system on liquefiable soil

- Five-span bridge
- Pile group foundation
- Liquefiable soil / various layers
Target Bridge System

Seat wall abutment  Bridge structure  Pier section  Soil type

- Embankment
- Med. stiff clay
- Loose-med sand
- Stiff clay
- Dense sand

Soil type

6x1 pile group
3x2 pile group

N_{1,60} below embankments
Numerical modeling of target bridge system in OpenSees

Bearing pad spring

Pressure Independent Multi Yield material

Mackie & Stojadinovic (2003)

py spring (dry sand)

py (liquefiable)

py (stiff clay)

Nonlinear fiber beam column

Pressure Dependent Multi Yield material

Fluid Solid Porous material
Numerical modeling of target bridge system in OpenSees

Bridge Idealization

OpenSees model
Outline

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Input Motions and Intensity Measures (IMs)

- 4 hazards of input motions (I-880 bridge site, near-fault)
- Return periods (15, 72,475, 2475 years)
- 10 motions for each hazard

- Motions scaled to a constant value of a target magnitude corrected PGA
- Remove free-surface effect (Proshake)

<table>
<thead>
<tr>
<th>IM</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Ground Acceleration (PGA)</td>
<td>$\max</td>
<td>a(t)</td>
</tr>
<tr>
<td>Peak Ground Velocity (PGV)</td>
<td>$\max</td>
<td>v(t)</td>
</tr>
<tr>
<td>Arias Intensity ($I_a$)</td>
<td>$\frac{\pi}{2g} \int_0^{T_d} [a(t)]^{\frac{2}{3}} , dt$</td>
<td>cm/s</td>
</tr>
<tr>
<td>Cumulative Absolute Velocity (CAV)</td>
<td>$\int_0^{T_d} \left( \dot{\chi} \right)</td>
<td>a(t)</td>
</tr>
<tr>
<td>Spectral Acceleration ($S\alpha(T)$)</td>
<td>$S\alpha(T)$</td>
<td>g</td>
</tr>
<tr>
<td>Cordova Predictor</td>
<td>$S\alpha(T) \frac{S\alpha(2T)}{S\alpha(T)}$</td>
<td>g</td>
</tr>
</tbody>
</table>

$T_d$ = duration of earthquake motion
$\dot{\chi} = 0$, if $|a(t)| < 5 \text{ cm/s}^2$ and $\dot{\chi} = 1$, if $|a(t)| \geq 5 \text{ cm/s}^2$
System Response
Lateral Spreading

$T_R = 72 \text{ yrs}$
(50% in 50 yrs)

$T_R = 2475 \text{ yrs}$
(2% in 50 yrs)
System Response
Soil Strain Profile during shaking

Northridge motion (0.25g)
System Response

Soil Strain Profile during shaking

Loma Prieta (1.19g)
System Response
System response

5.5m depth in Pile 4

- Graphs showing force vs. displacement for pile caps 1, 2, 3, and 4.
System response

![Graph of System Response](image)

- **Abutment Pile (Left)**
  - Graph showing max BM (kN-m) against motion number for different values of $T_R$ (15 yrs, 72 yrs, 475 yrs, 2475 yrs).
  - max BM depth is also shown.

- **Abutment Pile (Right)**
  - Similar graph to the left, but with different data points and colors.
  - Graph includes motion number from 0 to 40.

Color legend:
- 0.0000
- 0.0001
- 0.0002
- 0.0004
- 0.0006
- 0.0008
- 0.0010
- 0.0012
- 0.0014
- 0.0016
- 0.0018
- 0.0020
- 0.0022
- 0.0024
- 0.0026
- 0.0028
- 0.0030
- 0.0032
- 0.0034
- 0.0036
- 0.0038
- 0.0040
System response

(a) seat abutment structure
- wing wall
- possible soil failure line
- passive earth pressure
- backwall shear-off
- pile resistance

(b) bridge deck-abutment-soil
- left abutment
- deck left end
- before shaking
- after shaking

- right abutment
- deck right end
- before shaking
- after shaking
System Response

Abutment spring (bearing pad + break-off wall)

Passive earth pressure spring

Initial gap (10cm)

contact to abut. wall

Abut. wall shear-off
EDP groups in bridge system

<table>
<thead>
<tr>
<th>EDP group</th>
<th>EDP description</th>
<th>EDP symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>column</td>
<td>drift ratio</td>
<td>$C_1^{[\text{drift, max}]}$, $C_2^{[\text{drift, max}]}$, $C_3^{[\text{drift, max}]}$, $C_4^{[\text{drift, max}]}$</td>
</tr>
<tr>
<td>pile cap</td>
<td>pile cap drift (displacement)</td>
<td>$P_0^{[\text{drift, res}]}$, $P_1^{[\text{drift, res}]}$, $P_2^{[\text{drift, res}]}$, $P_3^{[\text{drift, res}]}$, $P_4^{[\text{drift, res}]}$, $P_5^{[\text{drift, res}]}$</td>
</tr>
<tr>
<td>abutment exp. joint</td>
<td>gap between deck and abutment</td>
<td>$E_{J1}^{[\text{gap, res}]}$, $E_{J2}^{[\text{gap, res}]}$</td>
</tr>
<tr>
<td>abutment backwall</td>
<td>backwall displacement</td>
<td>$BW_1^{[\text{dx, max}]}$, $BW_2^{[\text{dx, max}]}$</td>
</tr>
<tr>
<td>abutment approach</td>
<td>bridge approach vert. off-set</td>
<td>$BA_1^{[\text{dy, res}]}$, $BA_2^{[\text{dy, res}]}$</td>
</tr>
<tr>
<td>bearing pad</td>
<td>bearing pad displacement</td>
<td>$BP_1^{[\text{dx, max}]}$, $BP_2^{[\text{dx, max}]}$</td>
</tr>
<tr>
<td>embankment slope</td>
<td>lateral disp.</td>
<td>$E_1^{[\text{dx, res}]}$, $E_2^{[\text{dx, res}]}$</td>
</tr>
</tbody>
</table>

Numerical modeling allows evaluation of median values for each EDP and corresponding uncertainties.
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- PEER PBEE framework
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- Input Motions
- Bridge response
- **Uncertainty in EDP**
- Foundation Damage and loss
- Bridge damage and loss
Uncertainties in EDP estimation

- Model Parameters
- Input Motions
- Spatial Variability
- Uncertainty in EDP Estimation
- Numerical Modeling
- Other Factors
Record-to-record uncertainty (EDP-IM relationship)

- **PGA**
  - $\text{EDP}_{PGA} = 0.20445 (IM)^{1.133}$
  - $\sigma_{\text{EDP}_{PGA}} = 0.290$

- **PGV**
  - $\text{EDP}_{PGV} = 0.16770 (IM)^{0.635}$
  - $\sigma_{\text{EDP}_{PGV}} = 0.289$

- **$l_a$**
  - $\text{EDP}_{l_a} = 0.00666 (IM)^{0.454}$
  - $\sigma_{\text{EDP}_{l_a}} = 0.177$

- **CAV_5**
  - $\text{EDP}_{CAV_5} = 0.00032 (IM)^{0.636}$
  - $\sigma_{\text{EDP}_{CAV_5}} = 0.145$

- **$S_a(T)$**
  - $\text{EDP}_{S_a(T)} = 0.16249 (IM)^{0.671}$
  - $\sigma_{\text{EDP}_{S_a(T)}} = 0.440$

- **Cordova**
  - $\text{EDP}_{Cordova} = 0.13812 (IM)^{0.668}$
  - $\sigma_{\text{EDP}_{Cordova}} = 0.277$
Record-to-record uncertainty (IM efficiency)

Why is the IM efficiency important?
### Parametric uncertainty

**Sensitivity analysis**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>used COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear modulus, G</td>
<td>0.4</td>
</tr>
<tr>
<td>undrained shear strength, c</td>
<td>0.3</td>
</tr>
<tr>
<td>friction angle, $\phi$</td>
<td>0.1</td>
</tr>
<tr>
<td>contraction parameter, contract ima</td>
<td>0.2</td>
</tr>
<tr>
<td>py spring (stiffness, $K_1$)</td>
<td>0.4</td>
</tr>
<tr>
<td>py spring (pult): clay</td>
<td>0.3</td>
</tr>
<tr>
<td>py spring (pult): sand</td>
<td>0.1</td>
</tr>
<tr>
<td>abutment earth spring (stiffness, $K_2$)</td>
<td>0.4</td>
</tr>
<tr>
<td>break-off wall capacity</td>
<td>0.1</td>
</tr>
<tr>
<td>bearing pad (stiffness, $K_3$)</td>
<td>0.05</td>
</tr>
<tr>
<td>Shear wave velocity, $V_s$</td>
<td>0.2</td>
</tr>
<tr>
<td>SPT resistance</td>
<td>0.3</td>
</tr>
<tr>
<td>density</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\[
x_i^+ = \overline{x}_i (1+\text{COV}/2)
\]
\[
\overline{x} = \overline{x}_i
\]
\[
x^- = \overline{x}_i (1+\text{COV}/2)
\]

**FOSM analysis**

\[
\sigma_Y^2 \approx \sum_{i=1}^{N} \sigma_{X_i}^2 \left( \frac{\partial g}{\partial X_i} \right)^2 + \sum_{i=1}^{N} \sum_{j \neq i}^{N} \rho_{X_i, X_j} \sigma_{X_i} \sigma_{X_j} \frac{\partial g}{\partial X_i} \frac{\partial g}{\partial X_j}
\]

**Tornado diagram**

EDP($\mu$ $\pm$ 0.5$\sigma$) normalized by EDP($\mu$)

- sand (phi)
- clay (c)
- contract data
- loose sand (G)
- embankment(G)
- clay (G)
- abutWall (y50)
- bearingPad (K)
- abutWall (pult)
- pile (resid)
- pileCap (pult)
- pileCap (y50)
- pile (pult)
- pile (y50)
- breakWall (Fy)

Slope res. lateral disp.
Spatial variability uncertainty

\[ F_{\text{stochastic}} = (1 + \text{COV}) F_{\text{trend}} F_{\text{Gaussian}} \]

After Phoon and Kulhawy (1999)

Gaussian random field
(Yamazaki and Shinozuka 1988)
Spatial variability uncertainty

Original field (mean) - 

Gaussian field (residual) - 

Gaussian stochastic field (mean + residual) -
Total uncertainty in EDP estimation

\[ \sigma_{\ln EDP|IM,total} = \sqrt{\sigma_{\ln EDP|IM,record}^2 + \sigma_{\ln EDP|IM,parameter}^2 + \sigma_{\ln EDP|IM,spatial}^2} \]

<table>
<thead>
<tr>
<th>EDP symbol</th>
<th>Efficient IM</th>
<th>record-to-record uncertainty</th>
<th>parametric uncertainty</th>
<th>spatial uncertainty</th>
<th>total EDP uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C1_{[\text{drift,max}]})</td>
<td>Cordova(T=0.5)</td>
<td>0.327 (84%)</td>
<td>0.134 (14%)</td>
<td>0.048 (2%)</td>
<td>0.356</td>
</tr>
<tr>
<td>(C2_{[\text{drift,max}]})</td>
<td>PGV</td>
<td>0.401 (98%)</td>
<td>0.031 (1%)</td>
<td>0.044 (1%)</td>
<td>0.404</td>
</tr>
<tr>
<td>(C3_{[\text{drift,max}]})</td>
<td>Sa(T=1.0)</td>
<td>0.432 (99%)</td>
<td>0.123 (1%)</td>
<td>0.018 (0%)</td>
<td>0.434</td>
</tr>
<tr>
<td>(C4_{[\text{drift,max}]})</td>
<td>PGV</td>
<td>0.311 (95%)</td>
<td>0.104 (2%)</td>
<td>0.050 (3%)</td>
<td>0.311</td>
</tr>
<tr>
<td>(P0_{[\text{dx, res}]})</td>
<td>CAV 5</td>
<td>1.275 (99%)</td>
<td>0.068 (1%)</td>
<td>0.062 (0%)</td>
<td>1.278</td>
</tr>
<tr>
<td>(P1_{[\text{dx, res}]})</td>
<td>(I_a)</td>
<td>1.026 (91%)</td>
<td>0.283 (7%)</td>
<td>0.141 (8%)</td>
<td>1.073</td>
</tr>
<tr>
<td>(P2_{[\text{dx, res}]})</td>
<td>Sa(T=0.5)</td>
<td>1.266 (89%)</td>
<td>0.384 (8%)</td>
<td>0.213 (3%)</td>
<td>1.340</td>
</tr>
<tr>
<td>(P3_{[\text{dx, res}]})</td>
<td>CAV 5</td>
<td>0.673 (95%)</td>
<td>0.119 (4%)</td>
<td>0.087 (1%)</td>
<td>0.689</td>
</tr>
<tr>
<td>(P4_{[\text{dx, res}]})</td>
<td>(I_a)</td>
<td>0.761 (98%)</td>
<td>0.087 (1%)</td>
<td>0.064 (1%)</td>
<td>0.769</td>
</tr>
<tr>
<td>(P5_{[\text{dx, res}]})</td>
<td>CAV 5</td>
<td>0.687 (97%)</td>
<td>0.105 (2%)</td>
<td>0.056 (1%)</td>
<td>0.697</td>
</tr>
</tbody>
</table>

90-95% 5-10%
EDP hazard

\[ \lambda_{IM} = k_0 (IM)^{-k} \]

\[ EDP = a (IM)^b \]

\[ \lambda_{EDP} = k_0 \left[ \frac{EDP}{a} \right]^{-k/b} \exp \left[ \frac{1}{2} \frac{k^2}{b^2} \sigma_{\ln EDP|IM,total}^2 \right] \]

Jalayer (2003)

Uncertainty-based amplification
EDP hazard

Pier 4 max. drift ratio (%)

Pile cap 4 res. lateral disp (cm)

$T_R = 475$ yrs
Importance of IM efficiency

Pier 4 max. drift

Pile cap 4 res. lateral disp
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- **Foundation Damage and loss**
- Bridge damage and loss
Integration of Uncertainties through PBEE Framework

*EDP = Pile cap 1 horizontal displacement*

- IM hazard curve
- EDP|IM relationship
- EDP hazard curve

DM fragility curves
DM hazard curve
DM fragility curve
DV hazard curve

\[ \lambda_{IM} = \frac{1}{15} \text{ years} \]
\[ \lambda_{IM} = \frac{1}{72} \text{ years} \]
\[ \lambda_{IM} = \frac{1}{475} \text{ years} \]
\[ \lambda_{IM} = \frac{1}{2475} \text{ years} \]
EDP Hazard to DM/DV Hazard

\[
\lambda_{dm(j)} = \sum_{i=1}^{N_{EDP}} P[DM > dm(j) \mid edp(i)] \Delta \lambda_{edp(i)}
\]

\[
\lambda_{dv(k)} = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} P[DV > dv(k) \mid dm(j)] P[DM = dm(k) \mid edp(j)] \Delta \lambda_{edp(j)}
\]
EDP Hazard to DM/DV Hazard

\[ \lambda_{dm(j)} = \sum_{i=1}^{N_{EDP}} P[DM > dm(j) \mid edp(i)] \Delta \lambda_{edp(i)} \]

\[ \lambda_{dv(k)} = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} P[DV > dv(k) \mid dm(j)] P[DM = dm(k) \mid edp(j)] \Delta \lambda_{edp(j)} \]
EDP Hazard to DM/DV Hazard

**DM fragility matrix**

<table>
<thead>
<tr>
<th>damage state</th>
<th>~4 cm</th>
<th>4 ~ 10 cm</th>
<th>10 ~ 30 cm</th>
<th>30 ~ 100 cm</th>
<th>100 cm ~</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>0.95</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Minor</td>
<td>0.05</td>
<td>0.80</td>
<td>0.20</td>
<td>0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.05</td>
<td>0.10</td>
<td>0.60</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>Severe</td>
<td>0.00</td>
<td>0.05</td>
<td>0.15</td>
<td>0.55</td>
<td>0.10</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
<td>0.15</td>
<td>0.85</td>
</tr>
</tbody>
</table>

**Equations**

\[
P(DM > \text{Negligible} | \text{edp}) = P(DM > \text{Minor} | \text{edp}) = 0.10 \\
P(DM > \text{Minor} | \text{edp}) = 0.05 \\
P(DM > \text{Moderate} | \text{edp}) = 0.00 \\
P(DM > \text{Severe} | \text{edp}) = 0.00 \\
P(DM > \text{Catastrophic} | \text{edp}) = 0.00
\]
## EDP Hazard to DM/DV Hazard

**DV fragility matrix**

<table>
<thead>
<tr>
<th>Repair Cost Ratio</th>
<th>Negligible</th>
<th>Minor</th>
<th>Moderate</th>
<th>Severe</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.95</td>
<td>0.10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.1</td>
<td>0.05</td>
<td>0.60</td>
<td>0.15</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.2</td>
<td>0.00</td>
<td>0.20</td>
<td>0.50</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.3</td>
<td>0.00</td>
<td>0.10</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>0.4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.15</td>
<td>0.15</td>
<td>0.00</td>
</tr>
<tr>
<td>0.5</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>0.6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.25</td>
<td>0.00</td>
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<tr>
<td>0.7</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.10</td>
<td>0.00</td>
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<tr>
<td>0.8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.10</td>
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<tr>
<td>0.9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.20</td>
</tr>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Repair Cost Ratio</th>
<th>Negligible</th>
<th>Minor</th>
<th>Moderate</th>
<th>Severe</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>P(DV &gt; RCR=0.0</td>
<td>DM)</td>
<td>0.05</td>
<td>0.90</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.1</td>
<td>DM)</td>
<td>0.00</td>
<td>0.30</td>
<td>0.85</td>
<td>1.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.2</td>
<td>DM)</td>
<td>0.00</td>
<td>0.10</td>
<td>0.35</td>
<td>1.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.3</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.15</td>
<td>1.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.4</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>P(DV &gt; RCR=0.5</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>P(DV &gt; RCR=0.6</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.10</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.7</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>P(DV &gt; RCR=0.8</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=0.9</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>P(DV &gt; RCR=1.0</td>
<td>DM)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
EDP Hazard to DM/DV Hazard

DV fragility curve

RCR = 0.1
RCR = 0.2
RCR = 0.3
RCR = 0.4
RCR = 0.5
RCR = 0.6
Integration of Uncertainties through PBEE Framework

**$EDP = Pile\ cap\ 1\ horizontal\ displacement$**

**IM hazard curve**  
**EDP|IM relationship**  
**EDP hazard curve**

**DM fragility**  
**DM hazard curve**  
**DM fragility**  
**DV hazard curve**
Integration of Uncertainties through PBEE Framework

EDP = Pile cap 1 horizontal displacement

IM hazard

DM hazard

DV hazard

Repair Cost Ratio

Damage State

PGV (cm/sec)

EDP: pile cap 1 disp. (m)

- 10^7

IM hazard

EDP hazard

DM hazard

DV hazard

72 yrs

475 yrs

Repair Cost Ratio

Damage State

PGV (cm/sec)

EDP: pile cap 1 disp. (m)

- 10^7

IM hazard

EDP hazard

DM hazard

DV hazard

72 yrs

475 yrs

Repair Cost Ratio

Damage State

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EDP hazard

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- 10^7

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EDP hazard

DM hazard

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72 yrs

475 yrs

Repair Cost Ratio

Damage State

PGV (cm/sec)

EDP: pile cap 1 disp. (m)

- 10^7

IM hazard

EDP hazard

DM hazard

DV hazard

72 yrs

475 yrs

Repair Cost Ratio

Damage State
Outline

- PEER PBEE framework
- Target bridge structure and modeling
- Input Motions
- Bridge response
- Uncertainty in EDP
- Foundation Damage and loss
- Bridge damage and loss
Bridge Damage and Loss

A series of repair cost analyses were performed using the Matlab code developed by Mackie et al. (2006). This code is set up to produce conditional probabilities of various repair cost levels given an intensity measure, which was taken as peak velocity.

<table>
<thead>
<tr>
<th>Performance Group</th>
<th>EDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column (4)</td>
<td>Maximum and residual tangential drift ratios</td>
</tr>
<tr>
<td>Expansion joint (2)</td>
<td>Longitudinal abutment displacement</td>
</tr>
<tr>
<td>Bearings (2)</td>
<td>Bearing displacement (absolute)</td>
</tr>
<tr>
<td>Back wall (2)</td>
<td>Back wall displacement</td>
</tr>
<tr>
<td>Approach slab (2)</td>
<td>Vertical abutment displacement</td>
</tr>
<tr>
<td>Deck segment (5)</td>
<td>Depth of spalling</td>
</tr>
<tr>
<td>Abutment pile groups (2)</td>
<td>Horizontal displacement</td>
</tr>
<tr>
<td>Interior pile groups (4)</td>
<td>Horizontal displacement</td>
</tr>
</tbody>
</table>

Total repair cost = $S$ Repair methods and cost

IM -> Total repair cost

Mackie & Stojadinovic damage and loss model
Bridge Damage and Loss

\[ \lambda_{DV}(d\nu_1) = \sum_{i=1}^{N_{IM}} P[DV > d\nu_1 | IM = im_i] \Delta \lambda_{IM}(im_i) \]

\[ P[DV_i | IM_i] = \sum_{k=1}^{N_{DM}} \sum_{j=1}^{N_{EDP}} \sum_{l=1}^{N_{IM}} P[DV | DM_k]P[DM_k | EDP_j]P[EDP_j | IM_i] \]

Mackie & Stojadinovic damage and loss model

**IM hazard**

**DV/IM fragility**

**DV hazard**

45% total repair cost
Deaggregation of Repair Cost

Greatest repair cost
temporary support of the superstructure

For 475 year return period greatest repair cost is temporary support of the superstructure followed by additional piling
Liquefaction case

Non-Liquefaction case

Fixed-base case
Liquefaction case

Non-Liquefaction case

Fixed-base case

Graphs showing the relationship between IM (PGV SRSS in cm/s) and DV (Total repair cost ratio (%)). The graphs compare the median and 75/-1σ values for liquefaction cases. There are also markers indicating 1/100yr and 1/1000yr events with repair cost ratios of 15% and 50% respectively.
Liquefaction case

Non-Liquefaction case

1/100yr

5%

20%

1/1000yr
Sensitivity of Bridge Losses to Soil Conditions

![Graph showing sensitivity of bridge losses to soil conditions. The graph plots the repair cost ratio against the log scale of the repair cost ratio. The graph includes three lines: red for 'Liq', blue for 'noLiq', and green for 'Fixed'.]
Sensitivity of Bridge Losses to Soil Conditions

All three curves coincide – soil relatively stiff, no pore pressure generation.
Sensitivity of Bridge Losses to Soil Conditions

Total stress and fixed base cases similar – strains low enough that soil remains relatively stiff.

Pore pressure generated – soil stiffness and strength decrease.
Sensitivity of Bridge Losses to Soil Conditions

Fixed based case more demanding than total stress case due to base isolation effect in clay layer.
Sensitivity of Bridge Losses to Soil Conditions

Repair cost less than 40% for fixed based case even at 100,000 years return periods.

Total stress similar to effective stress case due to large deformations in clay layer.
At PGV < 65 cm/sec
greatest repair cost are
repairs o cracks and spalls
At PGV’s 65-140 cm/sec greatest repair cost is temporary support of the abutment
At PGV >140 cm/sec greatest repair cost is temporary support of the superstructure.
Sensitivity of Bridge Losses to Uncertainty

Uncertainty in response, damage, and loss modeling not significant for return periods < than 200 yrs
Sensitivity of Bridge Losses to Uncertainty

Uncertainty in response, damage, and loss modeling not significant for return periods < than 5000 yrs
Thank You
Questions and Comments
### Input Motions and Intensity Measures (IMs)

#### Table 1: Input motions (hazard: 50 % in 50 years)

<table>
<thead>
<tr>
<th>Record</th>
<th>File</th>
<th>Earthquake</th>
<th>Magnitude</th>
<th>MSF</th>
<th>$PGA_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coyote Lake Dam abutment</td>
<td>A01</td>
<td>Coyote Lake</td>
<td>5.7</td>
<td>2.247</td>
<td>0.672</td>
</tr>
<tr>
<td>Gilroy #6</td>
<td>A02</td>
<td>(6/8/1979)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temblor</td>
<td>A03</td>
<td>Parkfield</td>
<td>6.0</td>
<td>1.931</td>
<td>0.578</td>
</tr>
<tr>
<td>Array #5</td>
<td>A04</td>
<td>(6/27/1966)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Array #8</td>
<td>A05</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Fagundes Ranch</td>
<td>A06</td>
<td>Livermore</td>
<td>5.5</td>
<td>2.497</td>
<td>0.747</td>
</tr>
<tr>
<td>Coyote Lake Dam abutment</td>
<td>A08</td>
<td>Morgan Hill</td>
<td>6.2</td>
<td>1.753</td>
<td>0.524</td>
</tr>
<tr>
<td>Anderson Dam DS</td>
<td>A09</td>
<td>(4/24/1984)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halls Valley</td>
<td>A10</td>
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<td></td>
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<td></td>
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</tbody>
</table>

#### Table 2: Input motions (hazard: 10 % in 50 years)

<table>
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<tr>
<th>Record</th>
<th>File</th>
<th>Earthquake</th>
<th>Magnitude</th>
<th>MSF</th>
<th>$PGA_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Gatos Presentation Ctr</td>
<td>B01</td>
<td>Loma Prieta</td>
<td>7.0</td>
<td>1.226</td>
<td>0.799</td>
</tr>
<tr>
<td>Saratoga Aloha Avenue</td>
<td>B02</td>
<td></td>
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</tr>
<tr>
<td>Corralitos</td>
<td>B03</td>
<td></td>
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<tr>
<td>Gavilan College</td>
<td>B04</td>
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<tr>
<td>Gilroy Historic</td>
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<td></td>
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<tr>
<td>Lexington Dam abutment</td>
<td>B06</td>
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<td></td>
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</tr>
<tr>
<td>Kobe JMA</td>
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<td>Kobe, Japan</td>
<td>6.9</td>
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<tr>
<td>Kofu</td>
<td>B08</td>
<td>Tottori, Japan</td>
<td>6.6</td>
<td>1.458</td>
<td>0.951</td>
</tr>
<tr>
<td>Hino</td>
<td>B09</td>
<td>(10/6/2000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erzincan</td>
<td>B10</td>
<td>Erzincan</td>
<td>6.7</td>
<td>1.395</td>
<td>0.909</td>
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</table>

#### Table 3: Input motions (hazard: 2 % in 50 years)

<table>
<thead>
<tr>
<th>Record</th>
<th>File</th>
<th>Earthquake</th>
<th>Magnitude</th>
<th>MSF</th>
<th>$PGA_M$</th>
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<tbody>
<tr>
<td>Los Gatos Presentation Ctr</td>
<td>C01</td>
<td>Loma Prieta</td>
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<td>1.226</td>
<td>1.228</td>
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<tr>
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<tr>
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<tr>
<td>Erzincan</td>
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<td>Erzincan</td>
<td>6.7</td>
<td>1.395</td>
<td>1.398</td>
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</table>

#### Table 4: Input motions (hazard: 97 % in 50 years)

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<th>Magnitude</th>
<th>MSF</th>
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<tr>
<td>Coyote Lake Dam abutment</td>
<td>D01</td>
<td>Coyote Lake</td>
<td>5.7</td>
<td>2.247</td>
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</tr>
</tbody>
</table>
Liquefaction Effects

**Soil displacement (liquefaction)**

After Northridge earthquake motion (PGA=0.224g)

**Soil displacement (no liquefaction)**
Local Responses

Locations of max. pile curvature (left abutment)

- Abutment pile (left)
  - max. curvature (mm)
  - motion number

- Pile group 1
  - max. curvature (mm)
  - motion number

15 yrs  72 yrs  475 yrs  2475 yrs
Parametric Uncertainty

Tornado diagrams (small shaking)

Bridge column 4: max. curvature

EDP(μ +/- 0.5σ) normalized by EDP(μ)

- clay (c)
- loose sand (G)
- embankment(G)
- sand (phi)
- contract para
- clay (G)
- pile (y50)
- pileCap (y50)
- pile (puit)
- pileCap (puit)
- abutWall (puit)
- bearingPad (K)
- abutWall (y50)
- pile (resid)
- breakWall (Fy)

EDP(μ) = 0.0024065

- pileCap (y50)
- pileCap (puit)
- pile (y50)
- loose sand (G)
- clay (G)
- pile (puit)
- clay (c)
- sand (phi)
- contract para
- bearingPad (K)
- embankment(G)
- abutWall (puit)
- abutWall (y50)
- pile (resid)
- breakWall (Fy)

EDP(μ +/- 0.5σ) normalized by EDP(μ)
EDP Hazard to DM/DV Hazard

DV fragility curve
Integration of Uncertainties through PBEE Framework

Bridge column damage uncertainty

| Damage State     | Median EDP | $\sigma_{ln(\text{DM}|\text{EDP})}$ |
|------------------|------------|-------------------------------------|
| DS1: cracking    | 0.50       | 0.30                                |
| DS2: spalling    | 2.04       | 0.33                                |
| DS3: bar buckling| 6.46       | 0.25                                |
| DS4: failure     | 9.01       | 0.35                                |

DM fragility curves

DM hazard curve

No uncertainty in repair cost estimation from DM

EDP hazard curve

$\lambda_{\text{EDP}} = 1.044e-006 \text{ (EDP)}^{-2.49}$
\[
\lambda_{edp_j} = \sum_{i=1}^{N_{IM}} P[EDP > edp_j \mid im_i] \Delta im_i
\]

EDP\textsubscript{j} fragility curve
\[
\lambda_{EDP_i} = \sum_{i=1}^{N_{IM}} P[EDP > EDP_j \mid IM_i] \Delta\lambda_{IM_i}
\]

\[
\Delta\lambda_{IM_i} = \lambda_{IM_{i+1}} - \lambda_{IM_i}
\]
\[ \lambda_{dv_i} = \sum_{k=1}^{N_{dm}} \sum_{j=1}^{N_{edp}} \sum_{i=1}^{N_{im}} P[DV > dv_i | dm_k] P[DM = dm_k | edp_j] P[EDP = edp_j | im_i] \Delta \lambda_{im_i} \]