Application of Performance Based Earthquake Engineering (PBEE) to Caltrans Ordinary Standard Bridge Design

California Dep. of Transportation
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Part A – Approach and Theoretical Background
Components of Performance Based Earthquake Engineering

• **Hazard Analysis:**
  
  Hazard Identification: Location, Intensity, Risk Loading: Seismic Intensity -> Acceleration Record/Input Motion

• **Structural Analysis:**
  
  Structural Analysis: Modeling Guidelines & Software

• **Damage Analysis:**
  
  Displacement, Ductility, & Strain

• **Loss Analysis**
1. Hazard Analysis

- **Linear Spectral Analysis:** Acceleration Response Spectra: ARS Online

- **NLTHA:** Uniform Excitation $\rightarrow$ Acceleration Time History
  - Basis of Design: Site-Specific Design (Target) ARS obtained from ARS online
  - Synthetic Records (captures important site characteristics)
  - Record Selection (subset of all generated records)
  - Spectral Matching (Modify record to have its ARS match a target ARS)
  - Average of 7 Records
PBEE Application – Part A

1. Hazard Analysis

Synthetic Record Generation:

- UCB Synthetic Record Generation Algorithm (By Prof. ADK)

Input Parameters:
F, M_w, V_{s30}, R, etc

Random Model Parameters: Ia, D_{5.95}, etc

White Noise

Random Model Parameters: Ia, D_{5.95}, etc

White Noise

Random Model Parameters: Ia, D_{5.95}, etc

White Noise

Synthetic Records

• Modeling of Velocity Pulse
Parameters Needed for Record Generation:

• **Fault Type**: Strike-Slip or Non-Strike-Slip

• **Moment Magnitude, \( M_w \)**: Can be chosen between 5.5 to 8

• **Fault Distance, \( R \)**: Between 0 km and 30 km

• **Shear Wave Velocity, \( V_{s30} \)**: Between 100 m/s and 2100 m/s

• **Directivity Angle, \( \theta \)**: Between 0 and 90 degrees

• **Distance, \( S \)**: Between 0 km and 70 km
PBEE Application – Part A

1. Hazard Analysis

Synthetic Record Generation - Example

Pseudo-acceleration response spectra at 5% damping of the NGA record #285 (black thick line), of 20 simulated ground motions using the fitted parameters (grey lines), and their geometric mean (thick grey line)
PBEE Application – Part A

1. Hazard Analysis

Record Selection:

- Spectral Matching using TDSMatch based on Time Domain algorithm by Norm Abrahamson used in RSPMatch

![Design ARS with ARSs from Synthetic GMs](image)

TDSMatch
PBEE Application – Part A

1. Hazard Analysis

Input Motion Generation/Selection:

• Generate Design ARS from ARS Online (Target ARS), based on 1000-year return period

• Generate Synthetic Records: 50 Records (with near field velocity pulse if near field effect is needed)

• Select 7 records (from set of 50) with closest match to target ARS within $0.5 < T < 3.0$ seconds

• Scale Records: Use TDSMatch to adjust the 7 selected records to the target ARS

• Use the adjusted records for analysis
PBEE Application – Part A

2. Structural Analysis

Nonlinear Time History Analysis (NLTHA):

• Bridge Behavior in Seismic event is NONLINEAR
• NLTHA is the most accurate method available
• Current tools are efficient enough for NLTHA
• Response Spectrum Analysis does not capture some key nonlinear responses (e.g., column plastic hinge, span hinge, shear key, abutment response, & isolation bearing)
• Equal displacement principal is an approximation
PBEE Application – Part A

2. Structural Analysis

What is needed for Nonlinear Time History Analysis:

• Loading Guidelines (i.e., Acceleration Time History Records):
  ➢ Intensity, peak acceleration, #of peaks
  ➢ Duration
  ➢ Frequency content
  ➢ Near-Field Effect

• Modeling Guidelines: PEER 2008-03

• Reliable Software: CSI-Bridge, OpenSees, & Midas-Civil

• Acceptance Criteria: $\Delta_{\text{capacity}} / \Delta_{\text{demand}}$, Ductility, etc.
PBEE Application – Part A

2. Structural Analysis
Modeling Nonlinear Behavior:

• Column Hinge

• Abutment Springs

• Hinge impact & Shear key

• Soil Structure Interaction (p-y, t-z, & q-z)
PBEE Application – Part A

2. Structural Analysis

Response Calculation:

• Apply each input motion in longitudinal and transverse directions (and more directions if curved or highly skewed)

• Record maximum displacements in longitudinal and transverse directions

• Calculate average of the maximum displacements (in each direction) as displacement demand

Capacity Calculation:

• Perform push-over analysis in longitudinal and transverse directions

• Calculate displacement capacity based on strain limits given in SDC
PBEE Application – Part A

3. Damage Analysis

Acceptance Criteria / Damage Assessment:

- Displacement-based, Current SDC Limits:
  - $\Delta_{\text{demand}} =$ average $\Delta_{\max.\text{col}}$ of each column
  - $\Delta_{\text{capacity}} =$ From Push-over analysis of bent or frame
  - $\mu_{d.\text{col}} = \frac{\Delta_{\text{demand}}}{\Delta_y}$; $\mu_{c.\text{col}} = \frac{\Delta_{\text{capacity}}}{\Delta_y}$
  - $\Delta_{\text{demand}} \leq \Delta_{\text{capacity}}$ &
  - $\mu_{d.\text{col}} \leq 4$ (single column) or 5 (multi-column) &
  - $\mu_{c.\text{col}} \geq 3$
3. Damage Analysis

Possible Future Acceptance Criteria / Damage Assessment:

• No Push-over Analysis needed, instead calculate the ultimate curvature for each plastic hinge

• Compare Curvature demand and capacity:
  ➢ Yield curvature = \( \phi_y \), based on SDC idealized M-\( \phi \) curve
  ➢ Curvature demand = \( \phi_d \) = Average of maximum curvatures of the 7 analysis cases
  ➢ Curvature capacity = \( \phi_c \) (based on SDC strain limits), i.e.: \( \phi_d \leq \phi_c \)
  ➢ Curvature Ductility: \( \phi_c / \phi_y \geq 10 \) (using SDC values)

• Identify Damage Index:
  ➢ Curvature demand \( \rightarrow \) Max strain demand \( \rightarrow \) Damage Index
### 3. Damage Analysis

**Possible Future Acceptance Criteria / Damage Assessment:**

**Damage State (DS) Index with Associated Strain Threshold and Repair Cost**
Based on the work by Saini and Saiidi, 2014

<table>
<thead>
<tr>
<th>Damage State (DS)</th>
<th>Description</th>
<th>Trigger</th>
<th>Trigger Value</th>
<th>Item - Strategy</th>
<th>Units</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Concrete Cover Strain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concrete Core Strain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main Steel Strain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Confinement Steel Strain</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Surface cracks</td>
<td>Strain</td>
<td>&lt;= 0.002</td>
<td>OK</td>
<td>na</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>First spalling</td>
<td>Strain</td>
<td>0.002 &lt; ε ≤ 0.005</td>
<td>Patch Concrete</td>
<td>SQFT</td>
<td>$400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>na</td>
<td></td>
<td></td>
<td>$250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.002 &lt; ε ≤ 0.005</td>
<td>Epoxy Inject</td>
<td>LF</td>
<td>$100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.002 &lt; ε ≤ 0.005</td>
<td></td>
<td></td>
<td>$50</td>
</tr>
<tr>
<td>3</td>
<td>Major spalling</td>
<td>Strain</td>
<td>Spalled to core strain height</td>
<td>Patch Concrete</td>
<td>SQFT</td>
<td>$400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.005 &lt; ε ≤ 0.008</td>
<td></td>
<td></td>
<td>$250</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.005 &lt; ε ≤ 0.010</td>
<td></td>
<td></td>
<td>$100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.005 &lt; ε ≤ 0.010</td>
<td></td>
<td></td>
<td>$50</td>
</tr>
<tr>
<td>4</td>
<td>Exposed reinf.</td>
<td>Strain</td>
<td>Spalled</td>
<td>Steel Column Casing</td>
<td>EA</td>
<td>$61,200</td>
</tr>
<tr>
<td>5</td>
<td>Core shedding</td>
<td>Strain</td>
<td>Spalled</td>
<td>Replace Column</td>
<td>EA</td>
<td>$138,055</td>
</tr>
<tr>
<td>6</td>
<td>Failure (rupture)</td>
<td>Strain &amp; Displ.</td>
<td>Spalled</td>
<td>Replace Superstructure and Columns</td>
<td>EA</td>
<td>$1,455,840</td>
</tr>
</tbody>
</table>
Hazard Analysis - Loading (Input motions):
- Generate 50 synthetic records (Include near-field effect if needed)
- Select 7 records that best match design ARS in range $0.5s < T < 3.0s$
- Use TDSMatch to adjust selected records to design ARS

Structural Analysis - Modeling: Include major nonlinearities:
- Column plastic hinge, abutment spring, shaft p-y, & span hinge

Structural Analysis - Analysis: CSIBridge, OpenSees, or Misdas-Civil, etc.
- Perform Nonlinear analysis in long./transverse (and maybe more) directions
- Calculate maximum displacement demand (average of 7 motions)

Damage Analysis - Acceptance Criteria:
- Perform Push-over analysis, obtain displacement capacity
- Compare displacement demand vs. capacity (Current SDC)
- Future: Compare curvature demand demand vs. capacity
Continue to Part B..
Application of Performance Based Earthquake Engineering (PBEE) to Caltrans Ordinary Standard Bridge Design

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Part B –
Illustrative Example
PBEE Application – Part B

Design Scenario: An Ordinary Standard Bridge will be located in Bay Area, near San Mateo, at junction of highway 82 and 92. The bridge is a CIP/PT box girder bridge with two spans of 150 feet each. The bent consists of two 5’-6” diameter reinforced concrete columns. The footing is founded on competent rock.
PBEE Application – Part B

Step 1: Acceleration Record Generation & Selection

Step 2: Structural Analysis for Demand

Step 3: Structural Analysis for Capacity & Damage Assessment
PBEE Application – Part B

Step 1a: Acceleration Record Generation - Determine Target ARS from ARS Online and Obtain Parameters for Synthetic Ground Motion Generation.

Fault: Strike-Slip
Mw: 8.0
R: 5.4 km
V_{S30}: 760 m/sec
θ: 28 deg
s: 10 km
PBEE Application – Part B

Step 1a: Acceleration Record Generation - Determine Target ARS from ARS Online and Obtain Parameters for Synthetic Ground Motion Generation.

Location: LAT=37.550226 LONG=-122.311993 Vs30=760m/s

Minimum Deterministic Spectrum
- San Andreas (Peninsula) 2011 CFM (With Near Fault Factor Applied)
- San Gregorio fault (San Gregorio section) (With Near Fault Factor Applied)
- San Andreas (Santa Cruz Mts) 2011 CFM (With Near Fault Factor Applied)
- USGS 5% in 50 years hazard (2008) (With Near Fault Factor Applied)

Target ARS for Spectral Matching
PBEE Application – Part B

Step 1b: Acceleration Record Generation - Generate 50 ground motions.
PBEE Application – Part B

Step 1c: Acceleration Record Selection - Find 7 motions with lowest deviations from Target ARS.
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Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.
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Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.

**Scaled Velocity Time History**
Filename = scenario#1_Sim#2_FN_Acc_NoPulse_2013_6_20.txt, Scale Factor = 1.003, Sum of Error Squared = 0.017

**Scaled Displacement Time History**
Filename = scenario#1_Sim#2_FN_Acc_NoPulse_2013_6_20.txt, Scale Factor = 1.003, Sum of Error Squared = 0.017
PBEE Application – Part B

Step 1d: Acceleration Record Selection - Conduct Spectral Matching of 7 Motions to Target ARS.
PBEE Application – Part B

Step 2a: Structural Analysis – Idealize Bridge Model

Geometry & Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Deck</th>
<th>Bentcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (ksi)</td>
<td>4287</td>
<td>4287</td>
</tr>
<tr>
<td>$G$ (ksi)</td>
<td>1786</td>
<td>1786</td>
</tr>
<tr>
<td>$f'_{ce}$ (ksi)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$A_{CrossSection}$</td>
<td>79</td>
<td>79</td>
</tr>
<tr>
<td>$I_{xx}$ (ft$^4$)</td>
<td>-</td>
<td>156</td>
</tr>
<tr>
<td>$I_{yy}$ (ft$^4$)</td>
<td>418</td>
<td>-</td>
</tr>
<tr>
<td>$I_{zz}$ (ft$^4$)</td>
<td>13307</td>
<td>325</td>
</tr>
</tbody>
</table>
PBEE Application – Part B

Step 2a: Structural Analysis – Idealize Bridge Model

\[ P_{axial} = 1340 \text{ k} \]

DS5 \( \varepsilon_{ult} \) 0.06

Column Plastic Hinge
Fiber Model

Shear Key F-\( \Delta \)
PBEE Application – Part B

Step 2a: Structural Analysis – Idealize Bridge Model

Rayleigh Damping:
5 % damping @ T = 0.17 & 2 sec (f = 0.5 & 5.88 Hz)

Integration Type:
Newmark

Algorithm:
Modified Newton
PBEE Application – Part B


- Displacement time history in longitudinal direction:
  - Column top subjected Motion Rock2

- Displacement time history in transverse direction:
  - Column top subjected Motion Rock2

Displacement time history @ column top subjected Motion Rock2

Moment - Curvature History
@ column top subjected Motion Rock2
PBEE Application – Part B

**Step 3a: Structural Analysis for Capacity** – Conduct Push-over Analysis to determine Displacement & Curvature Capacity

Pushover results in transverse direction

<table>
<thead>
<tr>
<th>Damage State</th>
<th>$\Delta_y$ (in)</th>
<th>$\Delta_c$ (in)</th>
<th>$\phi_y$ (rad/in)</th>
<th>$\phi_c$ (rad/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 ($\varepsilon_{ult} = 0.06$)</td>
<td>2.3</td>
<td>1.8</td>
<td>12.9</td>
<td>10.4</td>
</tr>
</tbody>
</table>
## PBEE Application – Part B

### Step 3b: Acceptance Criteria / Damage Assessment

#### Displacement Based

<table>
<thead>
<tr>
<th>Motion ID</th>
<th>$\Delta_d$ (in)</th>
<th>$\mu_d$ (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Dir</td>
<td>Trans Dir</td>
</tr>
<tr>
<td>ROCK1</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>ROCK2</td>
<td>4.3</td>
<td>7.8</td>
</tr>
<tr>
<td>ROCK3</td>
<td>3.9</td>
<td>6.7</td>
</tr>
<tr>
<td>ROCK4</td>
<td>3.5</td>
<td>6.1</td>
</tr>
<tr>
<td>ROCK5</td>
<td>4.7</td>
<td>7.1</td>
</tr>
<tr>
<td>ROCK6</td>
<td>3</td>
<td>11.6</td>
</tr>
<tr>
<td>ROCK7</td>
<td>5.4</td>
<td>6.6</td>
</tr>
<tr>
<td>Avg</td>
<td>4.1 $&lt; \Delta_c$</td>
<td>7.8 $&lt; \Delta_c$</td>
</tr>
<tr>
<td>$\Delta_c$</td>
<td>12.9</td>
<td>10.4</td>
</tr>
<tr>
<td>$\mu_c$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
# PBEE Application – Part B

## Step 3c: Alternate Acceptance Criteria / Damage Assessment

### Curvature Based

<table>
<thead>
<tr>
<th>Motion ID</th>
<th>( \phi_d ) (in) @ Col 1</th>
<th>( \phi_d ) (in) @ Col 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long Dir</td>
<td>Trans Dir</td>
</tr>
<tr>
<td>ROCK1</td>
<td>2.8E-04</td>
<td>8.6E-04</td>
</tr>
<tr>
<td>ROCK2</td>
<td>3.5E-04</td>
<td>8.2E-04</td>
</tr>
<tr>
<td>ROCK3</td>
<td>3.3E-04</td>
<td>8.4E-04</td>
</tr>
<tr>
<td>ROCK4</td>
<td>2.9E-04</td>
<td>6.8E-04</td>
</tr>
<tr>
<td>ROCK5</td>
<td>4.5E-04</td>
<td>6.8E-04</td>
</tr>
<tr>
<td>ROCK6</td>
<td>3.8E-04</td>
<td>9.1E-04</td>
</tr>
<tr>
<td>ROCK7</td>
<td>4.5E-04</td>
<td>7.0E-04</td>
</tr>
<tr>
<td>Avg</td>
<td>3.6E-04 &lt; ( \phi_c )</td>
<td>7.8E-04 &lt; ( \phi_c )</td>
</tr>
</tbody>
</table>

\( \phi_c \)

| \( \phi_c \) | 1.3E-3 | 9.1E-4 | 1.3E-3 | 9.1E-4 |
| \( \phi_c / \phi_y \) | 19.7 > 10 | 13.0 > 10 | 19.7 > 10 | 13.0 > 10 |
PBEE Application – Part B

The above example was performed applying the motions in bridge longitudinal and transverse directions only. The complete analysis can be made repeating steps 2 & 3 by orienting the ground motions at different orientations (30 & 60 deg) per MTD 20-17.
PBEE Application – Part B

Question?