A Computational Framework for Systematic Bridge Performance-Based Earthquake Engineering Applications

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Motivation

- As critical lifelines in transportation network, highway bridges have received much research attention.

- Disruption of function after an earthquake can result in substantial, negative wide-scale economic consequences.

- PBEE is a framework that seeks to go beyond traditional design practice and address issues related to safety, functionality, and economy from the perspective of stakeholders.

I-5 Damage (http://www.dot.ca.gov/hq/paffairs/about/retrofit.htm)
Objectives

• Increase understanding of nonlinear analysis of bridge systems.

• Provide a robust, data accessible, easily implementable tool that enables PBEE framework within an integrated simulation environment.

photo of the Samoa Channel Bridge
(http://www.strongmotioncenter.org)
PEER PBEE

Hazard Model

Demand Model

Damage Model

Loss Model
<table>
<thead>
<tr>
<th>PG</th>
<th>Engineering Demand Parameters</th>
<th>DS0</th>
<th>DS1</th>
<th>DS2</th>
<th>DS3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG1</td>
<td>Maximum column drift ratio</td>
<td>Concrete cracking</td>
<td>Concrete cover</td>
<td>Longitudinal reinforcing bar buckling</td>
<td>Failure</td>
</tr>
<tr>
<td>PG2</td>
<td>Residual column drift ratio</td>
<td>Threshold</td>
<td>Thicken pier</td>
<td>Re-center column</td>
<td>Failure</td>
</tr>
<tr>
<td>PG3 &amp; PG4</td>
<td>Maximum relative longitudinal deck-end/abutment displacement for left &amp; right abutments</td>
<td>Joint cleaning</td>
<td>Joint seal assembly replacement</td>
<td>Backwall (retaining wall) spalling</td>
<td>Backwall (retaining wall) failure</td>
</tr>
<tr>
<td>PG5 &amp; PG6</td>
<td>Maximum lateral bearing displacement for left &amp; right abutments</td>
<td>Yield</td>
<td>Failure</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PG7 &amp; PG8</td>
<td>Approach residual vertical displacement for left &amp; right abutments</td>
<td>Pavement repair</td>
<td>Asphalt concrete regrade</td>
<td>Rebuild</td>
<td>-</td>
</tr>
<tr>
<td>PG9 &amp; PG10</td>
<td>Residual lateral pile displacement at ground surface for left &amp; right abutments</td>
<td>Add pile threshold</td>
<td>Enlarge foundation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PG11</td>
<td>Column residual pile displacement at ground surface</td>
<td>Add pile threshold</td>
<td>Enlarge foundation</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
PBEE (Mackie et al. 2012)

Maximum column drift damage states

<table>
<thead>
<tr>
<th>DS</th>
<th>Damage state limit description</th>
<th>$\lambda$ (%)</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS0</td>
<td>Concrete cracking</td>
<td>0.24</td>
<td>0.3</td>
</tr>
<tr>
<td>DS1</td>
<td>Onset of spalling</td>
<td>1.65</td>
<td>0.33</td>
</tr>
<tr>
<td>DS2</td>
<td>Buckling of bars</td>
<td>6.85</td>
<td>0.25</td>
</tr>
<tr>
<td>DS3</td>
<td>Failure</td>
<td>7.55</td>
<td>0.35</td>
</tr>
</tbody>
</table>
MSBridge (Lu et al. 2016)

- A computational user interface (MSBridge) is developed to combine nonlinear (THA) with an implementation of a PBEE methodology.
- OpenSees is employed to conduct Nonlinear THA.
MSBridge: Capabilities

Curved bridge with foundation of soil springs

Bridge with different numbers of columns for bents (with Foundation stiffness matrix)

p-y models: a) Soft clay (Matlock); b) Stiff clay without free water (Reese); c) Sand (Reese); and d) Liquefied sand (Rollins)

Foundation matrix (Lam and Martin 1986)
MSBridge: Capabilities

Abutment models

Elastic
SDC 2004

Roller
SDC 2004 Sand
SDC 2010 Clay
EPP-Gap
HFD Model
MSBridge: Capabilities

- Ground motion viewer
- Ground motion intensity measures
- Visualization of plastic hinges
- Mode shape analysis
Bridge Description (Ketchum et al. 2004)

- The case of study presented in this paper is straight, single column bents, box girder, reinforced concrete bridge with five spans. The columns have a circular cross section of 1.22 m in diameter, 11.9 m wide two-cell box girder for the deck, and 15.2 m for the clear column heights.
FE Modeling

Column cross-section

Fiber sections

Core Concrete01

Cover Concrete01

Steel01

Moment curvature

1.22 m diam.

#10 tot 30

Strain

Stress (MPa)

fc, fcu

Curvature (1/m)

Moment (kN-m)

fc, fcu

Stress (MPa)

fy

Stress (MPa)

Strain

Stress (MPa)

Strain
Ground Motions

A set of 100 ground motions selected to be representative of seismicity in typical regions in California was employed in this study (Mackie et al. 2007). The motions are divided into 5 bins:

i) moment magnitude (Mw) 6.5–7.2 and closest distance (R) 15–30 km (LMSR),

ii) Mw 6.5–7.2 and R 30–60 km (LMLR),  iii) Mw 5.8–6.5 and R 15–30 km (SMSR),

iv) Mw 5.8–6.5 and R 30–60 km (SMLR), v) Mw 5.8–7.2 and R 0–15 km (Near).

PGV distribution for the SRSS of two lateral ground motion components
PBEE Outcomes: Repair costs by PGs

![Graph showing repair costs by PGs](image)

Legend:
- PG1: max. tangential drift ratio (col 1)
- PG2: res. tangential drift ratio (col 1)
- PG3: max rel. deck disp. (left abut.)
- PG4: max rel. deck disp. (right abut.)
- PG5: max. bearing disp. (left abut.)
- PG6: max. bearing disp. (right abut.)
- PG7: Approach res. vertical disp. (left abut.)
- PG8: Approach res. vertical disp. (right abut.)
- PG9: res. pile disp. (left abut.)
- PG10: res. pile disp. (right abut.)
- PG11: res. pile displ. (col 1)
PBEE Outcomes

![Graph showing repair cost ratio and repair time for PBEE outcomes.](image)

- **Repair cost ratio (%):**
  - Mean line
  - +/- 1 σ line

- **Repair time (CWD):**
  - Mean line
  - +/- 1 σ line

PGV (cm/s) vs Repair cost ratio (%)
PGV (cm/s) vs Repair time (CWD)
Samoa Channel Bridge

Pile Groups (Plan View)

Liquefaction-induced lateral spreading
Conclusions

• A computational framework (MSBridge) is developed to combine nonlinear Time History Analysis (THA) of multi-span bridge systems with an implementation of a performance-based earthquake engineering (PBEE) methodology.

• By coupling a refined graphical user interface for modeling of bridge FE models with a PBEE framework. MSBridge has enabled more transparent access to performance-based assessment for typical highway bridges.

• The abutments repairs are among the most significant parameters that contribute in the expected costs and times.
Thank you