Bridge PBEE and Resilience

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PEER’s Mission

“Advance and apply performance-based earthquake engineering tools to meet the needs of various stakeholders”
What’s the Point?

PBEE Provides framework and tools to:

- Allow stakeholders to make informed decisions
- Balance competing objectives
- Consider variety of performance levels
- Evaluate/develop new materials and systems
Transportation System Objectives

- Economical
  - Construction (include disruption?)
  - Maintenance and inspection
  - Repair
  - Disposal
Transportation System Objectives

“Safe”
- Very low likelihood of loss of life
- Very, very low likelihood of collapse

Kobe
Northridge
Transportation System Objectives

- Disaster Resilient
  - Minimize disruption to **community**
  - Available soon/immediately to aid recovery
  - Minimal inspection and repair costs/time
  - Minimal loss of revenue (fares, tolls, contracts)
Transportation System Objectives

- Sustainable
  - Durability
  - Environmental impact
    - Embodied carbon
      - Construction
      - Use
      - Destruction
    - Construction noise
    - Construction traffic congestion
    - Fish migration
How is Bridge PBEE Doing??

- **Soft Implementation**
  - Language/concepts
  - Major bridges
  - Education

- **Hard Implementation** (AAHSTO Guide Spec.)
  - Displacement-based design
  - Discussion of hazard and performance criteria
  - Displacement capacity of RC columns (4.8.1)
TSRP Projects

- Enabling Technologies: Overcoming Implementation Barriers/Complexities
  - Ground-motion selection (Baker)
  - Ground-motion stochastic modeling (Der Kiureghian)
  - Long-duration motions (Deierlein, Kramer)
  - OpenSEES tools for uncertainty analysis (Scott, Mackie, Conte)
  - Software platform for PBEE of Bridge Systems (Elgamal)
  - Size effects in bridge columns (Mosalam)
  - PBEE of Humboldt Bridge (Conte)
TSRP Projects

- Developing New Resilient/Sustainable Systems
  - High-performance fiber-RC (Ostertag, Billington)
  - Post-tensioned CIP Columns (Mahin)
  - Dual-shell steel columns (Restrepo)
  - Precast, pre-tensioned bridge bents (Stanton)
  - Rocking foundations (Kutter, Panagiotou)
  - Isolation of bridge segments (Mahin)
TSRP Projects

http://peer.berkeley.edu/transportation/projects/
Enabling Technologies
The product: several standardized ground motion sets

New Ground Motion Selection Procedures and Selected Motions for the PEER Transportation Research Program

Jack W. Baker
Ting Lin
Shrey K. Shahi
Department of Civil and Environmental Engineering
Stanford University
Nirmal Jayaram
Risk Management Solutions, Inc.

PEER Report 2011/03
Documentation of targets, selection methodology and summary data for each selected set (106pp)
Stochastic dynamic analysis of bridges subjected to spatially varying ground motions

Katerina Konakli
and Armen DerKiureghian
University of California, Berkeley
Motivation
Use of RHA for investigation of “equal displacement” rule

$C_\mu$: ratio of nonlinear to linear response (pier drifts)

$\mu$: ductility ratio

case 1: uniform support motions

case 2: variable support motions
Graphical interface for integrated PBEE

- Handle the input ground motion ensemble and computing the corresponding intensity measures
- Automatically generate user-defined bridge-ground FE models
- Post-processing capability to display seismic response ensembles and PBEE outcomes

PBEE outcomes: repair costs, repair times (loss models, fragility, or hazard)
BridgePBEE

- Graphical interface for integrated PBEE

**STEP 1: DEFINE MODEL**
- Analysis Type
  - Pushover
  - Eigenvalue
  - Base Shaking
- PBEE Analysis
  - Ground Shaking
- Model Definition
  - Bridge Parameters
  - Soil Parameters
  - Mesh Parameters
  - Analysis Options
- Boundary Conditions
  - B.C. Type: Shear Beam
  - Bedrock Type: Rigid Bedrock

**STEP 2: EXECUTE**
- Save Model & Run Analysis

**STEP 3: COMPUTE REPAIR**
- PBEE Quantities

Mackie/Elgamal
Performance-Based Earthquake Engineering Analysis of Humboldt Bay Middle Channel Bridge

Joel P. Conte, Ahmed Elgamal, Yuyi Zhang, and Zhaohui Yang

Dept. of Structural Engineering
University of California, San Diego

PEER
Pacific Earthquake Engineering Research Center
Humboldt Bay Bridge Testbed
OpenSEES Finite Element Model

- 10,889 nodes, 10,600 elements and 20,686 degrees of freedom
- Size of the soil domain $1050 \times 220m$, plane strain condition
- Thickness of the soil domain: 6.10 m, thickness of the abutments: 10.4 m
- Four-noded, bilinear, isoparametric finite elements with four integration points
- The maximum size of the soil elements is controlled to accurately propagate seismic waves up to 15Hz
Potential Failure Mechanisms and Associated EDPs

- Pier flexural failure (EDP: peak pier lateral drift)
- Shear key failure (EDP: peak shear key deformation)
- Unseating (EDP: peak unseating displacement)
Seismic Loss Hazard Analysis Results

- Contribution of pier failure
- Contribution of shear key failure
- Contribution of unseating
- Contribution of collapse

Total repair cost [$ million]

$M = S_a(T_1, \xi = 5\%) [g]$
Developing New Systems
Resilient Designs Options

- Origin-oriented hysteretic loops
  - Partially prestressed RC columns
  - Rocking of foundations

- Seismic Isolation

![Diagram of Origin-oriented hysteretic loops](image1)

![Diagram of Seismic Isolation](image2)
Partially Prestressed, Reinforced Concrete Self-Centering Column (Mahin)

Design method:
- Mild reinforcement reduced
- Prestressing force from a central unbonded tendon
Ductile Self-Centering Bridge Column

- $\mu > 10$, peak displacements within 10%
- Residual displacement < 0.6%
Advanced Precast Concrete

Dual-Shell Steel Columns

Gabriele Guerrini
Graduate Student Researcher

Jose' I. Restrepo
Professor, Principal Investigator

University of California, San Diego
Structural Engineering Department
Goals

- Accelerated bridge construction
- Resilient bridge pier seismic performance

Main Features

- Dual steel shells
- Postensioning / recentering
- Energy dissipation
- Fiber-reinforced mortar

Precast bent cap
Fiber-reinforced mortar
PT bar
Energy dissipator
Dual steel shells
Full height
PT bar
Dual steel shells
Energy dissipator
Advantages

- Limited structural damage compared to monolithic systems
- Small residual displacements compared to monolithic case
- Operability right after strong shakes
- Added energy dissipation

Monolithic System

Self-Centering System

Shear-wall test results

(Restrepo, Mander, Holden)
Damage Resilient Precast Structures
(Stanton, UW)
<table>
<thead>
<tr>
<th>Connection Details</th>
<th>CIP RC (ref)</th>
<th>Precast RC</th>
<th>Precast Pretensioned</th>
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<tbody>
<tr>
<td>Cap-Beam to Column</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
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<tr>
<td>Column to Spread Footing</td>
<td><img src="image4" alt="Diagram" /></td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
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<tr>
<td>Column to Drilled Shaft</td>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
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Seismic Performance Evaluation of Bridges with Foundations Designed to Uplift

Grigorios Antonellis
Graduate Student Researcher
University of California, Berkeley

Marios Panagiotou
Assistant Professor,
University of California, Berkeley
“Fixed” base pier

Pier on rocking shallow foundation
Median Total Repair Cost

Total Repair Cost (million of $)

Sa (T = 1 sec), (g)

- Red line: Fixed Base
- Blue line: B=4D, Fsv=5.4
- Green line: Rocking pile-cap, B=3D

Fixed Base
B=4D, Fsv=5.4
Pile Cap, B=3D
Isolation of Segmented Bridges

PLAN VIEW

Impact

Offset

$\ddot{U}_g$
Segmental Displacement Control

Lock-Up Guides to retrain relative transverse displacement of segments

Linear Bearings at ends to restrain transverse displacement at abutments

PLAN VIEW
Segmental Displacement Control

- Isolated bridge with relative lateral restraint of independent segments

PLAN VIEW

$\bar{U}_g$
Segmental Displacement Control

- Lock-Up Guide
Test Observations
Concluding Remarks

- PBEE has transformed bridge engineering culture.
- In process of transforming standard practice
- Transportation System Research Program (TSRP) focused on developing/validating
  - Enabling Technologies
  - New resilient and sustainable systems.
- PLEASE PARTICIPATE IN TSRP SESSIONS TOMORROW.