Foundation *Rocking* as a Bridge

Design Strategy

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Past Research on Rocking Foundations

**Numerical** studies of single piers (Muto, Chopra and Yim), rigid blocks (Housner, Zhang and Makris) and bridge systems (Mergos and Kawashima).

**Experimental** studies include **Caltrans-funded** studies:

- Shake table tests of bridge piers on rocking shallow foundations
  *Espinoza and Mahin (2008)*

- **Centrifuge tests of Systems**
  *Deng, Kunnath and Kutter*
Can we design economical bridges at near-fault sites using rocking foundations to minimize earthquake induced damage and ensure post-earthquake functionality?
PART I

Seismic Design and Analysis of Bridges with Rocking Foundations at a Near-fault Site

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Graduate Student Researcher

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Assistant Professor

University of California (UC) Berkeley
Design concepts studied

Conventional fixed-base

Rocking pile foundation

Rocking shallow foundation

FB  RPF  RSF
Geometry of bridges

(a) Side view

Two column heights

\[ H_c = 15.2 \text{ m} \]

\[ H_c = 6.7 \text{ m} \]

(b) found.-column-deck elevation

(c) abutment-bearings section view
Description of site and ground motions

- Site: Oakland, California, 3 km from Hayward fault, $V_{s,30} = 400$ m/s (Soil type C)
- Bi-axial horizontal excitation
- 14 ground motions linearly scaled

Maximum Considered Earthquake (MCE): 2% probability of exceedance in 50 years
Fixed-base bridges

- $D_c = 1.8 \text{ m, } \rho_l = 2\%$
- Rubber bearings $D_b = 0.6 \text{ m}$

Rocking foundation bridges

Design Objectives at MCE

- Nominally elastic response of columns, deck and piles
- Less than 0.03B soil settlement

- $D_c = 2.5 \text{ m, } \rho_l = 3\%$
- **Lead rubber bearings**
  - $D_b = 1.3 \text{ m, } D_{lead} = 0.34 \text{ m}$
- Square $B=8 \text{ m shallow footings}$
- 25 m long piles -1.5 m diameter
3D Numerical Modeling (OpenSees)

(a) Abutment model

Force, (MN)

Displacement, (m)

Passive
Friction

(b) Shear key model

(c) Pile - vertical spring model

(d) Rocking pile foundation model
Analyses results

Lateral displacement and force profiles at 4% column drift ratio

(a) 17 m tall bridges - Displacement

(b) 8 m tall bridges - Displacement

(c) 17 m tall bridges - Force

(d) 8 m tall bridges - Force
## Analyses results (mean values)

<table>
<thead>
<tr>
<th></th>
<th>FB17</th>
<th>RPF17</th>
<th>RSF17</th>
<th>FB8</th>
<th>RPF8</th>
<th>RSF8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column drift ratio, (%)</td>
<td>4.9</td>
<td>4.1</td>
<td>4.0</td>
<td>3.6</td>
<td>4.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Residual drift ratio, (%)</td>
<td>0.15</td>
<td>0.01</td>
<td>0.17</td>
<td>0.07</td>
<td>0.07</td>
<td>0.16</td>
</tr>
<tr>
<td>Tensile strain at column base (%)</td>
<td>5.3</td>
<td>0.2</td>
<td>0.1</td>
<td>5.6</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Column axial compression force increase</td>
<td>0.2</td>
<td>0.7</td>
<td>0.4</td>
<td>0.5</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Less than 0.8% total tension strain in post-tensioning strands of the deck*
Analyses results (for individual motion)

Shallow foundation moment-rotation response

(a) RSF17

(b) RSF8
Analyses results (for individual motion)

System lateral resisted force versus lateral drift

(a) FB17

(b) RPF17
PART II

Large-scale shake table test of columns supported on *rocking shallow foundations*
Ongoing research project funded by California Department of Transportation (Caltrans)

**Principal Investigators**
- Marios Panagiotou, UC Berkeley
- Bruce Kutter, UC Davis
- Jose Restrepo, UC San Diego
- Patrick Fox, UC San Diego
- Stephen Mahin, UC Berkeley

**Graduate Student Researchers**
- Grigorios Antonellis, UC Berkeley
- Andreas Gavras, UC Davis
- Gabriele Guerrini, UC San Diego
- Andrew Sander, UC San Diego
NEES@UCSD large confinement soil box

9.1 m

7.6 m

4.6 m
Geometry of the specimens and test setup

- **Clean sand ~ 80% relative density**
- $FS_v \approx 11$
- $C_r \approx 0.26$
- $W_t/A_gf'_c = 5\%$

Soil surface

Cast concrete (test day 3 only)

Water level

Test Day 3

Test Day 2

Test Day 1
Geometry of specimens and test setup

Wood stoppers
Geometry of the specimens and test setup

Plan view

- Mass blocks
- Footing
- Soil box

0° specimen

skew (30°) specimen

Excitation
### Test protocol and linear spectra (1% damping)

**Table:**

<table>
<thead>
<tr>
<th>Motion</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Gilroy Array 1</td>
<td>1.0</td>
</tr>
<tr>
<td>2 Corralitos</td>
<td>0.8</td>
</tr>
<tr>
<td>3 El Centro Array 6</td>
<td>1.1</td>
</tr>
<tr>
<td>4 Pacoima Dam</td>
<td>0.8</td>
</tr>
<tr>
<td>5 Takatori</td>
<td>0.5</td>
</tr>
<tr>
<td>6 Takatori</td>
<td>1.0</td>
</tr>
<tr>
<td>7* Parachute Site</td>
<td>1.0</td>
</tr>
<tr>
<td>8* Parachute Site</td>
<td>-1.0</td>
</tr>
<tr>
<td>9* Parachute Site</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Only for test day 3*

**Graph:**

- **Sa (g):**
  - El Centro #6: 110%
  - Pacoima Dam: 80%
  - Takatori: 50%
  - Takatori: 100%
  - Parachute: 100%

- **Sd (m):**
  - For all motions, the time was compressed by 1.73
**Test results – 0° specimen**

Peak (and residual) responses

<table>
<thead>
<tr>
<th></th>
<th><strong>Roof drift ratio, $\Theta_t$ (%)</strong></th>
<th><strong>Edge settlement (mm)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test day 1</td>
<td>Test day 2</td>
</tr>
<tr>
<td><strong>Pacoima Dam 80%</strong></td>
<td>3.6 (0.2)</td>
<td>3.7 (0.2)</td>
</tr>
<tr>
<td><strong>Takatori 50%</strong></td>
<td>6.8 (0.4)</td>
<td>6.7 (0.7)</td>
</tr>
<tr>
<td><strong>Takatori 100%</strong></td>
<td>12.0 (2.7)</td>
<td>14.2 (7.3)</td>
</tr>
</tbody>
</table>
Main results – 0° specimen

Drift ratio, $\Theta_t$, response histories

- **Test day 1**
  - El Centro #6 110%
  - Pacoima Dam 80%
  - Takatori 50%
  - Takatori 100%
  - Residual 2.7%

- **Test day 2**
  - Residual 7.3%

- **Test day 3**
  - Residual 1.1%
Test day 3 – detailing around the footings

Plastic sheet

0.3 m

Concrete, $f'_c \approx 3.5$ MPa
(cast one day before the test)
Test day 3 results – 0° specimen

Drift ratio, $\Theta_t$, time history

- El Centro #6 110%
- Takatori 50%
- Pacoima Dam 80%
- Takatori 100%
- Parachute 100%
- Parachute -100%
- Parachute 110%

$\Theta_t$ (%) vs. time (s)
Test results – 0° specimen

Foundation moment versus foundation rotation (Takatori 50%)
Test results – 0° specimen

Foundation moment versus foundation rotation (test day 3)

Pacoima Dam 80%

Takatori 50%

Takatori 100%

Parachute Site 100%
Test day 3 results

Foundation rotation versus vertical displacement (test day 3)

Pacoima Dam 80%

Takatori 50%

Takatori 100%

Parachute Site 100%
Thank you
Detailing of rocking pile cap
3D Numerical Modeling (OpenSees)
**Instrumentation**

- 76 Accelerometers
- 33 String potentiometers
- 20 Linear potentiometers
- 8 Pore pressure transducers
- 21 Cameras

[Image of construction site with labeled instruments]