Seismic Response of PT Rocking Bridge Columns with Energy Dissipation Bars

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Outline

◆ Research Objectives
◆ Simplified Modeling of PT Rocking Piers with ED bars
◆ Descriptions of PT Rocking Pier and ED bars
◆ Cyclic and Seismic Responses
◆ Remarks and Conclusions
Research Objectives

- PT rocking pier with ED bars (Controlled Hybrid Rocking System)
  - Palermo et al. (2005)

Hybrid Rocking Piers: PT Rocking column + ED bars

- PT Rocking column has large displacement capacity and small damage at the base
  (Damage Avoidance Design, Mander et al., 1997)
  * Rocking column is like a slender or flexible rocking block

- Adding ED bars to increase energy dissipation in Hybrid system

- PT tendon is used to increase a self-centering capability
Research Objectives

- PT segmental rocking pier with Mild steel ED bars – Wang et al. (2008)

Without ED bars

With ED bars

Increased the dissipated energy

Without ED bars

With ED bars
Research Objectives

- PT segmental rocking piers with Mild steel ED bars – Ou et al. (2010)

Without ED bars

In increased the dissipated energy

With ED bars
Research Objectives

◆ PT segmental rocking pier with Superelastic SMA ED bars – Roh and Reinhorn (2010)

Tendon anchorage
Unbonded posttensioned tendons

N Segments
Bolt
N segment joint
Base segment joint
Flexible tube
Spherical edge
T-threaded studs
Anchor plate
Strong Concrete foundation
SMA anchorages
SMA rods
Unbonded Superelastic SMA rods
Shear keys

1 inch-diameter SMA rods

Numerical simulation

Lateral force (kN)
Lateral drift ratio (%)
Research Objectives

- To develop a simplified model of PT rocking pier with ED bars (Hybrid system)

- To investigate the effect of ED bars - yield level on the seismic response of PT rocking pier

- To investigate the effect of ED bar-post-yield stiffness ratio on the seismic response of PT rocking pier
Simplified Modeling of PT Rocking Piers

- PT rocking pier with ED bars (Hybrid system)

- Simplified Modeling (IDA RC2D basis Reinhorn et al., 2009)

Diagram:
- Rocking column element
- Rigid element
- Inelastic rotational spring element (ED bars, tendon)
- Lumped mass
- Moment release

零长度

Zero length
Simplified Modeling of PT Rocking Piers

- PT Rocking Pier Modeling (Rohan and Reinhorn, 2011)
- Sectional moment-curvature envelope
- Opening, yielding, rocking, overturning points
- Negative stiffness behavior after the rocking point

“Apparent” means that the load...
Simplified Modeling of PT Rocking Piers

**Tendon modeling**
- **Bilinear inelastic rotational spring model**
  \[ M_T = k_{\theta,T} \times \theta_b \]
  where 
  \[ k_{\theta,T} = \frac{E_T A_T}{l_T} \left( d - d_{c,u} \right)^2 \]
  \[ M_T = \sigma_T A_T \left( d - d_{c,u} \right) / 2 \]

**Mild steel ED bars Modeling**
- **Bilinear inelastic rotational spring model**
  \[ M_d = k_{\theta,d} \times \theta_c \]
  \[ k_{\theta,d} = \frac{E_d A_d}{l_d} \left( d + d_d - d_{c,u} \right)^2 \]
Descriptions of PT Rocking Pier

- Description of PT rocking pier with ED bars

Envelope curve of the PT rocking pier

Concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>$f'_c$</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>$E_c$</td>
</tr>
<tr>
<td>Yield strain</td>
<td>$\varepsilon_Y$</td>
</tr>
</tbody>
</table>

Reinforcement

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>$E_Y$</td>
</tr>
<tr>
<td>Yield strength</td>
<td>$f_Y$</td>
</tr>
</tbody>
</table>
Descriptions of PT Rocking Pier

- **Tendon – Bilinear inelastic rotational spring model**

- **Total length**: 1,000,000 mm

- **Total sectional area**: 2,660 mm²
  (0.22% of cross sectional area of the column)

- **PT force**: 2,248 kN
  : 50% of the tendon yield strength
  : 4.64% of the nominal axial strength of the column

- **Elastic modulus**: 196.5 GPa

- **Yield strength**: 1,690 MPa
  (G 270 )
**Descriptions of PT Rocking Pier**

- **Mild steel ED bars – Bilinear inelastic rotational spring model**
  - Three levels of yield moment considered: Half, Equal, Two times of the peak moment of the rocking column

**Post-yield Stiffness ratio:**
- **Without hardening consideration**
  - 0.1% of the elastic stiffness

- **With hardening consideration**
  - 3% of the elastic stiffness

**ED bars**

<table>
<thead>
<tr>
<th>Cross-sectional area (each side)</th>
<th>1,200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>1,200 mm</td>
</tr>
<tr>
<td>Length</td>
<td>9,000 mm</td>
</tr>
<tr>
<td>ED bar ratio</td>
<td>0.97%</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>210 GPa</td>
</tr>
</tbody>
</table>
Pushover result of total combined model

Slightly negative stiffness behavior

< Negative system >

0.1% of post-yield stiffness ratio

< Positive system >

3% of post-yield stiffness ratio
Cyclic and Seismic Responses

- Total cyclic response of PT rocking pier
  - 0.1% of post-yield stiffness ratio of ED bars (Negative system)
  - Half rocking moment

- 3% of post-yielding stiffness ratio of ED bars (Positive system)

Equal the rocking moment

Two times the rocking moment
**Cyclic and Seismic Responses**

- Equivalent viscous damping ratio

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**Contribution of each element to total lateral resistance**

- **Case of Equal rocking moment**

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<table>
<thead>
<tr>
<th>4% drift ratio</th>
<th>Positive system</th>
<th>Negative system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Two times</td>
<td>25</td>
<td>28</td>
</tr>
</tbody>
</table>

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**Rocking column**

**Tendon**

**ED bars**

**Total lateral force (kN)**

---

**Negative system**

**Positive system**
# Cyclic and Seismic Responses

## Ground motion selection: SAC Ground Motions

<table>
<thead>
<tr>
<th>EQ code</th>
<th>Description</th>
<th>Magnitude</th>
<th>Distance (km)</th>
<th>Scale Factor</th>
<th>Duration (sec)</th>
<th>PGA (g's)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA01</td>
<td>Imperial Valley, 1940, El Centro</td>
<td>6.9</td>
<td>10.0</td>
<td>2.0</td>
<td>39.38</td>
<td>0.46</td>
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<tr>
<td>LA02</td>
<td>Imperial Valley, 1940, El Centro</td>
<td>6.5</td>
<td>4.1</td>
<td>1.0</td>
<td>39.38</td>
<td>0.39</td>
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<td>LA03</td>
<td>Imperial Valley, 1979, Array #05</td>
<td>6.5</td>
<td>1.2</td>
<td>0.84</td>
<td>39.08</td>
<td>0.36</td>
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<tr>
<td>LA04</td>
<td>Imperial Valley, 1979, Array #05</td>
<td>7.3</td>
<td>36.0</td>
<td>3.2</td>
<td>79.98</td>
<td>0.45</td>
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<tr>
<td>LA05</td>
<td>Imperial Valley, 1979, Array #06</td>
<td>7.0</td>
<td>12.0</td>
<td>1.79</td>
<td>39.98</td>
<td>0.67</td>
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<tr>
<td>LA06</td>
<td>Imperial Valley, 1979, Array #06</td>
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<td>6.7</td>
<td>1.0</td>
<td>59.98</td>
<td>0.68</td>
</tr>
<tr>
<td>LA07</td>
<td>Landers, 1992, Barstow</td>
<td>7.3</td>
<td>25.0</td>
<td>2.17</td>
<td>79.98</td>
<td>0.52</td>
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<tr>
<td>LA08</td>
<td>Landers, 1992, Barstow</td>
<td>7.3</td>
<td>25.0</td>
<td>2.17</td>
<td>79.98</td>
<td>0.52</td>
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<tr>
<td>LA09</td>
<td>Landers, 1992, Yermo</td>
<td>7.3</td>
<td>25.0</td>
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<tr>
<td>LA10</td>
<td>Landers, 1992, Yermo</td>
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<tr>
<td>LA11</td>
<td>Loma Prieta, 1989, Gilroy</td>
<td>7.0</td>
<td>12.0</td>
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<tr>
<td>LA12</td>
<td>Loma Prieta, 1989, Gilroy</td>
<td>7.0</td>
<td>12.0</td>
<td>1.79</td>
<td>39.98</td>
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<tr>
<td>LA13</td>
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<td>LA14</td>
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<tr>
<td>LA15</td>
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<td>14.94</td>
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<td>LA16</td>
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<td>7.5</td>
<td>0.79</td>
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<td>0.53</td>
</tr>
<tr>
<td>LA17</td>
<td>Northridge, 1994, Sylvan</td>
<td>6.7</td>
<td>7.5</td>
<td>0.79</td>
<td>14.94</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Cyclic and Seismic Responses

- Seismic response of PT bridge pier for LA01
  - 0.1% post-yield stiffness (Negative system)

Half

Equal

Two times

Base shear (kN) vs Drift ratio (%) Graphs

Time (sec) vs Drift ratio (%) Graphs
Cyclic and Seismic Responses

Effect of yield level of ED bars
(0.1% post-yield stiffness ratio - Negative system)

The average peak drift ratios and the average peak accelerations are shown in the table below:

<table>
<thead>
<tr>
<th>Method</th>
<th>Average Peak Drift Ratio</th>
<th>Average Peak Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half</td>
<td>3.37%</td>
<td>0.138 g</td>
</tr>
<tr>
<td>Equal</td>
<td>2.88%</td>
<td>0.172 g</td>
</tr>
<tr>
<td>Two times</td>
<td>2.32%</td>
<td>0.242 g</td>
</tr>
</tbody>
</table>
Cyclic and Seismic Responses

Effects of post-yield stiffness ratio

Half Equal Two times

Peak acceleration (g)

Peak drift ratio (%)

0.1% PYSR 3% PYSR

Peak base shear (kN)

EQ code No. (LA00)

0.1% PYSR 3% PYSR

0.1% PYSR 3% PYSR

0.1% PYSR 3% PYSR
Remarks and Conclusions

- Simplified model of the hybrid rocking bridge pier is developed through the combination of rocking column element and inelastic rotational spring elements

- The equivalent viscous damping ratio of the PT rocking bridge column increase when the ED bars have a higher yielding moment

- From the nonlinear time-history analyses using twenty LA ground motions, the use of higher yield moment ED bars decreases the peak drift response while it increases the peak accelerations

- Almost constant base shear responses are obtained through the negative system

- Even though the post-yield stiffness ratio of the ED bars is increased to 3% (positive system), the peak seismic responses such as lateral drift and
Thank you for your attention