Influence of Vertical Ground Shaking on Design of Bridges Isolated with Friction Pendulum Bearings

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Motivation: Results of Full-Scale Building Tests at E-Defense

Isolated with triple friction pendulum bearings (TPB)

Isolated with hybrid configuration of lead-rubber and cross-linear bearings

Fixed at the base

Period $T = 0.7$ sec
First Yield Base Shear $\sim 0.67W$
## Experimentally Observed Influence of Vertical Shaking in Isolated Buildings - Summary

<table>
<thead>
<tr>
<th>Effect</th>
<th>Building Configurations Affected</th>
<th>Predicted Significance for Bridges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased Base Shear due to Friction</td>
<td>TPB</td>
<td>Bridges will experience increased base shear, similar to buildings. Expected to influence column design.</td>
</tr>
<tr>
<td>Increased Horizontal Accelerations due to H-V Coupling</td>
<td>Primarily TPB (small in LRB, fixed base)</td>
<td>Insignificant for bridges</td>
</tr>
<tr>
<td>Floor Slab Vibration as a Direct Effect of Vertical Shaking</td>
<td>All configurations</td>
<td>Bridge spans may be susceptible to large vertical accelerations mid-span.</td>
</tr>
</tbody>
</table>
Objective/Scope of PEER Pendulum Bearing Study

- **Objective 1:** Comprehensively evaluate influence of vertical shaking on base shear/column forces in representative isolated bridges.
- **Objective 2:** Based on study, develop guidance for accounting for the influence of vertical shaking in design (e.g. required time history analysis, amplification factor based on V/H, etc.)

**Scope of Investigation:**
- Develop computational models in OpenSees for archetype bridges isolated with FPB
- Include important parameter variation (e.g. number of spans, span length, pier/column flexibility, and isolation system parameters).
- Statistical evaluation of isolator/column shear and other responses of interest through time history analysis to a suite of 3D motions
Ramanathan (2012) conducted a comprehensive investigation of the California bridge inventory to develop fragility curves for common bridge types. NBI provides information regarding number of spans, maximum span length, deck width, minimum vertical under clearance. Column heights were inferred from vertical clearance. Bridge classes in California are classified under thirteen main types, where the three most common are listed below.

<table>
<thead>
<tr>
<th>Bridge Class</th>
<th>Nomenclature</th>
<th>Bridge Count</th>
<th>Suitable for Isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-span continuous concrete box-girder</td>
<td>MSCBG</td>
<td>5314</td>
<td>20.89</td>
</tr>
<tr>
<td>Multi-span continuous slab</td>
<td>MSCSL</td>
<td>4004</td>
<td>15.74</td>
</tr>
<tr>
<td>Multi-span continuous concrete girder</td>
<td>MSCG</td>
<td>2164</td>
<td>8.51</td>
</tr>
</tbody>
</table>

• Members: Allaoua Kartoum (Caltrans), Bijan Khalegi (WashDOT), Mason Walters (Forell-Elsesser)
• Continuous bridge configurations are preferred, and expansion joints are generally not needed.
• Concrete box girder is the preferred bridge class in California, with span lengths from 150-200 ft.
• Steel girder is the preferred bridge class in Washington. Use low number of girders with cross frames.
• Isolation system parameters: $T_2 = 2$ to 5 sec, $Q/W = 0.04$ to 0.08.
• Include foundation springs to represent site conditions.
- Three-span continuous concrete box girder bridge
- Middle span length = 120'; end spans = 100'
- Two column bents:
  - Column height = 20'; column diameter = 5'
  - Bent depth = 5', Distance between columns = 25'
- Superstructure = 3 cell box girder
  - Girder dimensions
- Seat type abutment with unlimited expansion gap
Continuous Concrete Box Girder Bridge: Modeling Assumptions

Modeling Assumptions

• Spine Model; Uses Elastic Frame Elements for Superstructure, Columns, Bent Cap

• Discretization of Superstructure Elements to Distribute Mass

• Unrestrained Movement at the Abutment

• Rayleigh Damping Applied to Non-Bearing Elements

• Translational/Rotational Foundations Springs Representing Stiff Soil
TPB Isolator Modeling Assumptions

**Isolator Model**
- Used Triple Pendulum Bearing Element in OpenSees
- Bearing has sufficient capacity so that stiffening regime is not engaged.
- Bearing vertical stiffness calibrated to $T_v = 0.03$ sec
### Ground Motion Selection

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>NGA #</th>
<th>Event</th>
<th>Year</th>
<th>Station</th>
<th>$M_W$</th>
<th>$R_{rup}$ (km)</th>
<th>$V_{s30}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFPU</td>
<td>77</td>
<td>San Fernando</td>
<td>1971</td>
<td>Pacoima Dam (upper left abut)</td>
<td>6.61</td>
<td>1.81</td>
<td>2016</td>
</tr>
<tr>
<td>IIB</td>
<td>285</td>
<td>Irpinia, Italy-01</td>
<td>1980</td>
<td>Bagnoli Irpinio</td>
<td>6.9</td>
<td>8.18</td>
<td>1000</td>
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<tr>
<td>IIS</td>
<td>292</td>
<td>Irpinia, Italy-01</td>
<td>1980</td>
<td>Sturino</td>
<td>6.9</td>
<td>10.84</td>
<td>1000</td>
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<tr>
<td>LPG</td>
<td>763</td>
<td>Loma Prieta</td>
<td>1989</td>
<td>Gilroy - Gavilan Coll.</td>
<td>6.93</td>
<td>9.96</td>
<td>729.7</td>
</tr>
<tr>
<td>CAM</td>
<td>825</td>
<td>Cape Mendocino</td>
<td>1992</td>
<td>Cape Mendocino</td>
<td>7.01</td>
<td>6.96</td>
<td>513.7</td>
</tr>
<tr>
<td>LAL</td>
<td>879</td>
<td>Landers</td>
<td>1992</td>
<td>Lucerne</td>
<td>7.28</td>
<td>2.19</td>
<td>1369</td>
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<tr>
<td>NPD</td>
<td>1050</td>
<td>Northridge-01</td>
<td>1994</td>
<td>Pacoima Dam (downstr)</td>
<td>6.69</td>
<td>7.01</td>
<td>2016.1</td>
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<tr>
<td>NPA</td>
<td>1051</td>
<td>Northridge-01</td>
<td>1994</td>
<td>Pacoima Dam (upper left)</td>
<td>6.69</td>
<td>7.01</td>
<td>2016.1</td>
</tr>
<tr>
<td>KCL</td>
<td>1148</td>
<td>Kocaeli, Turkey</td>
<td>1999</td>
<td>Arcelik</td>
<td>7.51</td>
<td>13.49</td>
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<td>CT46</td>
<td>1486</td>
<td>Chi-Chi, Taiwan</td>
<td>1999</td>
<td>TCU046</td>
<td>7.62</td>
<td>16.74</td>
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<td>CT78</td>
<td>3473</td>
<td>Chi-Chi, Taiwan-06</td>
<td>1999</td>
<td>TCU078</td>
<td>6.3</td>
<td>11.52</td>
<td>443</td>
</tr>
</tbody>
</table>

### Selection and Scaling
- Used suite developed by Carlton (2014) for shallow crustal earthquakes with near-fault effects.
- Motions were rotated so that spectral acceleration $S_a$ at $T = 1.0$ sec was maximized, and amplitude scaled to represent the median and standard deviation (distribution) of the target spectrum.
- We developed a vertical target spectrum from the horizontal target spectrum, and scaled the vertical components accordingly.

Ground motions were further sorted into bins according to vertical acceleration intensity (vPGA)

<table>
<thead>
<tr>
<th>Group #</th>
<th>Motions Included</th>
<th>vPGA range (with Scaling)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 (Large vPGA)</td>
<td>SFPU, CAM, NPA</td>
<td>0.8g – 1.7g</td>
</tr>
<tr>
<td>Group 2 (Moderate vPGA)</td>
<td>LPG, LAL, NPD, CT78, IIS</td>
<td>0.5g – 0.7g</td>
</tr>
<tr>
<td>Group 3 (Small vPGA)</td>
<td>IIB, KCL, CT46</td>
<td>0.2g – 0.4g</td>
</tr>
</tbody>
</table>

**Horizontal Acceleration Spectra**

**Vertical Acceleration Spectra**
Representative History Responses: Isolator Displacement

SFPU (Group 1, Large vPGA)

Isolator Disp. (in) - Transverse

Isolator Disp. (in) – Longitudinal

LPG (Group 2, Moderate vPGA)

Time (s)

Displacement (in)

Time (s)
Representative Responses: Hysteresis Loop

SFPU (Group 1, Large vPGA)

LPG (Group 2, Moderate vPGA)

Isolator Force (k)
Transverse

Isolator Force (k)
Longitudinal

Displacement (in)

Displacement (in)
Representative History Responses

SFPU (Group 1, Large vPGA)

- Axial Force (kips)
- Vertical Acc at Bent 1 (g)
- Transverse Acc at Bent 1 (g)
- Longitudinal Acc at Bent 1 (g)

LPG (Group 2, Moderate vPGA)

- Axial Force (kips)
- Vertical Acc at Bent 1 (g)
- Transverse Acc at Bent 1 (g)
- Longitudinal Acc at Bent 1 (g)
Modal Properties of the Bridge

- **Mode 1:** Longitudinal mode (2.96 sec)
- **Mode 2:** Transverse mode (2.94 sec)
- **Mode 3:** Torsional mode (2.61 sec)
- **Mode 4:** First Vertical mode (0.35 sec)
- **Mode 5:** Second Vertical Mode (0.247 sec)
- **Mode 6:** Transverse structural mode (0.21 sec)
- **Mode 7:** Third Vertical Mode (0.204 sec)
- **Mode 8:** Rotational mode (0.143 sec)
- **Mode 9:** Deck torsional mode (0.118 sec)
- **Mode 10:** Torsional mode (0.113 sec)
Response Spectra and Higher Mode Coupling Effects
Response Spectra and Higher Mode Coupling Effects
Proposed Theoretical Formulation

**Hypothesis:** Amplified base shear can be estimated from $PGA_z$

1. In an SDOF system, the base shear coefficient $\approx$ peak horizontal acceleration

$$m\ddot{u} + V_b(u) = -m\ddot{u}_g \quad \Rightarrow \quad \frac{V_b}{W} = -\ddot{u}^t$$

2. Estimating the effect of vertical acceleration

$$V_b \propto \mu N \quad \text{where} \quad N = m(g + \ddot{u}_z^t)$$

$$\frac{V_{b(vert)}}{W} = \mu \cdot \ddot{u}_z^t$$

$\ddot{u}_z^t$ is the average peak vertical acceleration felt by the isolators
Hypothesis: Amplified base shear can be estimated from $PGA_z$

3. $\ddot{u}_z^t$ can be estimated from the vertical ground acceleration

$$\ddot{u}_z^t = AF \cdot PGA_z$$

- AF = amplification factor. It is the amplification of the vertical acceleration from the ground to the structure.

$$\frac{V_{b(vert)}}{W} = \mu \cdot \ddot{u}_z^t \quad \rightarrow \quad \mu \cdot AF \cdot PGA_z$$
Proposed Theoretical Formulation

An Example: SFPU (Group 1)

\( V_b/W = 0.133 \) (observed value for 2D)
\( \mu = 0.08 \)
\( \text{PGA}_z = 0.817g \)

\[
\frac{V_{b(\text{vert})}}{W} = \mu \cdot AF \cdot \text{PGA}_z \quad \text{and} \quad \frac{V_{b,3D}}{W} = \frac{V_{b,2D}}{W} + \frac{V_{b(\text{vert})}}{W}
\]

Case 1: \( AF = 1 \)

\[
= (0.08) \cdot (1) \cdot (0.817) = 0.065 \quad = 0.133 + 0.065 = 0.199
\]

Case 2: \( AF = \frac{S_a(0.2s)}{\text{PGA}_z} \)

\[
= (0.08) \cdot (1.98) \cdot (0.817) = 0.129 \quad = 0.133 + 0.129 = 0.262
\]
Evaluation of Base Shear Estimates

**Transverse Base Shear**
- Observed 2D
- Observed 3D
- Estimate $v_{PGA}$
- Estimate $S_a(T=0.2s)$

**Longitudinal Base Shear**
- Observed 2D
- Observed 3D
- Estimate $v_{PGA}$
- Estimate $S_a(T=0.2s)$
Preliminary Conclusions

\[ \frac{V_{b(vert)}}{W} = \mu \cdot AF \cdot PGA_z \]

Preliminary Conclusions

- “Estimate vPGA” (AF = 1 with no spectral amplification) usually gives a conservative estimate of the base shear.
- The approach may be unconservative when vPGA >1 (high frequency spikes due to uplift, pounding)
- The higher mode effects due to modal coupling are not strongly apparent in the base shear.
Future Work: Parameter Variation for Concrete Box Girder

<table>
<thead>
<tr>
<th>Sr No.</th>
<th>No. of Cell</th>
<th>Deck Width (ft)</th>
<th>Depth (ft)</th>
<th>Deck Thickness (in)</th>
<th>Soffit Thickness (in)</th>
<th>Wall Thickness (in)</th>
<th>Wall C-C spacing (ft)</th>
<th>Span Length (ft)</th>
<th>No. of Span</th>
<th>Column Height (ft)</th>
<th>No. of column /bent</th>
<th>Column Dia. (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>45</td>
<td>4.8</td>
<td>8.875</td>
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<td>12</td>
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<td>35</td>
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</tbody>
</table>

◊ Approach spans = 0.8 x span length

Research Question: Does base shear amplification depend on bridge and isolator parameters?
Acknowledgement:

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