Rocking Foundations

Validation using large scale shake table testing

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Project history

- Caltrans released a RFP for “innovative foundations”.
- Bruce Kutter (UCD) proposed use of “rocking foundations”.
- Several studies were performed at the UCD centrifuge.
- Numerical model and simplified design procedure developed
- Validation of numerical model and development of a full bridge design procedure
Basic concept

Single column bents:

- Conventional fixed-base
- Rocking foundation on piles
- Rocking shallow foundation

Plastic Hinge

Soil Yielding
Early testing

Centrifuge testing of different H/B ratios

SHAKING DIRECTION
(units: meter)
Rocking behavior

- **Typical results**

  ![Graphs showing moment vs. footing rotation and vertical displacement](image)

  - **Good energy dissipation**
  - **Too much uplift?**

  ![Diagram of footing rotation and residual settlement](image)
Trying to capture bridge behavior

- **Centrifuge testing of simple bridges**

To enable rocking, the pin must be moved from the bottom of the column to the top.
Analytical models

Simple hand calcs:

Transform into an equivalent SDF

Numerical models:

[Diagram of numerical models including nonlinear beam-column elements and stiff elements]
Stability evaluation

![Diagram of stability evaluation with dimensions 10 m and 6 m.]

- **CY = 0.4, CR = 0.3**
- **Rocking foundation**
- **T1 = 0.5 s, Hc = 10.0 m**

- **Elastic**
- **Nonlinear**
- **Instability limit**
- **Collapse**
Motivation for shake table testing

- Validate numerical model
- Investigate “off-axis” rocking
- Investigate pile-cap connection details
- Demonstrate that even under extreme shaking tip-over isn’t an issue
Test Layout

Key parameters

- $W = 290 \text{ kN}$
- $H / L = 2.0$
- $A / A_c = 13$
- $FS_v = 24$
- $C_r = 0.26$
- $C_y = 0.47$
Test layout
Test layout

Added to limit excessive rotation
Test specimen construction
Outrigger restrainer

Completed restraining system
Test specimen construction

- Adding the block mass
Soil box assembly

- Erection of vertical elements and post-tensioning to the shake table platen
Soil box assembly

- Placement of Concrete Panels
Soil box assembly

- Completed soil box

Interior box dimensions:
- Height: 7.6 m
- Width: 10.1 m
- Depth: 4.6 m
Soil box assembly

• Soil box interior

16 steel angles bolt to the platen to provide no-slip condition at the bottom boundary

4 PT rods running through the parts of corner column base plates sticking into the box
Filling and removal

- **Conveyor belt method**
  (slow and cheap)

- **Hopper and crane method**
  (fast and expensive)
Membrane placement

- A geotextile was placed first to protect the liner
Membrane placement

- Placement and patching
Soil placement

- Saturation and dewatering system
Soil placement

**Soil Compaction**

- Loose lifts of 200 mm thick compacted at a water content of 6% down to about 150 mm
- Walk-behind vibratory plate with 8 passes per lift
  - First 4 lifts after placement of liner and saturation/dewatering system
  - Lifts above the footings’ base elevation
  - Near box walls (in general)
- Skid-steer loader with an attached vibratory roller (1.22 m wide, 7.95 kN heavy vibrating at 40 Hz) with 6 passes per lift
Instrumentation

- Soil accelerometers placement

Marking of locations before placement

Placement of accelerometers

Covering with soil and cables running
Instrumentation

- *Pore Pressure Transducers (PPT) Placement*
  - Challenging to prevent desaturation of sensors during the 2-3 weeks period for which they remained above water table
Specimen placement
Instrumentation

 Structures’ Instrumentation
  - Mass Blocks’ String Potentiometers
    ✓ 6 linearly independent String Pots (3 horizontal + 3 vertical) to determine 6 DoFs
Instrumentation

Video Cameras Used

- Coaxial cameras [8]
  - Wired, power-supported, low resolution (768 × 494 pixels at 30 fps)
  - Live video streaming; can be played back during testing
  - 168 out of 168 events successfully recorded

- GoPro2 cameras [11]
  - Wireless, battery-supported, high resolution (1920 × 1080 pixels at 30 fps)
  - Can be accessed and played back after testing
  - 126 out of 231 events successfully recorded

- Sony cameras [2]
  - Man-operated, battery-supported, high resolution (1920 × 1080 pixels at 30 fps)
  - Can be accessed and played back after testing
  - 29 out of 42 events successfully recorded
Loading input

**Test protocol and linear spectra (1% damping)**

<table>
<thead>
<tr>
<th>Motion</th>
<th>Scale factor</th>
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<tbody>
<tr>
<td>Gilroy Array 1</td>
<td>1.0</td>
</tr>
<tr>
<td>Corralitos</td>
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</tr>
<tr>
<td>El Centro Array 6</td>
<td>1.1</td>
</tr>
<tr>
<td>Pacoima Dam</td>
<td>0.8</td>
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<tr>
<td>Takatori</td>
<td>0.5</td>
</tr>
<tr>
<td>Takatori</td>
<td>1.0</td>
</tr>
<tr>
<td>Parachute Site</td>
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<td>-1.0</td>
</tr>
<tr>
<td>Parachute Site</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Only for test day 3

For all motions the time was compressed by 1.73
Large-scale shake table test of columns supported on rocking shallow foundations
Test Response

- **Column Drift Ratio Time Histories for Test Days 1 and 2**

The graph shows the column drift ratio time histories for Test Days 1 and 2. Different scales and accelerations are used to illustrate the responses:

- **Test Day 1**
  - El Centro #6, 110%
  - Pacoima dam, 80%
  - Takatori, 50%
  - Takatori, 100%

- **Test Day 2**
  - Takatori, 50%
  - Pacoima dam, 80%
  - El Centro #6, 110%
  - Takatori, 100%

The Drift ratio, Θ (%), is plotted against Time, t (s), with specific values marked for each event. The graph visually represents the dynamic behavior under different conditions and accelerations.
Concluding Remarks

• The road from initial concept to deployment is a long one…
  
  – Positives: Better performance for less $. The shaketable testing provided a clear illustration of excellent performance under extreme loading.
  – Negatives: Requires a substantial change in design philosophy

• Need to work on pile-footing connection details to expand application to pile supported foundations

• Soil box assembly and disassembly is expensive
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