Seismic Retrofit of Pier 6 at Puget Sound Naval Shipyard using Lead-Rubber Bearings

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Project Location

United States

Pier 6 Location
Seismic Setting: Subduction and Crustal Faults

<table>
<thead>
<tr>
<th>Source</th>
<th>Maximum Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascadia Subduction Zone - Interface</td>
<td>9.0</td>
</tr>
<tr>
<td>Cascadia Subduction Zone - Intraslab</td>
<td>7.5</td>
</tr>
<tr>
<td>Crustal Faults</td>
<td>7.5</td>
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</tbody>
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Note: Base map prepared from drawing provided by USGS and the University of Washington, 2001.
Pier 6 - Overview

1315’ long x 100’ wide
Challenging soils
Portal cranes and Hammerhead Crane
Good condition

![Diagram of Pier 6 structure with dimensions and soil conditions.](image)
Pier 6 - Construction

1. Drive timber piles underwater, set precast hollow cylinder
2. Dewater and pressurize, muck out bell
3. Cylinder filled with concrete, superstructure built
Pier 6 – Construction – Precast Cylinders
Pier 6 – Construction – Setting Cylinders
Pier 6 – Construction – In-place Cylinders
Pier 6 – Construction – Crane
Retrofit Feasibility Study Goals

Define hazards and criteria
  ◦ Department of defense codes
  ◦ Civilian codes
  ◦ First principles

Evaluate existing condition
  ◦ Identify structural vulnerabilities
  ◦ Assess seismic performance

Produce and evaluate retrofit concept
Hazards and Criteria
Hazards and Criteria

MOTECS
- Level 1: 72-year Earthquake (minor damage)
- Level 2: 475-year Earthquake (controlled and repairable damage)

ASCE 61
- OLE: 72-year Earthquake (minor damage)
- CLE: 475-year Earthquake (controlled and repairable damage)
- DE: 2/3 MCE 975-year Earthquake (life safety)

Pier 6 has survived a “72-year” earthquake

Initial assessment indicated it would not survive 475-year earthquake
Retrofit Performance Criteria

Study used two-level approach:
- CLE from ASCE 61
- DE from future edition ASCE 61

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Retrofit Criteria</th>
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</thead>
<tbody>
<tr>
<td>475-year (PSA 1.1g)</td>
<td>Maintain Operations</td>
</tr>
<tr>
<td>975-year (PSA 1.3g)</td>
<td>Controlled and Repairable Damage</td>
</tr>
</tbody>
</table>
Evaluate Existing Conditions

Unreliable connections for cyclic inelastic loading
  ◦ Top of column
  ◦ Bottom of column

Battered columns under Hammerhead Crane
  ◦ Very stiff
  ◦ Weak and brittle
Top of Column

Bottom bars butted end to end
Longitudinal beam

Bent girder
Column bars not anchored into bent girder or longitudinal beams

Column

Column-to-Girder Connection Beam-to-Girder Connection

Top bars too short (not developed)
Bottom of Column

Column

Spiral not anchored into footing

Column-to-Footing Connection

Footing
Retrofits for Displacement Capacity

Brittle connections must be eliminated

Columns retrofits
  ◦ Jacket columns at footings to develop and maintain plastic hinge capacity
  ◦ Pin column tops to capacity protect deck for 12- to 18-inch displacement
  ◦ Remove battered columns

Displacement capacity retrofits alone are insufficient
Existing Seismic Performance
Retrofit Concept – Requirements

Gravity-load-resisting system
- Good existing condition
- Preserve existing system and add a new seismic-load-resisting system

Lateral-load-resisting system
- Add strength and stiffness
  - Mooring
  - Portal cranes
  - Seismic
- Minimize demolition of existing structure
- An LRB-dolphin system meets these criteria
Retrofit Concept – LRBs

Lead-rubber bearings (LRBs)
- Typically used for seismic isolation of buildings and bridges
- Provide critical damping ratios up to 35%
Retrofit Concept – Section

- Remove portion of existing slab to install LRB dolphin
- Retrofit the top of all columns to create a “pinned” connection
- Jacket the base of all columns
Retrofit Behavior

Multi-degree-of-freedom (MDOF) vs. single-degree-of-freedom behavior (SDOF)

Typical Pier Structure (SDOF)

Pier 6 South (MDOF)
Retrofit Modeling – LRB Dolphins

Gravity-load-resisting system must survive earthquake

Behavior of timber piles in soft clay was the primary concern

Will timber pile groups survive?
Retrofit Modeling – Timber Piles

Pile lateral load test from 1924
Retrofit Modeling – Timber Piles

Comparison between geotechnical recommendations and load test
Retrofit Modeling – Timber Piles

Restraint properties identified

Foundation displacements and rotations obtained from analytical model
Retrofit Concept – Plan

Concept
◦ Maintain existing gravity load path
◦ Add new seismic-load-resisting system
◦ Address detailing deficiencies

Specifics
◦ Install thirty-three LRB dolphins
◦ Retrofit column connections
◦ Integrate north and south segments
◦ Disconnect battered columns
◦ Provide sacrificial members at portal crane seismic joints
Retrofit Performance

Key retrofit features:
- LRB dolphins add strength, stiffness, and damping to the pier
- Criteria exceeded due to LRB performance:
  - LRBs tend to re-center the pier after an earthquake
  - Column retrofits allow large relative rotations without significant damage

References: