SEISMIC RETROFIT OF PIER 6
AT PUGET SOUND NAVAL SHIPYARD
USING LEAD-RUBBER BEARINGS

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ABSTRACT

Pier 6 at the US Navy’s shipyard in Bremerton, Washington was constructed in 1926. It consists of a concrete deck supported by large diameter concrete columns. More than half of the column footings are supported on long timber piles that penetrate a significant layer of soft clay to achieve bearing on dense, glacially-overridden soils. The surrounding region is subject to risk of seismic activity from the Cascadia Subduction Zone and the nearby Seattle Fault Zone. Because the seismic risk was not well understood at the time of construction, the reinforcement detailing at the connections is deficient and the performance of the long timber piles in the soft clay layer is suspect. Consequently, the pier in its existing condition is not expected to perform well in a major earthquake.

As part of its asset management plan, the U.S. Navy is evaluating the feasibility of seismically retrofitting Pier 6, which is in good condition for its age. The results of the feasibility study indicate the pier can be retrofitted to a design-level earthquake. This paper will present the pertinent details of the study, essential considerations when using lead-rubber bearings as seismic dampers for pier structures, and some unique challenges associated with Pier 6. These challenges included complex soil-structure interaction, multi-degree of freedom behavior of the pier bents, and the need for a retrofit that maintains the current functionality of the pier with minimally invasive construction.

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Introduction

Pier 6 is a 1,318-foot-long by 100-foot-wide pier, constructed in 1925-26, which supports the Hammerhead Crane, a landmark in the city of Bremerton, Washington. It consists of three different structures, Pier 6 Approach, Pier 6 North, and Pier 6 South, separated by expansion joints as shown in Figure 1. Pier 6 Approach and Pier 6 North are of similar construction consisting of a reinforced concrete deck supported on large concrete cylinders founded on spread footings. Pier 6 South was also constructed in a similar fashion except that its footings are founded on timber piles up to 108 feet long, driven underwater through a deep soft clay layer (see Figure 2). In addition, Pier 6 South is braced laterally in the vicinity of the Hammerhead Crane by four battered concrete brace cylinders also founded on timber piles. This paper presents the results of a study that assessed the current performance of the pier and the feasibility of retrofitting for an earthquake with a 975-year return period.

Figure 1. Pier 6 plan, elevation, and sections (US Navy).
Seismic Performance Criteria

The initial goal of the study was to meet the performance requirements of ASCE 61-14, “Seismic Design of Piers and Wharves” [1] as follows.

- Controlled damage in a contingency earthquake with a 475-year return period.
- Collapse prevention in a design earthquake, defined as two-thirds of an earthquake with a 2,475-year return period.

The next edition of ASCE 61, set to be published in 2019, is expected to redefine the design earthquake to one with a 975-year return period. Recognizing that any retrofits proposed in this study would likely not be accomplished until after 2019, the 975-year return period was used as the design earthquake in this study.

Initial Assessment

The initial assessment of Pier 6 involved a review of the 1926 record drawings focusing on detailing at critical locations. Several significant detailing deficiencies were noted as follows.

1. The column reinforcement is not anchored into the bent girders or longitudinal beams, and the reinforcement in the beams is not detailed for cyclic loading. A primary concern is that during cyclic loading the bottom reinforcement at the ends of the beams will pull out of the girders, precipitating an eventual shear failure. See Figure 3.
2. The spiral is not anchored into the footing at the base of the columns, see Figure 4.
3. The four brace cylinders under the Hammerhead Crane have no tension connection to the supporting timber piles.

After the initial drawing review was complete, the following conclusions were drawn.
- There is no apparent retrofit for the deficiencies shown in Figure 3 which will establish ductile frame action that does not involve reconstructing the pier superstructure.
- The column bases can be retrofitted by jacketing as shown in Figure 4.
- The brace cylinders on provide the majority of the lateral stiffness, but with no credible tension capacity they will be overwhelmed by demands from both the contingency and design earthquakes.

Figure 3. Top of column deficiencies.

Figure 4. Base of column deficiency and retrofit.

Figure 5 shows the resulting pushover curve of a typical pier bent in the longitudinal direction with the jacketing retrofit provided at the base of the columns. It is clear from the figure that jacketing the columns is not in itself a sufficient retrofit.
Based on the results of the initial assessment, the following retrofit concept was developed.

- Jacket the columns at the footings to allow the column to develop and maintain its plastic moment capacity during cyclic loading.
- Create effective pin connections at the tops of the columns to achieve a target rotation capacity between 0.02 and 0.03 radians, (i.e. a 12-inch to 18-inch displacement at the top of the typical 50-foot column). This provides capacity protection to the vulnerable connections at the ends of the longitudinal beams.
- Remove the brace cylinders under the Hammerhead Crane.
- Provide a new ductile lateral-force-resisting system for the pier deck.

**Retrofit Using Lead-Rubber Bearings**

Because the gravity system is in good condition, the goal of the retrofit is to preserve it while adding an appropriate lateral system. Addition of lead-rubber bearings (LRBs) mounted on individual, batter-pile dolphins was identified as a likely candidate for the new ductile lateral-force-resisting system.

**LRB-dolphin System**

This system sandwiches the bearings between the pier deck and pile-supported dolphin substructures, making them an integral part of the lateral load path for the deck (see Figure 6). LRBs have been used to enhance the seismic performance of buildings and bridges for several
decades and have also been used successfully on several piers. An LRB-dolphin system adds strength, stiffness, and additional damping to the pier. These systems are very efficient, requiring fewer piles than other batter-pile systems. Also, after a design earthquake, LRBs generally remain undamaged and will eventually re-center themselves. Consequently, major post-earthquake repairs are unlikely.

An LRB consists of a solid lead core and layers of vulcanized rubber reinforced by steel plates bonded to internal plates and mounting plates as shown in Figure 7. The lead core provides the initial lateral stiffness and energy dissipation, often resulting in equivalent viscous damping ratios of approximately 25%. The post-yield stiffness and re-centering force is provided by the layers of rubber reinforced by steel plates. The lateral displacement capacity of the bearing is governed by the allowable shear strain of the rubber, which can approach 200 percent. Testing of each bearing is typically required to verify the performance characteristics due to variations in properties of natural rubber (see Figure 8).
**Retrofit Strategy**

The global retrofit strategy incorporating an LRB-dolphin system is summarized below and shown in Figure 9 and Figure 10.

- Integrate Pier 6 North and Pier 6 South at the existing expansion joint.
- Provide isolated LRB-dolphins throughout the pier.
- Remove the brace cylinders under the Hammerhead Crane.
- Stiffen and strengthen Pier 6 Approach to minimize relative movements at the bulkhead.
- Install a seismic joint between the Pier 6 North and Pier 6 Approach.
- Conduct a future feasibility study for retrofitting the Hammerhead Crane if the owner wishes for it to remain.

![Figure 9. Plan of Pier 6 retrofit.](image)
Analysis of Retrofitted Pier

The retrofit strategy was confirmed by analyzing the Pier 6 in its retrofitted condition. The analysis was complicated by the pile-supported footings beneath Pier 6 South. These footings possess mass that is nearly equivalent to the tributary weight of the deck they support. In addition to their mass, the surrounding clay is especially soft, resulting in multi-degree of freedom (MDOF) behavior that is not typical of pier structures, which usually behave as single-degree of freedom (SDOF) oscillators (see Figure 11).
As consequence of this MDOF behavior, the feasibility of implementing an LRB-dolphin retrofit depends on the performance of the foundations. It is imperative that sufficient stiffness is present in the existing foundations to limit out of phase motion of the foundations relative to the deck so the gravity load path is maintained. An LRB-dolphin system provides additional lateral restraint to just one of the degrees of freedom, the deck. The other degrees of freedom (foundations) are still only restrained by the soft clay. Consequently, for an LRB-dolphin retrofit to be feasible, it must be shown that with the pier deck braced by the LRB-dolphins, the existing foundations will not fail during the seismic event considered.

Quantitative assessment of the LRB-dolphin retrofit concept was performed using the results of several analytical models. The modeling strategy is shown graphically with the flowchart in Figure 12. The following paragraphs describe each of these models.

**Figure 12. Flowchart of modeling strategy.**

**Timber Pile Model**

The geotechnical engineer provided recommended parameters for evaluating the lateral behavior of the timber piles in LPILE. Upper and lower bound soil values were used to obtain the lateral-force-displacement response of a single pile. This information was used to construct force-displacement curves representing the lateral response of the pile groups.
Pile Group Model

In addition to lateral soil parameters, the geotechnical engineer also provided recommended parameters that characterize the vertical-force-displacement relationship in skin friction and end bearing for the timber piles. These parameters were used to create a model of a pile group, in which each pile is restrained by nonlinear springs defined by these recommended parameters. The rotational response of the entire pile group was obtained from this model in the form of a moment-rotation curve.

Dynamic 2-D Bent Model

This 2-D model was built to represent the bent with the greatest depth of soft clay beneath it. The footings, columns, and girder are all explicitly included within this model. The tributary mass of the deck is distributed to the girder. The footings are restrained by springs with translational and rotational secant stiffnesses obtained from the results of the two models described previously. For evaluation of the retrofit, an additional spring was placed at the deck level to represent the LRB-dolphin stiffness.

Modal analyses of this model were performed iteratively, updating the secant stiffness values and damping of the response spectrum at each iteration. This provided an evaluation of the existing bents and an evaluation of the foundations in the retrofitted condition. The displacements and rotations at the footings obtained from this model were used to check the timber piles by comparing with published test results of timber-pile-to-concrete-cap connections [2].

This model was also used to obtain amplification factors for the deck mass necessary for the definition of the Global Spine Model (see Global Spine Model description). This amplification factor is approximately 1.6 and accounts for additional base shear in the LRBs due to the presence of the column and footing masses.

Static 2-D Bent Model

This 2-D model is very similar to that described in the previous section, with the exception that the translational and rotational springs restraining the footings are no longer defined using a secant stiffness. Instead, these springs are defined nonlinearly using the results of the Timber Pile and Pile Group models. This model was analyzed using a traditional “pushover” analysis to obtain the force-displacement curve of the bent at the deck level.

Global Spine Model

This model was used to layout the location and quantity of the LRB-dolphins. The model represents the diaphragm of the pier using a frame element that matches the diaphragm stiffness and mass of the deck. The bents and LRB-dolphins are represented by springs with secant stiffnesses obtained from the results of the models described previously. An important feature of this model that must be considered is that it reduces the MDOF behavior of the pier bents to SDOF behavior. This has the consequence of potentially ignoring mass from the foundations and columns that contribute to the base shear resisted by the LRB-dolphins. Consequently,
additional mass was included to account for participation of the foundations and columns (see previous description of the Dynamic 2-D Bent Model).

Results

The performance of the pier in its retrofitted condition is summarized in Figure 13. The addition of the LRB-dolphins significantly improves the strength and stiffness of the structure while the additional damping, totaling approximately twenty-five percent, effectively reduces the seismic demand, resulting in acceptable seismic performance of the pier.

![Pier 6 Global Longitudinal Pushover](image)

Figure 13. Pier 6 global pushover with column and LRB-dolphin retrofits.

Conclusions

Although Pier 6 is nearly 100 years old and was constructed without considering seismic loading, LRB-dolphins provide a feasible retrofit option for a design-level earthquake by adding significant strength, stiffness, and damping to the structure.

References