# Innovative Wharf Details: Elastomeric Bearing Pile-Deck Connection and Finned Monopile

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## ABSTRACT

For moment frame wharf structures, the pile-to-deck connections are most susceptible to seismic damage. Even in minor earthquakes, spalling is expected at the landside piles. Recent research indicates that providing a fiber-reinforced elastomeric bearing pad at the pile-to-wharf interface will significantly improve seismic performance. The pad limits localized stresses, reduces damage in earthquakes, and increases connection flexibility, permitting greater lateral displacements without reduced connection strength.

Monopile structures that cantilever from the ground develop large soil stresses near the ground surface when laterally loaded. Adding fins to the piles near the ground surface reduces the required pile diameter and length.

This paper presents the following:

Fiber-reinforced elastomeric bearing pile connection design − the design provides improved connection rotation, eliminates potential damage in an operating level earthquake, and includes a sealed connection for acceptable corrosion performance. The calculated performance is compared to a traditional pile connection.

Finned monopile design − the design results in shorter, smaller diameter piles. The design will be compared with non-finned piles.

## ELASTOMERIC BEARING PILE CONNECTION

### Introduction

The design on a recent pier repair project had to meet 2007 California Building Code (CBC) criteria, which are more stringent than those of the 1985 Uniform Building Code that was used for the original design. Also, for environmental reasons, the new piling cross section could not be larger than that of the original piles. An initial analysis indicated that using a conventional pile connection would result in severe damage due to small lateral displacements—much less than required by the 2007 CBC. The typical pier section is shown in Figure 1.

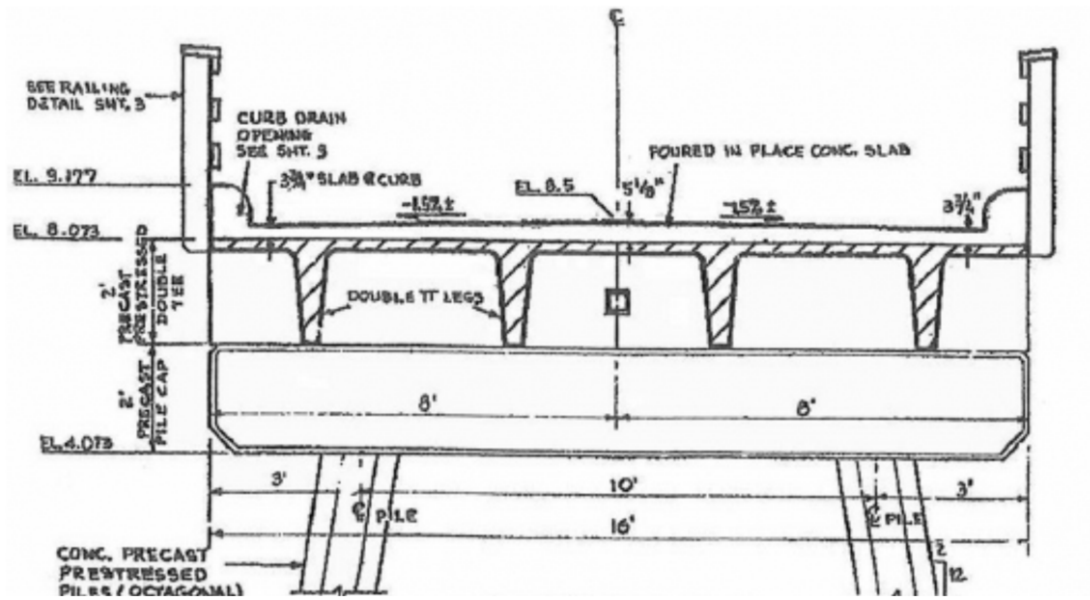


**Figure 1. Typical pier section.**

To meet the design requirements, a flexible pile connection was designed that was ductile and also stiff enough to prevent significant P-$\Delta$ moments.

## Design Basis

The flexible pile connection design is based on previous tests of similar components on a variety of full-sized prototype connections as part of a research study for the National Earthquake Engineering Simulation Research Seismic Risk Management of Port Systems (NEESR-SRMPS).

As a member of the advisory committee for the NEESR-SRMPS study, the authors helped develop flexible pile connections specifically designed to mitigate seismic damage between piles and wharf decks. As part of this study, researchers, under the direction of Professor Charles Roeder at the University of Washington, designed, fabricated, and tested a variety of pile connection designs.

This study determined that providing a layer of strong, but relatively flexible, material in the pile-wharf interface significantly reduced damage from pile rotation, while achieving connection strengths similar to a traditional pile connection.

Details and test results for traditional and flexible pile connections are provided in Figure 2. The test results are for 24 in (0.6 m) octagonal piles with 450 k (200 t) compressive axial loads. The percentages in the figures present the pile connection rotation; the forces are in kips. (Note: 1 t = 1 metric tonne = 1,000 kg; 1 k = 1 kip = 1,000 lbs).

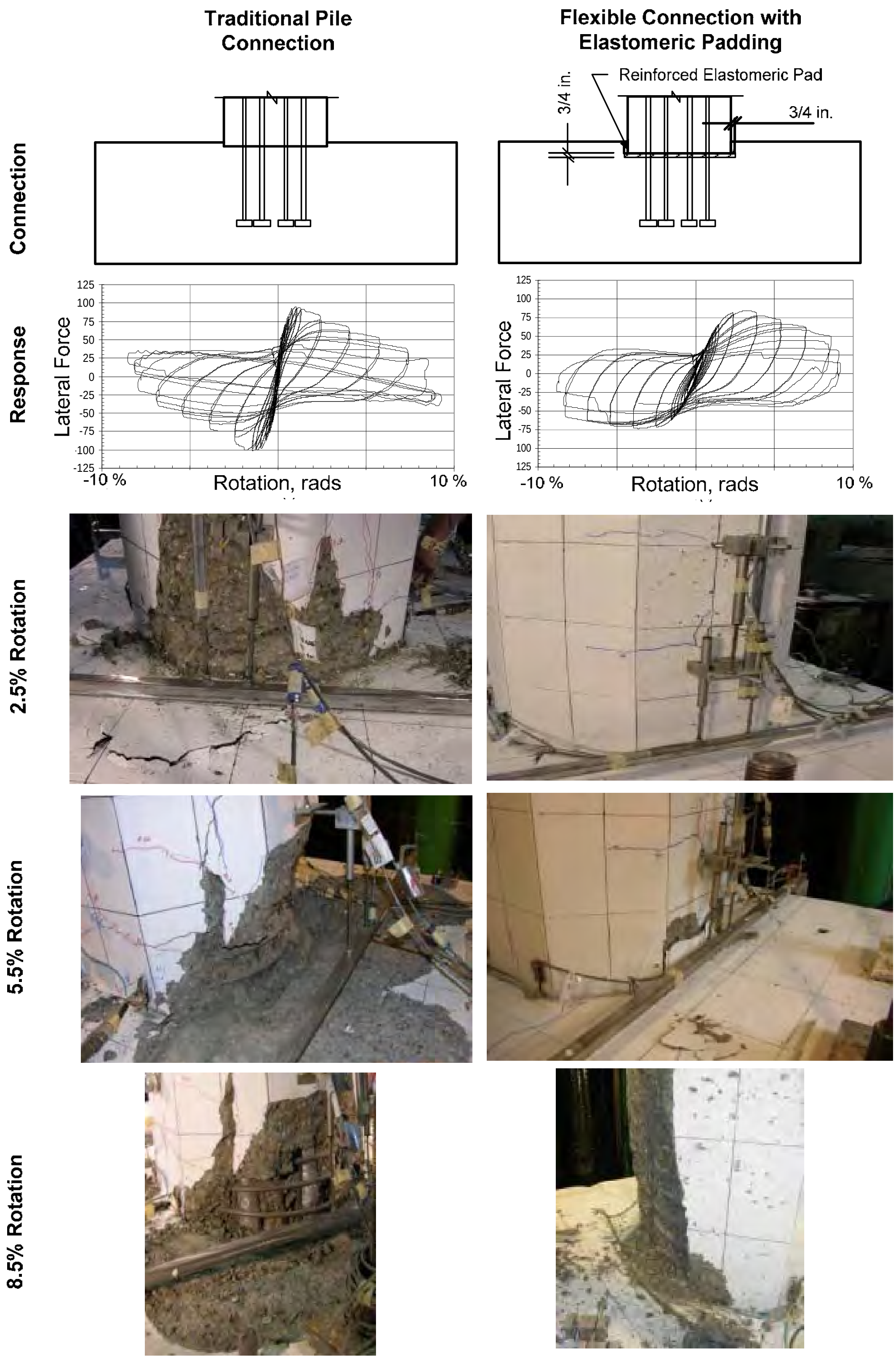


**Figure 2. NEESR-SRMPS pile connection test results (by Charles Roeder).**

Notice:

1. The flexible connection is nearly as strong as the traditional connection at small rotations and is stronger than the traditional connection at large rotations.
2. As the pile rotation increases, the traditional connection loses more lateral capacity than the flexible connection. The flexible connection prevents spalling damage.
3. For both connections, the lateral load decreases with rotation due to P-$\Delta$ effects.
4. Under cyclical loading, both traditional and flexible connections degrade due to spalling. After spalling occurs, both connections ultimately fail when the dowels buckle and fracture.

## Connection Design

The flexible pile connection for the pier repair project is shown in Figure 3.

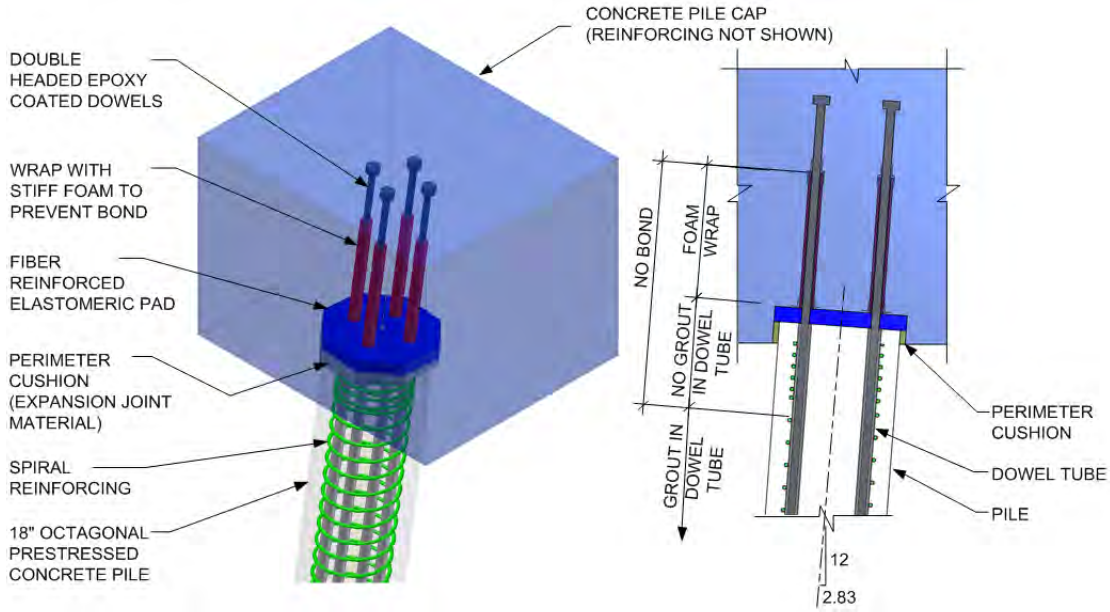


**Figure 3. Flexible pile connection.**

The key elements of the flexible pile connection are the fiber-reinforced elastomeric pad, perimeter cushion, and unbonded dowel length.

Fiber-reinforced elastomeric pads are commonly used to limit impact forces and to control vibrations in structural and mechanical systems. They are used in structural bearings such as bridge bearings. The pad used in this project is strong and flexible, having a 10 ksi (69 MPa) breakdown stress and a secant modulus of elasticity of about 25 ksi (172 MPa).

The elastomeric pad is flexible enough that it compresses about ½ in (13 mm) for the design earthquake. The unbonded length of dowel permits axial dowel deformation over a much longer distance than if no unbonded length were provided. The pad required in this design is significantly thicker than that tested in the NEESR-SRMPS study; also, the unbonded dowel length is longer.

Unbonding the pile and pile cap reinforcing prevents spalling due to dowel elongation.

The pile shear forces are small and are carried mainly by the expansion joint material when the pile is in compression, and jointly by the dowels and expansion joint material when the pile is in tension.

The perimeter cushion expansion joint material enables movement. The joint is sealed using silicone caulking.

**Expected Performance**

The calculated moment-rotation relationships for the flexible and traditional pile connections are shown in Figure 4. The flexible connection is rotationally more flexible than the traditional connection and, more importantly, the pile outer shell fails at a much larger rotation. Accommodating large rotations without spalling greatly reduces the risk of earthquake damage.

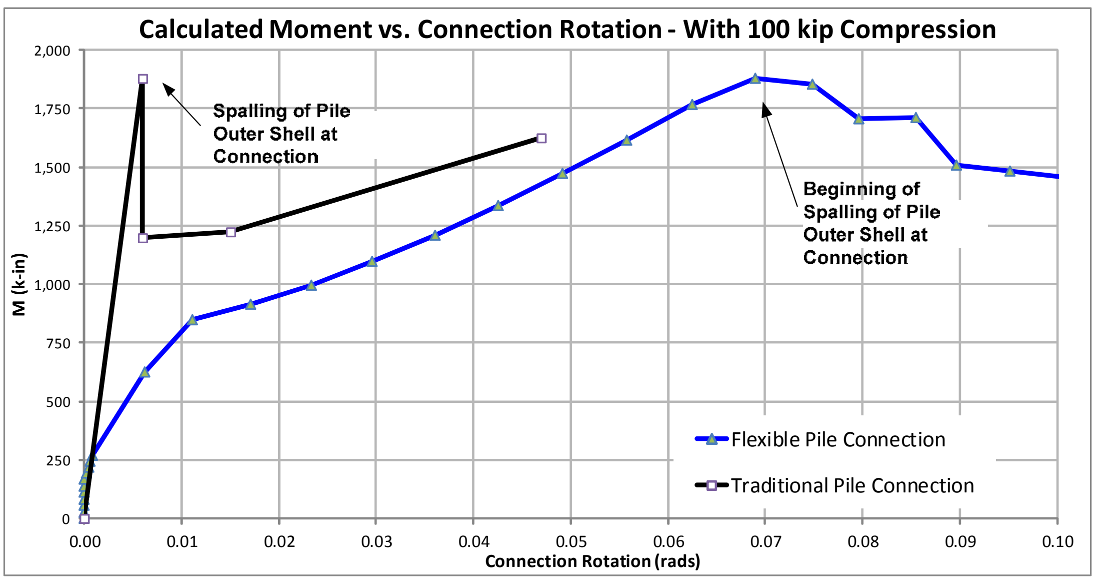


**Figure 4. Pile connection moment vs. rotation.**

The calculated pier pushover curve based on a non-linear analysis considering P-Δ effects is provided in Figure 5 for both flexible and traditional pile connections.

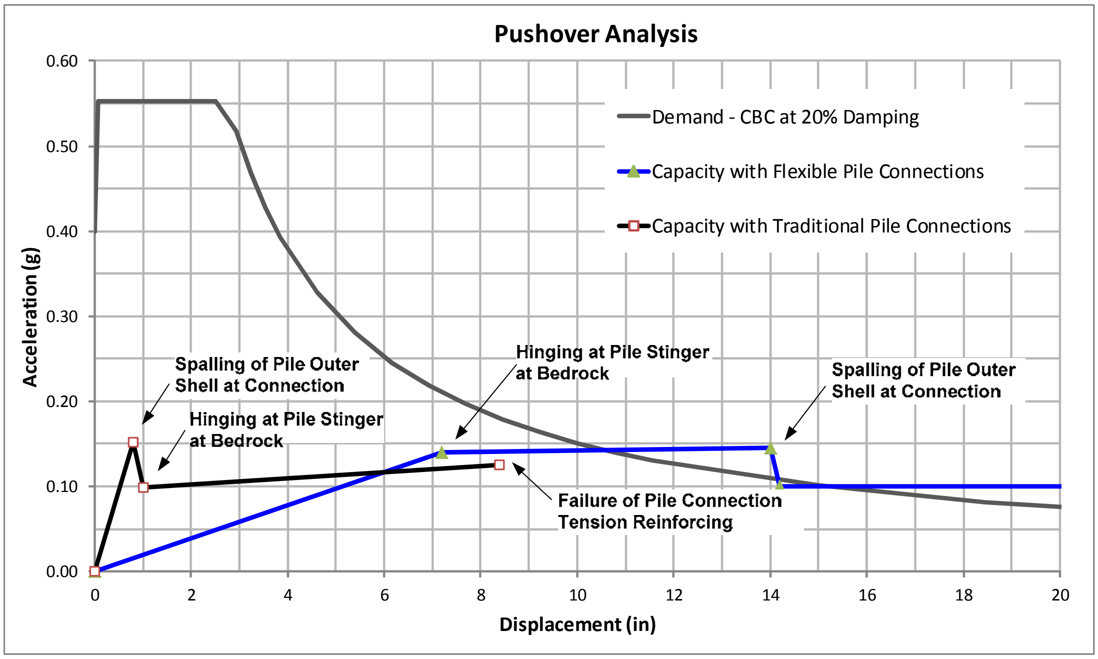


**Figure 5. Pushover analysis including P-Δ effects.**

The NEESR-SRMPS pile test results shown in Figure 2 indicate that degradation of the connection under cyclic loading is a major risk for a pile connection. Ultimately, failure occurs due to local buckling of the dowel reinforcing after the pile concrete cover spalls.

As shown in Figure 5, the flexible pile connection permits enough rotation that the pile outer shell is not expected to spall even in the design earthquake. The pile connection and pile cap are expected to have little damage in the design earthquake.

The sealed flexible pile connection is shown in Figure 6.

**Figure 6. Photograph of sealed pile connection.**

### Summary – Elastomeric Pile Bearing Connections

A flexible pile connection using a fiber-reinforced bearing pad, isolated embedded pile perimeter, and unbonded dowels significantly improved the performance of the connection and the entire structure for little additional cost.

## FINNED MONOPILE

### Introduction

When you put a fence post in the ground and pull it back and forth, the soil at the surface deforms the most. Adding fins near the surface is an effective method of increasing strength and stiffness. See Figure 7.

**Figure 7. Finned fence post.** *Source: Agway.com*

The same improvement can be applied to laterally loaded piles. See Figure 8.

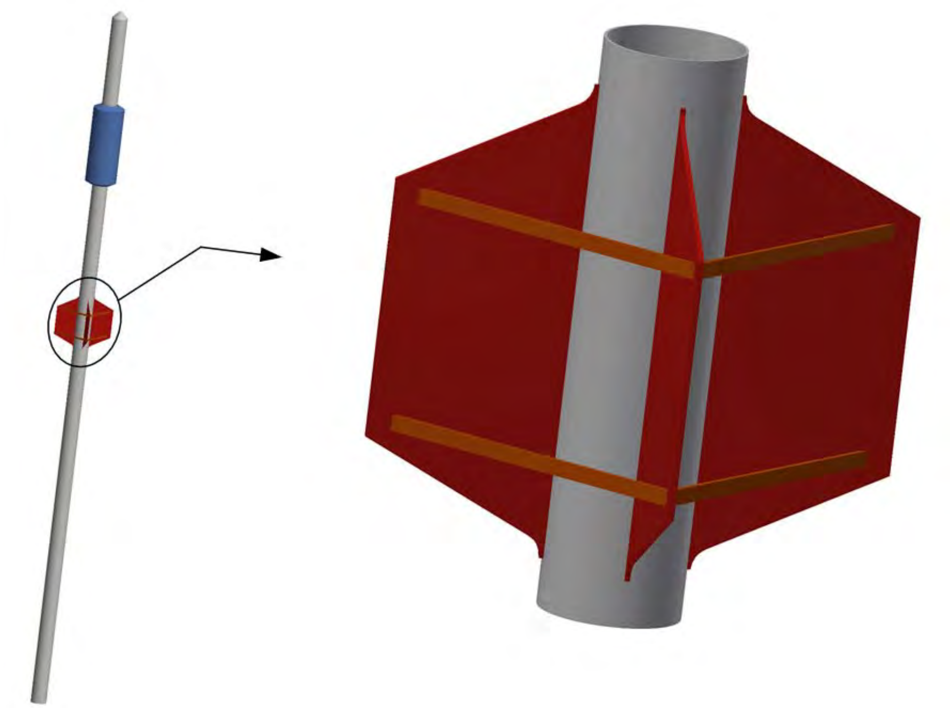

**Figure 8. Finned dolphin pile isometric.**

This portion of the paper will present findings on two projects where pile fins were used, and also some design considerations for using fins.

**Project 1 – Fixed Pile Diameter – Stiff and Strong Soil at Mud Line**

This project, on the Sacramento River, involved the design of a mooring dolphin. The soil near the mud line was reasonably stiff and strong. A single pile dolphin solution was preferred. The contractor preferred available 5 ft (1.5 m) diameter piling. A pile of this size, however, could not resist the design load. Instead of using a larger diameter pile, the lateral resistance of the pile was increased by adding orthogonal steel plate fins just below the mud line. The five-foot diameter pile had a 1½ in (38 mm) thick wall and was 115 ft (35 m) long. Each of the four fins was 1¾ in (45 mm) thick, 2 ft-6 in (0.76 m) wide, and 20 ft (6 m) long. The fins added 13% to the pile weight, but saved two piles, or the need to purchase a larger, stronger single pile.

**Project 2 – Repeated Large Berthing Loads – Thick Layer of Soft Bay Mud**

The WETA South San Francisco Ferry Terminal includes four berthing dolphins. Two of the dolphins are subjected to frequent, large berthing loads. Three-foot diameter dolphin piles were driven into a thick layer of soft bay mud.

Piles without fins could resist the load, but they might become noticeably out-of-plumb due to the frequent large berthing loads.

Piles with fins just below the mud line were less apt to become out-of-plumb.

Piles with four 1 in (25 mm) thick, 4 ft (1.2 m) wide, and 10 ft (3 m) long fin plates were selected for the frequently loaded dolphins. The fins added 10% to the pile weight. See Figure 9.

Several fin locations were considered. Analyses indicated that the fins should be located 15 ft (4.6 m) below the mud line to maximize their effect. See Figure 10.

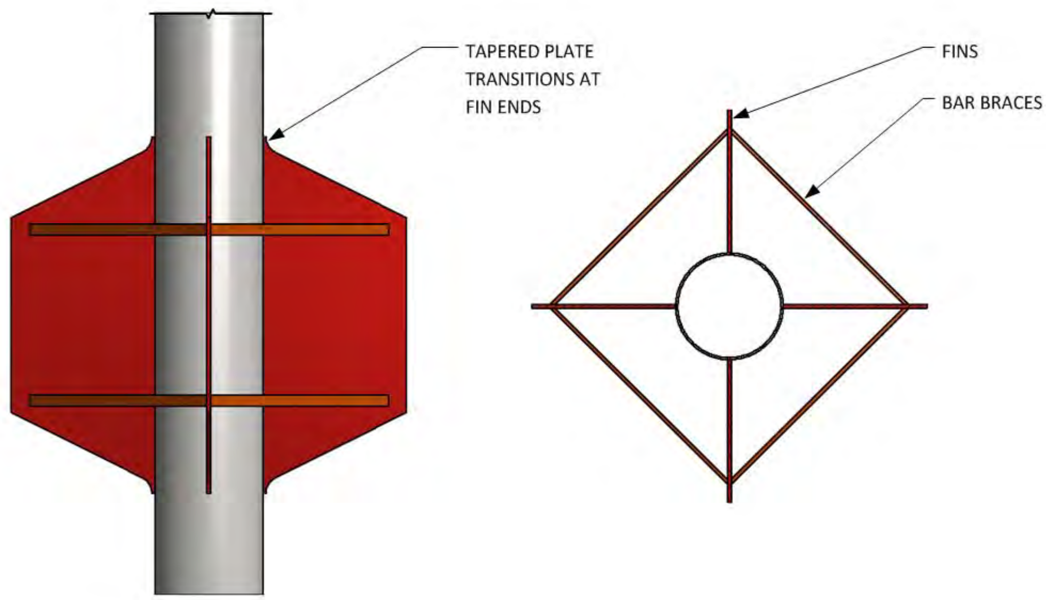


**Figure 9. Fin details, Project 2 – WETA Ferry Terminal.**

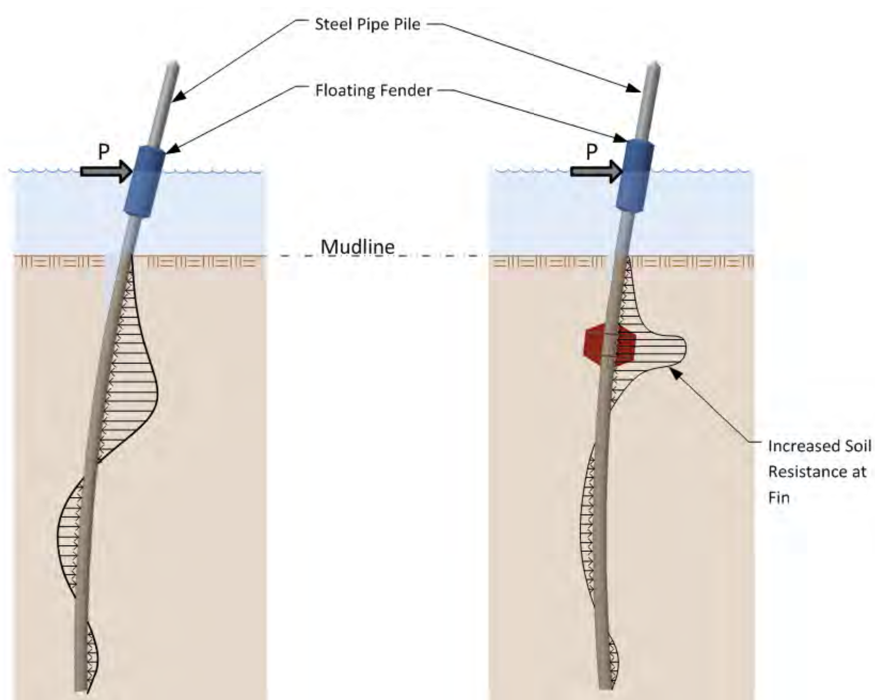


**Figure 10. Soil resistance and pile deflection – without and with fins.**

## Design Considerations

Some design considerations:

Fin plates should be weaker than the pile wall to ensure that the fins will yield and the wall will not. Slotting the pipe pile and running the fin plate through is an option for piles loaded in only one direction and requiring only two fins, or for piles with four fins that are large enough in diameter to permit welder access for the cruciform plate weld inside the pile.

The fins increase the pile strength and stiffness. The increase in stiffness may not be significant in stiff soil and when the fin length is limited.

A radius should be provided at the fin ends to reduce stress concentrations in the pile wall and reduce the probability of fatigue cracking in the pile at the end of the fin. See Figure 9.

For large fins, bar braces were provided between the fins for handling. See Figure 9.

## Summary

Adding fins to monopiles near the mud line can significantly increase the pile's lateral resistance and substantially improve the rigidity and strength of the monopile system.

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### Finned Pile

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