

## **Proposed Seismic Detailing Criteria for Piers and Wharves**

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### **ABSTRACT**

A new ASCE standard, Seismic Design of Pile Supported Piers and Wharves, is being developed by the Coasts, Oceans, Ports, and Rivers Institute. The standard will use displacement-based methods and build on the provisions of similar standards such as the Marine Oil Terminal Engineering and Maintenance Standards, the Port of Long Beach Wharf Design Criteria, and the Port of Los Angeles Container Terminal Seismic Code. As part of the development of the proposed standard, a significant effort was expended reviewing test data for a wide variety of deck systems and pile-to-deck connections commonly used throughout North America. A common finding of the tests is that the rotation at the pile-to-deck connection is concentrated at a large crack at the interface between the pile and the deck rather than over a short length of the pile at the top of the pile, which is the expected behavior for reinforced concrete in flexure.

This paper focuses on the detailing of pile-to-deck connections and summarizes the available test data for the connections that are considered in the proposed standard, along with permitted strategies for reducing earthquake damage at pile-to-deck connections.

### **INTRODUCTION**

The proposed ASCE standard, Seismic Design of Pile Supported Piers and Wharves, has been under development since 2005 by a committee of the Coasts, Oceans, Ports, and Rivers Institute (COPRI). The members of the committee are practicing structural engineers, geotechnical engineers, owners, and academics with specific expertise and experience in the marine and waterfront industries. The proposed standard is intended to reflect the current practice of seismic design of piers and wharves, which differs considerably from the conventional design of buildings or building-like structures. For example, load combinations for piers and wharves are unique; they include berthing and mooring loads that may govern the lateral load design in low seismic regions. Geotechnical issues are a prime concern for these

types of structures, with pile foundations often penetrating through weak soil layers. Liquefaction, lateral spreading, and slope stability are all special items that are primary considerations for the analysis and design of piers and wharves. The proposed standard also codifies the displacement-based design methods that have become widely used in the industry and are supported by a number of industry-sponsored testing programs.

This paper will focus on the detailing of pile-to-deck connections and presents an overview of test data for the connections that are considered in the proposed standard, along with permitted strategies for reducing earthquake damage at pile-to-deck connections.

## OVERVIEW

Pier and wharf construction throughout the United States typically consists of cast-in-place or precast deck superstructures supported by precast, prestressed concrete or steel pipe piles connected to the deck by methods that depend on location and project requirements. The goal of the proposed standard is to provide mandatory provisions and commentary for all commonly used connections that have been proved by testing to be ductile and suitable for seismic applications.

The proposed standard recognizes that selection of the pile-to-deck connections should be based on the relationship among a number of parameters such as the type of structure (pier or wharf), seismic demand, length of pile, type of pile, soil stiffness, magnitude of other lateral loads such as waves and mooring, post-earthquake reparability, corrosion, and life cycle cost. Therefore, connections may have full or partial moment capacity. These connections are listed according to pile type, e.g., steel pipe piles or prestressed concrete piles. Committee members reviewed the literature and gathered test data for all the connections discussed in the proposed standard (see Table 1). Other connections are permitted provided their performance is verified by testing and/or appropriate analysis.

## TERMINOLOGY

A brief description of several key pile-to-deck connection terms used in the proposed standard follows (see Figure 1).

**Capacity Protected.** Elements designed to elastically resist forces and moments imposed by adjacent yielding element(s).

**Interface.** The construction joint between the top of the pile and the deck.

**Joint Region.** The portion of the deck above the pile which transfers forces and moments from the pile to the deck.

**Plastic Hinge Zone.** The region of the pile and/or connection where inelastic action occurs in an earthquake.

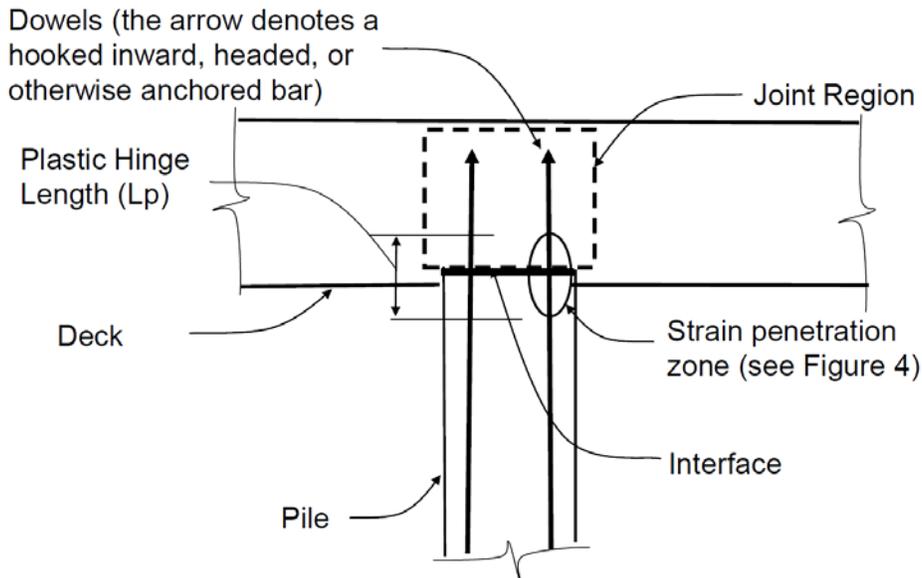
**Strain Penetration Length.** The distance of dowel debonding on each side of the interface.

**Full Moment Connections.** Connections which develop the moment capacity of the pile. The connections may or may not fix the pile head against rotation.

**Partial Moment Connections.** These connections are under-reinforced at the interface with respect to the body of the pile. As a result, the inelastic behavior and damage is confined primarily to a short length of the dowels just above and below the connection interface, i.e., the strain penetration length.

**Table 1. Pile-to-Deck Connections Considered in the Proposed Standard**

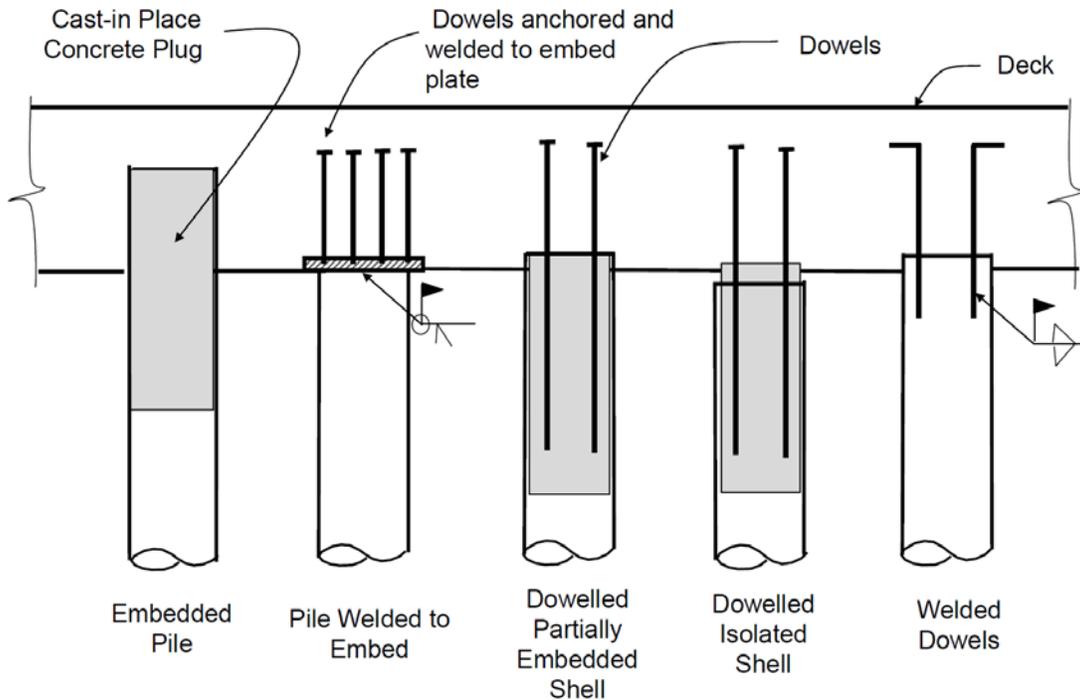
Connection Type	Full Moment	Partial Moment
<b>Pipe Pile Connections</b>		
Embedded Pile	X	
Pile Welded to Embed Plate	X	
Dowelled with Embedded Shell		X
Dowelled with Isolated Shell		X
Welded Dowels		
<b>Prestressed Concrete Pile Connections</b>		
Embedded Pile	X	
Pile Build-Up	X	
Extended Strand	X	X
Dowelled	X	X
Hollow Dowelled		X
Isolated Interface		X



**Figure 1. Pile-to-deck connection terms.**

## PIPE PILE CONNECTIONS

Figure 2 illustrates the pipe pile connections listed in Table 1. A summary of the significant test data follows.



**Figure 2. Pipe pile connections.**

**Embedded Pile.** Tests by Stephens and McKittrick (2005) for piles embedded one diameter and loaded in the long direction of a bridge bent cap indicate it is possible to develop the plastic moment in a pipe pile and effectively fix the pile head against rotation.

**Pile Welded to Embed Plate.** Tests by Steunenburg et al. (1998) indicate the plastic moment capacity was developed by welding the pipes to thick plates anchored to the precast pile caps with deformed bar anchors stud-welded to the plate. However, a significant number of the deformed bars fractured at the weld. Therefore, the proposed standard will have criteria to ensure the plastic hinge forms in the pile and the anchorage is capacity protected.

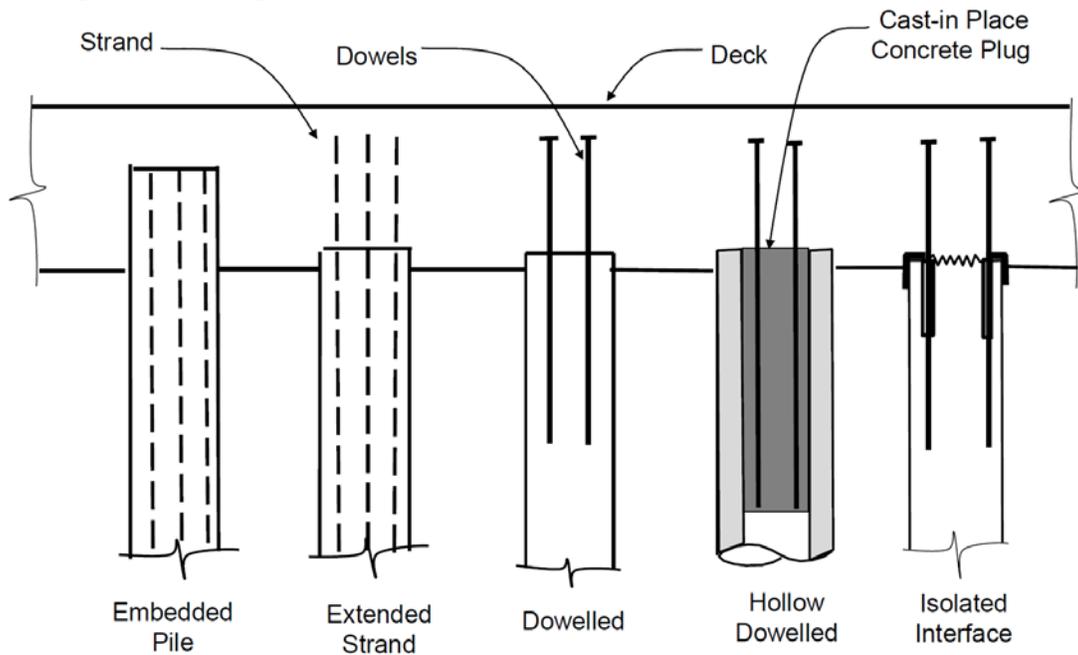
**Dowelled with Partially Embedded or Isolated Shell.** These connections as shown are usually considered partial moment connections, as it takes a large amount of reinforcement to develop a plastic hinge in the pile. Both connections have been shown to achieve remarkable ductility. Tests by Park et al. (1983) on concrete filled and partially embedded pipe piles connected to the deck with reinforcing bars extending from the concrete into the deck exhibited extremely large ductility with dependable moment capacity, and the connections exhibited strengths well in excess of theoretical predictions due to the large lever arm created by bearing of the pile

shell on the deck. Tests by Silva et al. (2001) used pipe piles with discontinuous casing at the interface to minimize the overstrength moment.

**Welded Dowels.** This connection, which uses reinforcing field welded to the pile shell. No test results were found for this connection. Therefore, the connection is not permitted if inelastic performance of the dowels is desired, as the presence of the weld creates the potential for brittle fracture of the dowel.

### PRESTRESSED CONCRETE PILE CONNECTIONS

Figure 3 illustrates the prestressed concrete pile connections listed in Table 1. A description of the significant test results follows.



**Figure 3. Prestressed concrete pile connections.**

**Embedded Pile.** Tests of this connection by Harris and Petrou (2001) under constant axial loading determined that with adequate embedment length, the connection would develop the moment capacity of the pile. The proposed standard sets the minimum embedment at one pile diameter or 50 strand diameters.

**Extended Strand.** Joen and Park (1990) tested six pile-cap connections. All of the connection details developed the moment capacity of the pile while exhibiting satisfactory ductile behavior. The proposed standard allows extended strand connections, provided the strands are anchored into the deck and undamaged.

**Dowelled.** This is the most commonly used connection for pier and wharf construction and has been the subject of significant research. The performance of prestressed concrete piles with dowelled connections varies depending on the amount of reinforcement and the axial load on the pile. This is illustrated in tests by Restrepo et al. (2007) on 24-inch prestressed concrete piles with typical Port of Los Angeles

(POLA) connections using either eight #10 or four #9 bars. The eight #10 bar connection develops the moment capacity of the pile and is used for short piles at the bulkhead with large seismic moments (referred to as seismic piles by POLA). The four #9 bar connection is used for longer piles with smaller seismic moments referred to by POLA as a secondary-seismic pile. In tests of both connections, a large crack developed at the pile-deck interface while a few hairline cracks developed in the piles. The seismic pile performed adequately but exhibited a significant reduction in capacity when the cover spalled at a ductility demand of about 3. Other tests by Roeder et al. (2001), Priestley and Sritharan (2004), Blandon (2007), and Jellin (2008) indicate similar performance for dowelled connections.

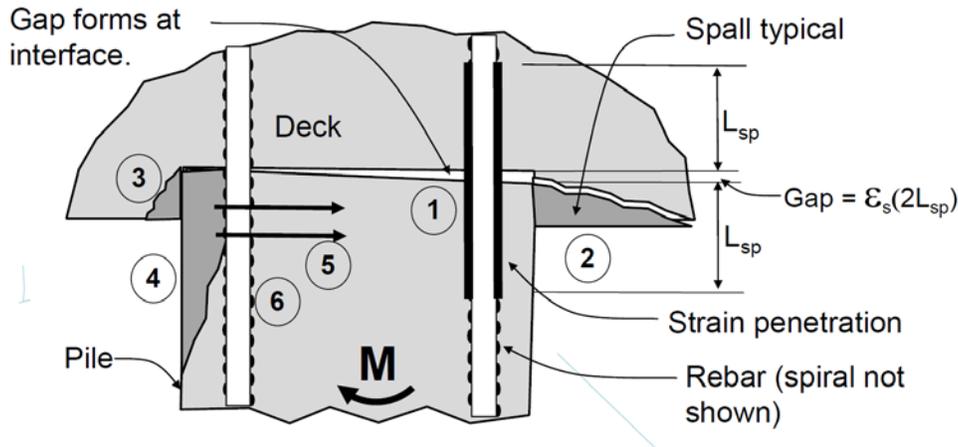
**Hollow Dowelled.** Dowels are commonly extended from a concrete plug due to the difficulty of extending reinforcement from the shell into the deck. The committee was unable to obtain relevant test data for this connection. However, calculations indicate that if the connection is too strong, longitudinal cracks may develop in the shell due to splitting forces caused by horizontal reactions of the plug bearing on the shell. Therefore, it is recommended that this connection be designed as a partial moment connection.

**Isolated Interface.** Tests by Jellin (2008) indicate the seismic performance of a prestressed concrete extended dowel connection is significantly enhanced by isolating the pile-to-deck interface, and sleeving the dowels to minimize spalling of the deck and reduce the strain in the dowels. Compared to the conventional connection, the isolated interface connection permits larger pile rotation before damage, and provides larger hysteretic energies, although the tests indicate the moment capacity of the connection is reduced compared to the dowelled connection due to the smaller lever arm. The isolation material should be of closed cell foam or other material suitable for the marine environment.

## **PILE-TO-DECK CONNECTION KINEMATICS**

Tests on dowelled connections often find rotation at the pile-to-deck connection, concentrated at the interface between the pile and the deck and attributable to the type of prying action shown in Figure 4. During the cyclical earthquake loading, the gap opens and closes repeatedly, resulting in these events—generally in this order.

1. Tension and compression yielding causes the deformations to grind an annulus in the concrete adjacent to the bar. This debonding is also known as strain penetration.
2. Deck spalling occurs on the tension side of the connection due to prying.
3. Deck spalling takes place on the compression side of the connection due to bearing.
4. Cover spalling occurs on the compression side of the pile due to bearing.
5. Yielding of the spiral is present, which results in loss of confinement of the concrete core and reduction in lever arm and shear strength.
6. The dowels buckle and fracture.



**Figure 4. Pile-to-deck connection kinematics.**

The strain penetration length,  $L_{sp}$ , is commonly defined by the following expression (Priestley and Park 1984).

$$L_{sp} = 0.15 f_{ye} d_b; \quad L_{sp} = 0.022 f_{ye} d_b \quad (f_{ye} \text{ in ksi, MPa}) \quad (\text{Equation 1})$$

where

$L_{sp}$  is the strain penetration length (inches, mm), taken as equal in the pile and deck

$f_{ye}$  is the expected yield stress (ksi, MPa) and  $d_b$  is the bar diameter (inches, mm)

In the proposed standard, the plastic hinge length,  $L_p$ , will be defined as twice the strain penetration length for all dowelled connections.

To illustrate the magnitude of the deformations at the interface, consider that for a connection with #10 bars at  $f_{ye} = 66$  ksi (442 MPa), the calculated strain penetration length is 12.3 inches (312mm) and the plastic hinge length is 24.6 inches (625 mm). The bar elongation, i.e., the gap at the interface, is obtained by multiplying by the strain in the bar by the plastic hinge length. At the OLE and CLE strain limits of 0.01 and 0.05, the gap is therefore 0.23 inches (6 mm) and 1.1 inches (28 mm), respectively.

## **DAMAGE REDUCTION STRATEGIES**

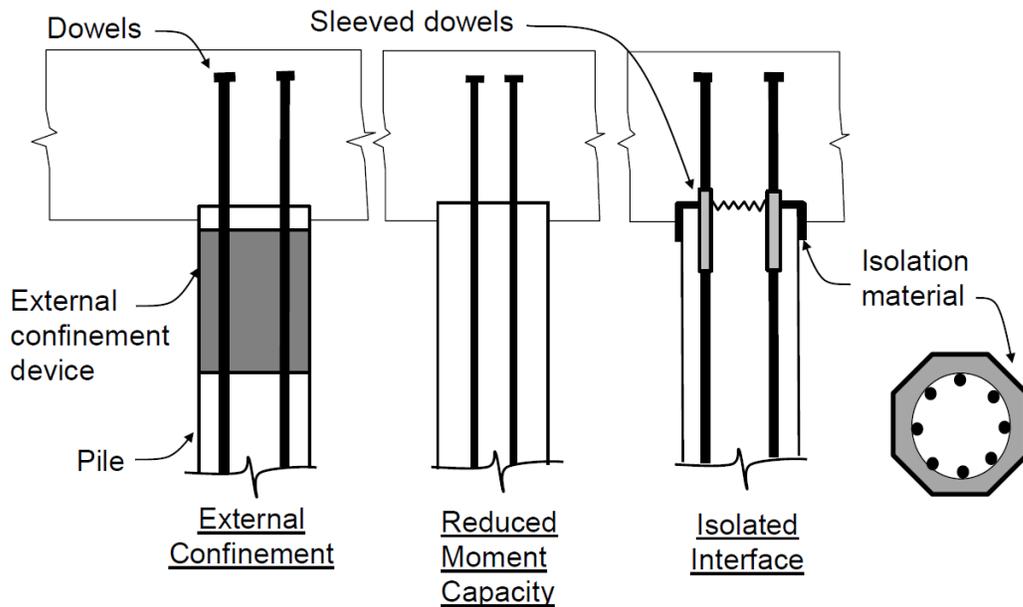
As shown in Figure 4, the damage to a prestressed pile connection is progressive and results in connection failure. All of the behaviors are avoidable except for strain penetration. There is no strain penetration if the connection remains elastic. Figure 5 illustrates three strategies to reduce damage.

**External Confinement.** The first strategy is similar to that used for retrofit of concrete columns to produce a highly ductile connection, as illustrated by the

performance of dowelled pipe pile connections. Unfortunately, this strategy introduces an additional element, increases complexity and cost, and does not prevent deck spalling.

**Reduced Moment Capacity.** The second strategy, used by POLA for secondary seismic piles, uses an under-reinforced connection to reduce the moment demand and minimize spalling of the pile cover, but does not prevent deck spalling. The reduced demand keeps the joint region uncracked, thereby allowing the dowels to be anchored below the top mat of deck reinforcement to simplify construction (Restrepo et al. 2007).

**Interface Isolation.** The third strategy uses interface isolation on the top to prevent concrete-to-concrete contact at low to moderate rotations, thereby minimizing pile damage (Jellin 2008). Figure 6, (Jellin 2008) shows the effectiveness of the isolated connection versus the dowelled connection as the damage to the dowelled connection is substantially less than the dowelled connection.



**Figure 5. Damage reduction strategies.**



5% Drift



5% Drift



8% Drift

Dowelled Connection



8% Drift

Dowelled Connection with  
Isolated Interface

**Figure 6. Performance of dowelled versus isolated interface connections.**

## **SUMMARY**

The proposed standard codifies displacement-based design methods that have become widely used in the industry over a period of several years and are supported by a number of industry-sponsored testing programs. The paper described detailing of pile-to-deck connections and presented an overview of the test data for the connections considered along with strategies for reducing earthquake damage at the pile-to-deck connections.

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