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IMPROVED PILE-TO-WHARF CONNECTIONS TO REDUCE SEISMIC DAMAGE OF WHARFS

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ABSTRACT

Pile-supported marginal wharves are a critical component of port infrastructure. Experience indicates that the connection between the pile and the wharf deck is a major source of earthquake damage. Previous studies indicate that although connections designed using current guidelines can sustain cyclic deformation demands; they sustain significant deterioration in resistance and damage. Therefore, there is an interest in improving the performance and seismic capacity of precast pile connections, and a study to improve the performance of pile-wharf connections is summarized. Several structural concepts are proposed including (1) intentional debonding of the headed reinforcing bars, (2) supplemental rotation capacity through the addition of a cotton duck bearing pad and (3) supplemental material to sustain the lateral deformations while minimizing deck damage. The test results will be presented relative to current practice and achieving performance-based design objectives.

Introduction

Ports are an important social and economic investment for society, and they are susceptible to earthquake damage. The economic loss when shipping is interrupted is very large. For example, the direct damage to the port of Kobe, Japan during the 1995 earthquake exceeded U.S.$11 billion [EQE (1995)], but the actual financial loss to the region was much larger, since the port of Kobe has recovered only a portion of its pre-earthquake volume, while surrounding ports in Asia and Japan increased their volumes by 40% to 100% [Landers (2001)]. Marginal wharfs are a primary element in US port facilities, and they are typically pile-supported structures as depicted in Fig. 1. The pile-wharf connection is important to the seismic performance of marginal wharves, because the piles support the large gravity loads while providing lateral resistance to the structural system. The system is comprised of a soil or rock dike or embankment, a concrete deck, and piles that support the deck loads and resist lateral

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seismic forces. These piles may be vertical piles with moment resisting connections as illustrated in Fig. 1b or lateral resistance may be provided by steel batter piles as shown in Fig. 1c.

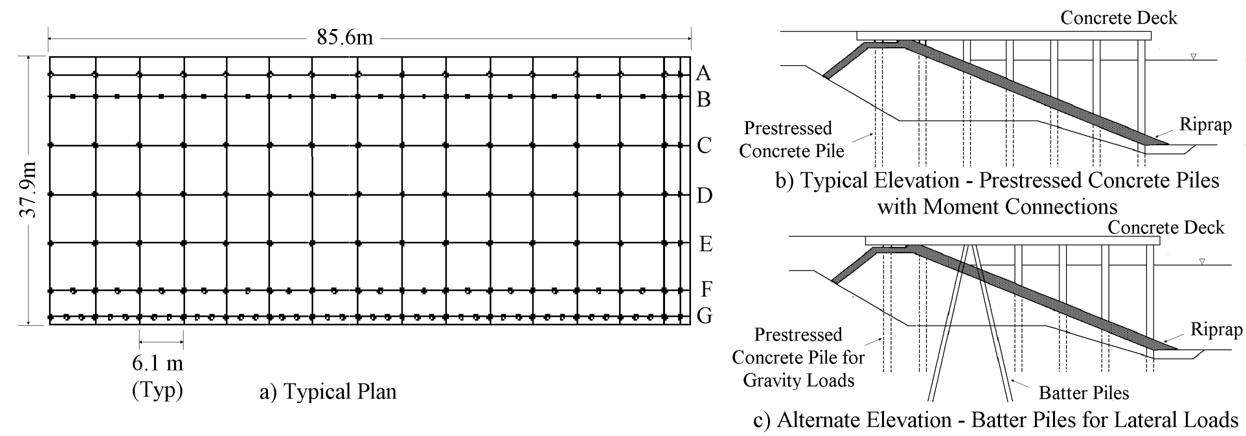


Figure 1. Typical Marginal Wharf

Vertical prestressed concrete piles with moment resisting connections are most commonly used for current seismic design. Most are solid 610 mm diameter octagonal piles, but hollow core concrete piles may be used for supporting gravity loads. The shorter piles provide the bulk of the lateral resistance. Most wharf decks are cast-in-place concrete or a combination of cast-in-place concrete with precast concrete elements that support the concrete during construction. Before the deck is cast, the pile heads are cut to approximately 50 to 75 mm above the bottom of the deck. If a pile is driven below deck level, an extension is added to the end of the pile to bring it to the desired elevation. Economical seismic design requires that detailing of the pile-deck connection must be sufficient to develop the necessary lateral resistance and to form plastic hinges that are capable of significant inelastic rotations. A wide range of connection details for moment-resisting precast pile connections have been employed in past US practice as illustrated in Fig. 2.

Figure 2a shows a detail where dowel bars are bonded into corrugated tubes in the ends of precast piles and bent outward in a radial or orthogonal pattern within the confined concrete near the top of the wharf deck. There have been wide variations in this connection design including:

- the number and size of the dowel bars,
- the length of the bar embedment into the wharf deck and into the end of the pile,
- the use of spiral steel to confine the concrete within the connection, and
- the placement of the embedded bars relative to the top layer of flexural reinforcement in the wharf deck.

Wharves commonly use piles that are slightly longer than required and are driven until the compressive resistance is achieved. However, some piles are overdriven to achieve the required compressive resistance, and pile extensions as illustrated in Fig. 2b are required. For piles that extend about the wharf deck, the concrete in the pile is cut off to the desired elevation. In older wharf structures, the concrete in the pile above the bottom line of the deck was crushed (after the pile was driven), and the prestressing strands from the crushed pile were then fanned out into the wharf deck to provide the moment transfer as illustrated in the Fig. 2c. This connection is not commonly used today due to nicks and cuts caused by the concrete crushing device commonly nicked and the reduced connection ductility that results.

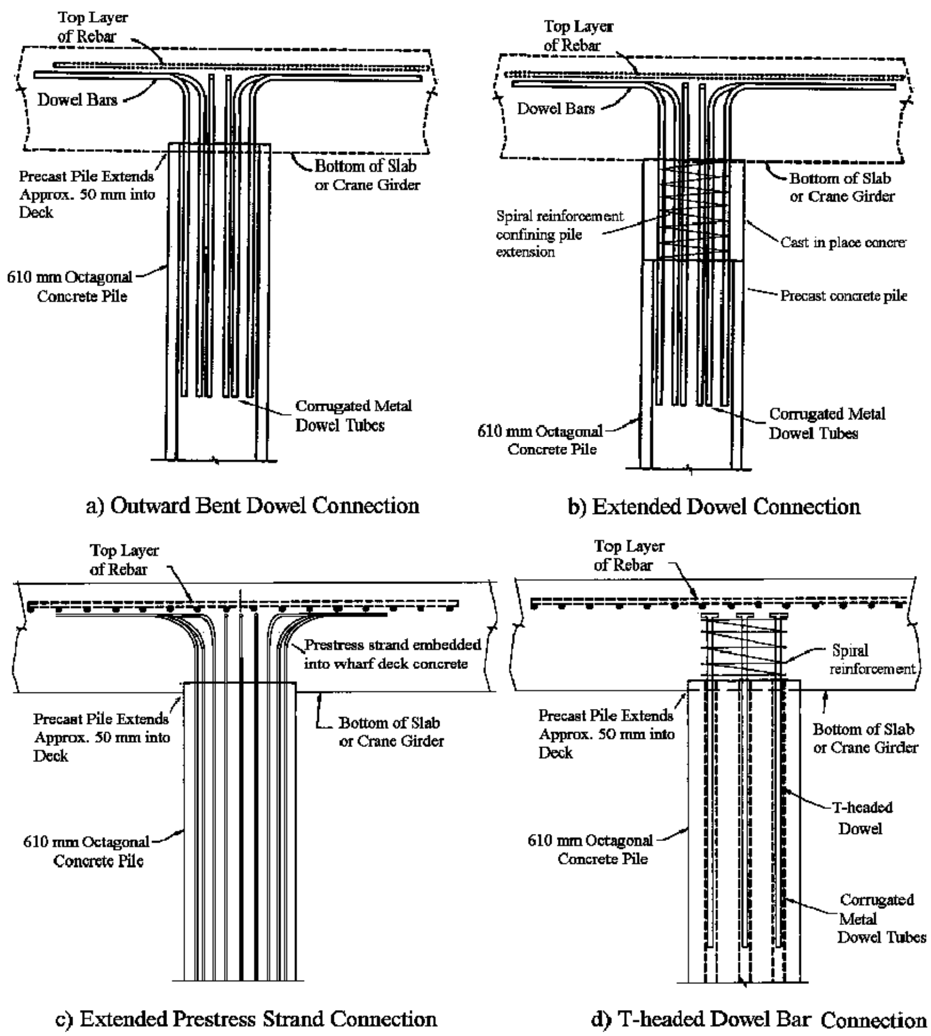


Figure 2. Typical Pile-Wharf Connections Used in US Practice

The bent dowel bar and embedded strand connection details described in Figs. 2a, 2b, and 2c cause considerable interference for placement of the wharf deck reinforcement. As a result, connections with T-headed dowel bars as shown in Fig. 2d have been used to overcome this economic concern. The dowels are bonded into corrugated steel ducts as with the previous details, but the bars are not bent to provide moment transfer into the wharf deck. Instead the T-headed bars transfer moment to the wharf deck. This connection detail reduces the interference to the deck flexural reinforcement, and thereby reduces construction cost. In addition, it is easier to employ spiral reinforcement about the connection zone with this connection.

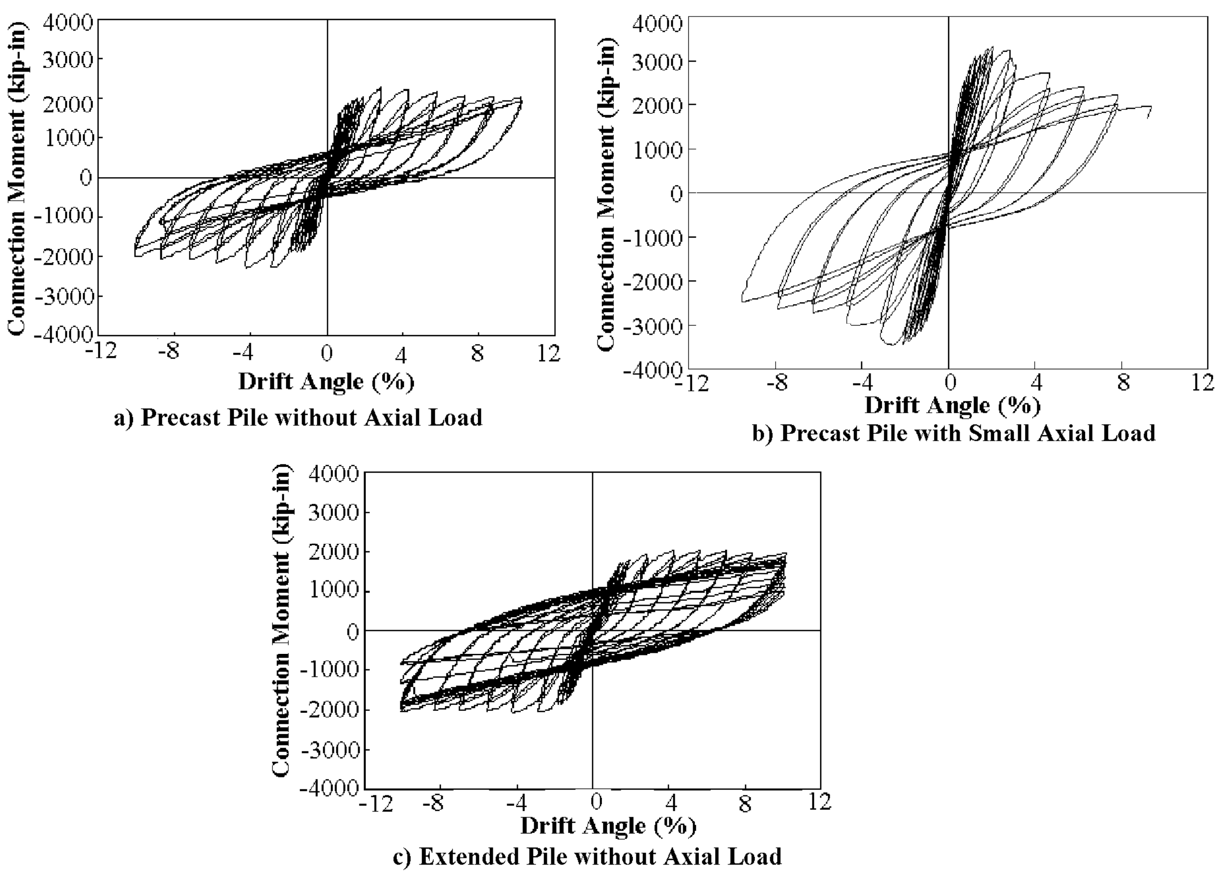
As noted earlier, steel batter piles such as shown in Fig. 1b are preferred by some engineers, and have been used in some wharf construction projects. Precast concrete batter piles have been used in the past, but they have not been used recently, because their performance was poor during past earthquakes. Today, batter piles used in seismic design of port facilities are steel H-sections, steel tubes, or concrete filled steel tubes. Batter pile usage is limited because of recommendations developed for Naval port facilities and damage noted during past earthquakes, but this limitation is not totally rational, because the past earthquake damage for piles on wharf structures was entirely concentrated in precast concrete batter piles. As a result, some steel batter piles are used today in US west coast port construction in combination with vertical precast concrete piles for support of gravity loads. Connection details for these steel batter piles are inherently different and are not the focus of this paper.

Prior to starting this study, only limited research into the seismic performance of pile-wharf connections was completed. Pizzano (1984) examined the extended prestress strand connection illustrated in Fig. 2c, and very mixed performance was achieved. Sritharan and Priestley (1998) tested one connection with the T-headed dowel bars. This specimen provided very good performance, but this test excluded axial load on the pile, and it considered an extended pile detail. Xiao and others (1999) evaluated steel H-pile connections, and Pam and Park (1990) evaluated prestressed concrete pile connection details that are typical of those used in New Zealand.

Prior Research on Prestressed Pile Dowel Connections

A comprehensive research study on moment-resisting precast concrete pile-wharf connections was completed [Roeder et al. (2001, 2005)]. An experimental program was designed to evaluate the seismic performance of piles and pile connections used in recent wharf construction. Eight 69% scale specimens of prototype structures from the ports of Los Angeles and Oakland were fabricated by methods similar to those used in field construction. The specimens were then tested under cyclic lateral load with and without axial load. The tests included dowel connections with reinforced concrete pile extensions as required when the pile is driven to below the bottom surface of the wharf deck and precast concrete pile connections as used for other applications. A wide range of reinforcement details and connection configurations including those illustrated in Figs. 2a, 2b, and 2c were evaluated.

The experimental results were evaluated and analyzed,. Generally all connection types tolerated large inelastic deformations while maintaining the basic integrity and compressive load capacity of the connection as illustrated in Fig. 3. However, extended pile connections distribute their inelastic deformation along the length of the pile, and flexural yielding for the extension initiates at modest inelastic deformations as shown in Fig. 4b Extended pile connection have full hysteresis curves with little deterioration of resistance as shown in Fig. 3c. Precast pile connections are inherently stronger than the extended pile connections, but they concentrate their inelastic deformation within the wharf deck. They have little initial yielding in the pile as shown in Fig. 4a, and they display pinched hysteretic behavior as shown in Figs. 3a and 3b. Deterioration in resistance is increased significantly with small compressive loads (10% of compressive capacity of the pile) as shown in Fig 3b. Figure 3 shows significant deterioration in resistance of precast pile connections. The deterioration shown in Fig. 3a is caused by damage to the pile and its connection. P-Δ moments significantly increase this deterioration in resistance through increased spalling of the pile and the deck and through the increased moment consumed by the P-Δ effects. The initial damage to the prestressed pile connection is local damage within the deck structure, because the pile is inherently stronger than the connection. However, later damage is concentrated on end of the pile due to spalling and damage to the concrete with little flexural yielding of the pile, because of the edge loading of the pile end at larger deformations as shown in Fig. 4c. Extended pile connections have flexural yielding that is typical of reinforced concrete members as shown in Fig. 4d and is quite extensive over the pile depth. Added confinement of the reinforcement dowels in the deck section influenced cracking patterns and of inelastic deformation but did not have a significant impact on the overall performance or ductility of the connection. The experimental results were correlated and compared to the predicted performance of prototype structures through elastic and inelastic analyses. Computer analyses were performed with the Raumoko computer program with models that were calibrated to the experimental results. The ultimate lateral load capacity of one prototype Port of Los Angeles wharf was approximately 34% of the dead weight of the structure if no deterioration in connection resistance is noted, but the computed maximum resistance was reduced to 24% of the dead weight of the structure if deterioration of resistance as noted in Fig. 3 was considered. Deterioration in resistance also significantly increased the inelastic response with some earthquake acceleration records. The shortest piles contribute most of the lateral stiffness and resistance of marginal wharves. Because of the very short pile lengths, the ductility demands on the pile connections are often very large even though the wharf deck movements are modest. Decreased pile length and increased pile diameter decrease the expected connection ductility.

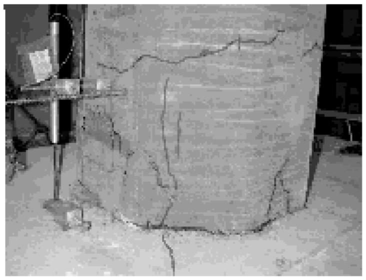


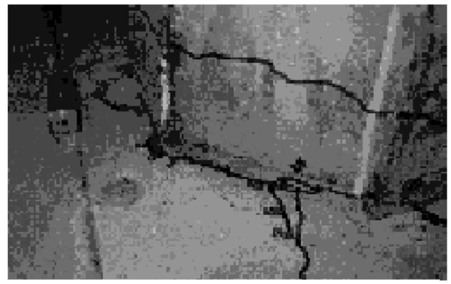
a) Precast Pile without Axial Load

b) Precast Pile with Small Axial Load

c) Extended Pile without Axial Load

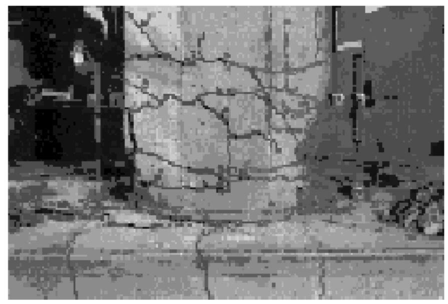
Figure 3. Typical Lateral Force-Deflection Curves from Test Program





a) Precast Pile @ 0.0175 Rotation Angle

b) Extended Pile @ 0.0175 Rotation Angle



c) Precast Pile @ 0.045 Rotation Angle

d) Extended Pile @ 0.045 Rotation Angle

Figure 4. Photo of Pile Connection Damage

Improved Seismic Performance of Pile-Wharf Connections

The prior tests shown that precast, prestressed pile to wharf connections are relatively strong with good inelastic deformation capacity, but they sustain significant damage due to pile spalling at moderate deformations with significant deterioration in resistance at intermediate deformation levels. A more recent research study has experimentally examined the performance of full scale precast pile to wharf connections with the goal of improving the performance and serviceability of the connection without adversely affecting the stiffness, resistance, and deformation capacity of the connection. Four tests were completed (Jellin 2008). The connections all employed T-headed dowel bars as depicted in Fig. 2d without additional spiral reinforcement around the dowels. The specimens were built simulating field construction practice. The four specimens were designed to achieve a sequence of improved system performance as schematically illustrated in Fig 5. Specimen 1 employed T-Headed dowel bars as normal in current practice. Specimen 2 employed a 375 mm length of unbonded dowel bars. Half this length was in the pile ducts and the other half in the wharf deck. The unbonded length permits yielding of the steel without corresponding cracking and debonding of the concrete, and this was expected to improve the performance of the specimen. Specimen 3 retained the T-Headed dowels and the 375 mm unbonded length, but a 19mm thick cotton duck bearing pad was placed over the head of the pile. Prior tests also showed that the pile rotates relative to the wharf deck, and this rotation causes significant edge loading on the pile. It was postulated that this edge loading causes early spalling of the pile and deterioration of resistance in the connection. The cotton duck pad provides a softer, more flexible interface for the edge loading, and this may reduce spalling of the pile and deterioration of the connection. Finally, Specimen 4 retained the T-Headed dowels, the 375 mm unbonded length and the cotton duck bearing pad, but it added a flexible filler material around the embedded perimeter of the pile. This was done, because past tests also showed significant spalling of the wharf deck surrounding the connection. This spalling was postulated as caused by the wrenching action of the embedded pile as the pile connection rotates. The flexible material was expected to reduce the wrenching action and reduce spalling of the wharf deck, and the reduced spalling was expected to improve the durability and seismic performance of the connection.

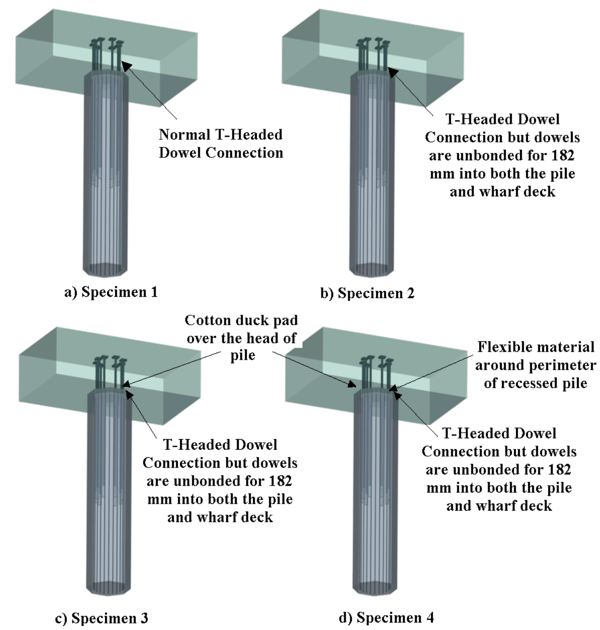
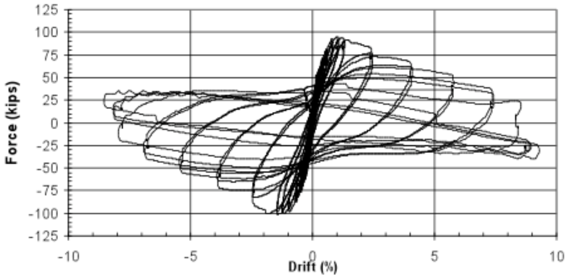
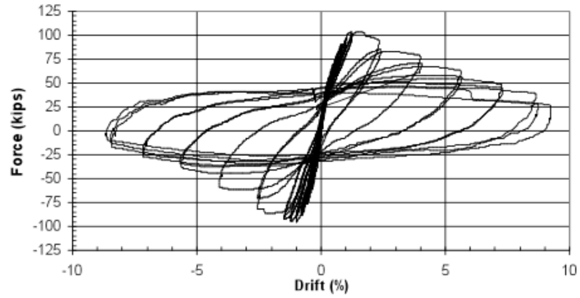


Figure 5. Schematic of Test Specimens

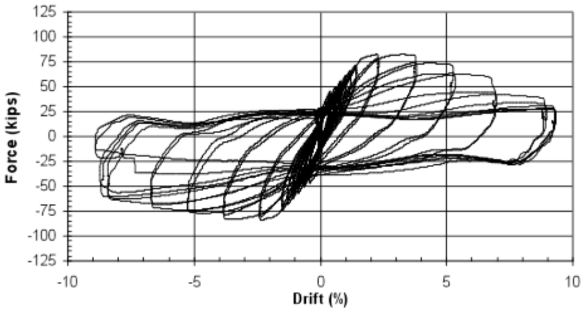
Figures 6, 7 and 8 briefly summarize the results of the four tests. Figure 6 shows the force deflection behavior of the four specimens. Figure 8 and 9 provide photos of the piles and connections at 2.5% and 5.5% connection rotation, respectively. Comparison of these figures and relative performance of various specimens illustrates a number of important observations. Comparison of Specimen 2 to Specimen 1 shows that the addition of unbonded dowel segments has little impact on the total resistance and deformation capacity as seen in Figs. 6a and b, but it decreases the deterioration of resistance slightly. Figs 7a and b and 8a and b show relatively little effect on the pile and connection damage. The addition of the cotton duck pad over the head of the pile, significantly reduces the damage to the pile at relatively large deformation levels as shown in Figs. 7 and 8. However, it delays but still sustains significant spalling on the underside of the wharf deck. Figure 6c shows that it results on limited reduction in resistance but significant decreases in deterioration of resistance at large deformations. Specimen 4 includes the unbonded bars, the cotton duck bearing pad over the head of the pile, and a flexible material around the perimeter of the pile. Figures 7 and 8 shows that this option significantly reduces spalling damage to both the pile and the wharf deck. This reduced damage is important, because wharves are constructed in hostile environment, and spalled concrete results in significant repair costs after small or moderate earthquakes to avoid corrosion and further deterioration of the connection. Further, Fig. 6d shows that the reduced spalling also results in significantly less deterioration of resistance at large connection rotations.



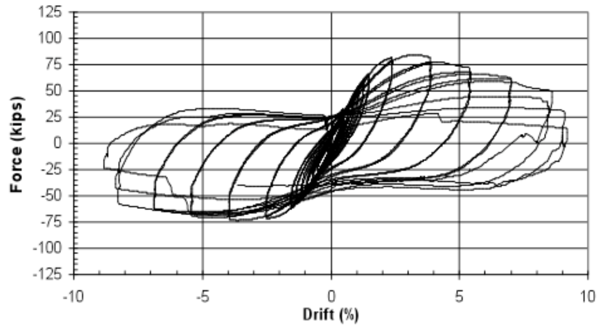
a) Specimen 1



b) Specimen 2

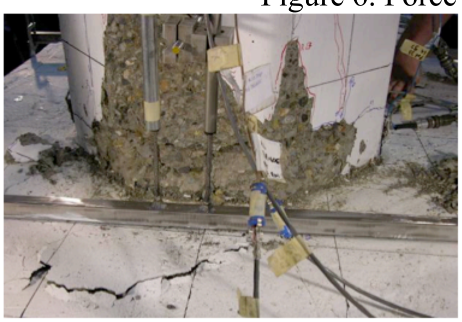


c) Specimen 3



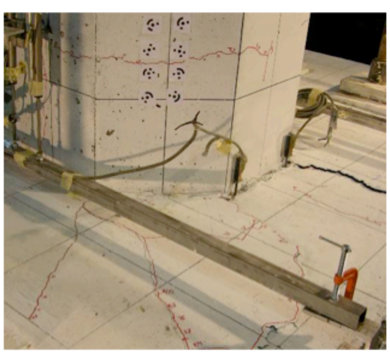
d) Specimen 4

Figure 6. Force-Deflection Behavior

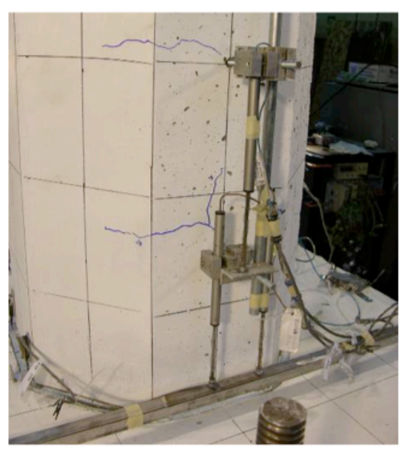


a) Specimen 1

b) Specimen 2

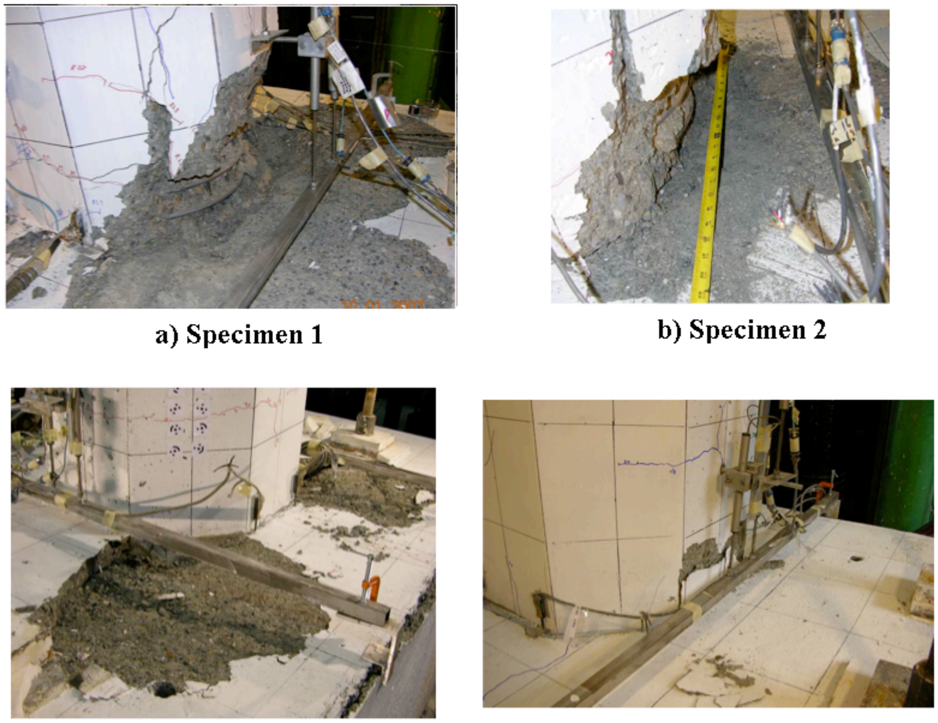


c) Specimen 3



d) Specimen 4

Figure 7. Photos of Piles and Connections at 2.5% Connection Rotation



a) Specimen 1 b) Specimen 2

c) Specimen 3 d) Specimen 4

Figure 8. Photos of Piles and Connections at 5.5% Connection Rotation

Specimen 4 is viewed as a controlled rotation (CR) connection that will result in greater serviceability of port facilities and an asset for performance based design goals. Further research on this concept is needed to define appropriate stiffen limits for the cotton duck bearing pad and the flexible perimeter material. However, the CR connection concept offers considerable potential for improved seismic performance of precast pile to wharf connections and port facilities.

Conclusions

This paper has briefly described recent research on the seismic performance of pile to wharf connections. Precast concrete piles with moment resisting connections are commonly employed. Current applications of these connections provide significant resistance and rotational capacity, but they result in significant damage to the pile and the wharf deck, and this damage results in significant deterioration of resistance starting at modest deflection levels. It is shown that this damage is less prevalent in extended pile connections, because extended piles behave as reinforced concrete columns and distribute yielding over a significant column length. Prestressed concrete piles sustain significant spalling damage at relatively modest seismic deformations, and this damage increases with axial load on the pile. A series of tests were completed to develop improved pile connection performance. The proposed CR connection has:

- a cotton duck bearing pad over the head of the pile,
- a flexible filler material around the perimeter of the embedded pile segment, and

- a short unbonded length of the dowel bars.

These combined effects lead to significant reductions in pile and wharf damage, and improved serviceability and seismic performance.

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