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SEISMIC PERFORMANCE OF WHARF AND PORT FACILITIES

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SUMMARY

Ports are large social and economic investments, and they are susceptible to earthquake damage and to economic loss when shipping is interrupted. Ports employ pile supported piers and wharves, which consist of a soil or rock embankment, a concrete deck structure, and piles that resist gravity and lateral loads. These structures have large mass, and the pile and pile-wharf connection must sustain large inelastic deformations during major earthquakes. Most US port structures use vertical precast concrete piles with moment-resisting connections, which are developed through dowels that are grouted into corrugated metal ducts in the pile ends and embedded into the concrete deck. Limited past research has been performed on these connections, so eight relatively large scale experiments were completed to evaluate the seismic performance of these connections. The test specimens simulate the wide range of connection designs presently noted in practice. These connections tolerate large cyclic, inelastic deformations but they also show significant deterioration in resistance and stiffness. Precast concrete pile connections are stronger than reinforced concrete pile connections, but they degrade more quickly. Axial load on the pile increases connection moment capacity but results in greater and more rapid deterioration in resistance. Deterioration in resistance significantly reduces the inelastic pushover resistance and increases the inelastic dynamic response demands on the system.

INTRODUCTION

Ports are a large economic investment for society, and they are susceptible to earthquake damage. Direct damage to the Port of Kobe during the 1995 Hyogoken-Nanbu earthquake exceeded U.S.$11 billion (EQE [1]). However, the total financial loss greatly exceeded this amount through lost economic activity, because the Port of Kobe recovered less than 80% of its 1994 shipping volume by the year 2000, while surrounding ports in Japan and Asia increased their volumes by 40% to 100%.

Ports employ pile supported wharves or structures, which consist of a soil or rock embankment, a concrete deck structure, and piles that carry the deck and resist lateral loads as shown in Fig. 1. The wharf deck

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may be cast-in-place concrete or a combination of precast and cast-in-place concrete. The pile and the pile-wharf connection sustain large inelastic deformations during major earthquakes. The seismic performance of these connections influences the system performance, but few studies have investigated this behavior. As a consequence, there is considerable variation in the engineering design practice for these connections.

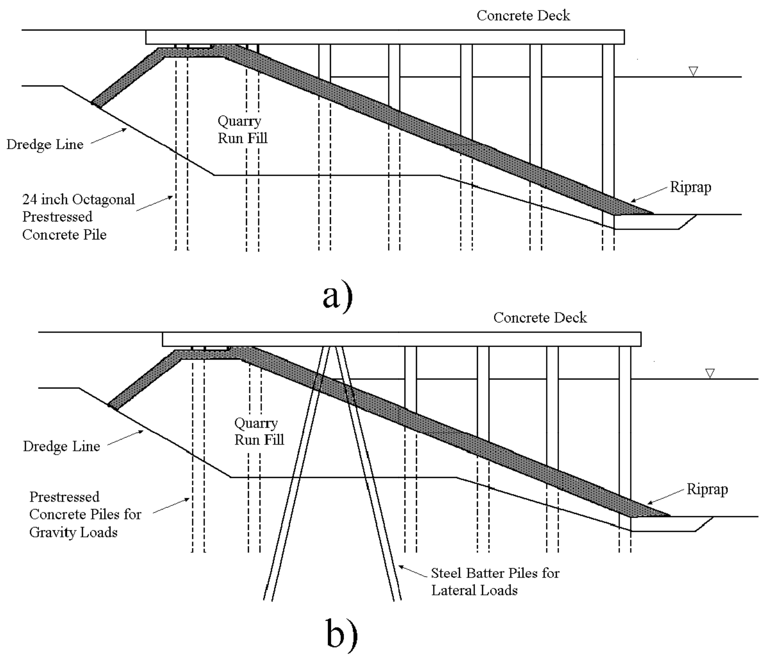

Figure 1. Typical Pile Supported Wharves; a) Precast Concrete Piles with Moment Resisting Connections, b) Steel Batter Piles

Most wharves constructed on the US west coast employ vertical precast concrete piles with moment-resisting connections as depicted in Fig. 1a, and Fig. 2 partially illustrates the variation in pile-wharf connection design. The pile normally extends 50 to 75 mm into the deck girder, and dowels are grouted into corrugated metal ducts in the pile ends and embedded into the deck concrete to develop the moment resisting connection. Figure 2a shows the most common detail, which is identified here as the outward bent dowel connection. Variations in the connection design occur through the number and size of dowel bars, the prestressing tendons in the pile, the length of embedment and anchorage for the dowels, the pile length, and the spiral reinforcement in the pile and possibly within the wharf deck. Outward bent dowel bars interfere with the deck reinforcement and placement of concrete. As a result, T-headed dowel bar connections (shown in Fig. 2c) may be used to reduce this interference and construction cost. The piles are driven to a depth which provides the necessary compressive load capacity, and this depth seldom coincides with the finished elevation of the pile top. Piles extending above the finished elevation are cut to the proper elevation, and the connection is formed by the dowel connections described here. However, many piles are driven to an elevation lower than the bottom of the deck, and extended reinforced concrete connections as illustrated in Fig. 2b are required. Extended pile connections are effectively reinforced column connections. Dowels are grouted into the pile end, and the dowels reinforce the pile extension and complete the pile connection as shown in the figure.

Other variations of these connections have been used but are not illustrated in Fig. 2. Inward bent dowel connections have dowels bent in the opposite direction to the outward bent dowel connection. This is sometimes done to better confine the concrete in the wharf deck connection. Bond bar connections are sometimes used to provide benefits similar to those achieved with the T-headed bar connection. The bond bars effectively increase the development length of the dowels without the interference in reinforcement and concrete placement caused by the bent bar details. Extended prestressing strands have also been used for the moment transfer, but they have not been used for seismic design recently, because of fears that the prestressing strand is damaged during pile placement and construction.

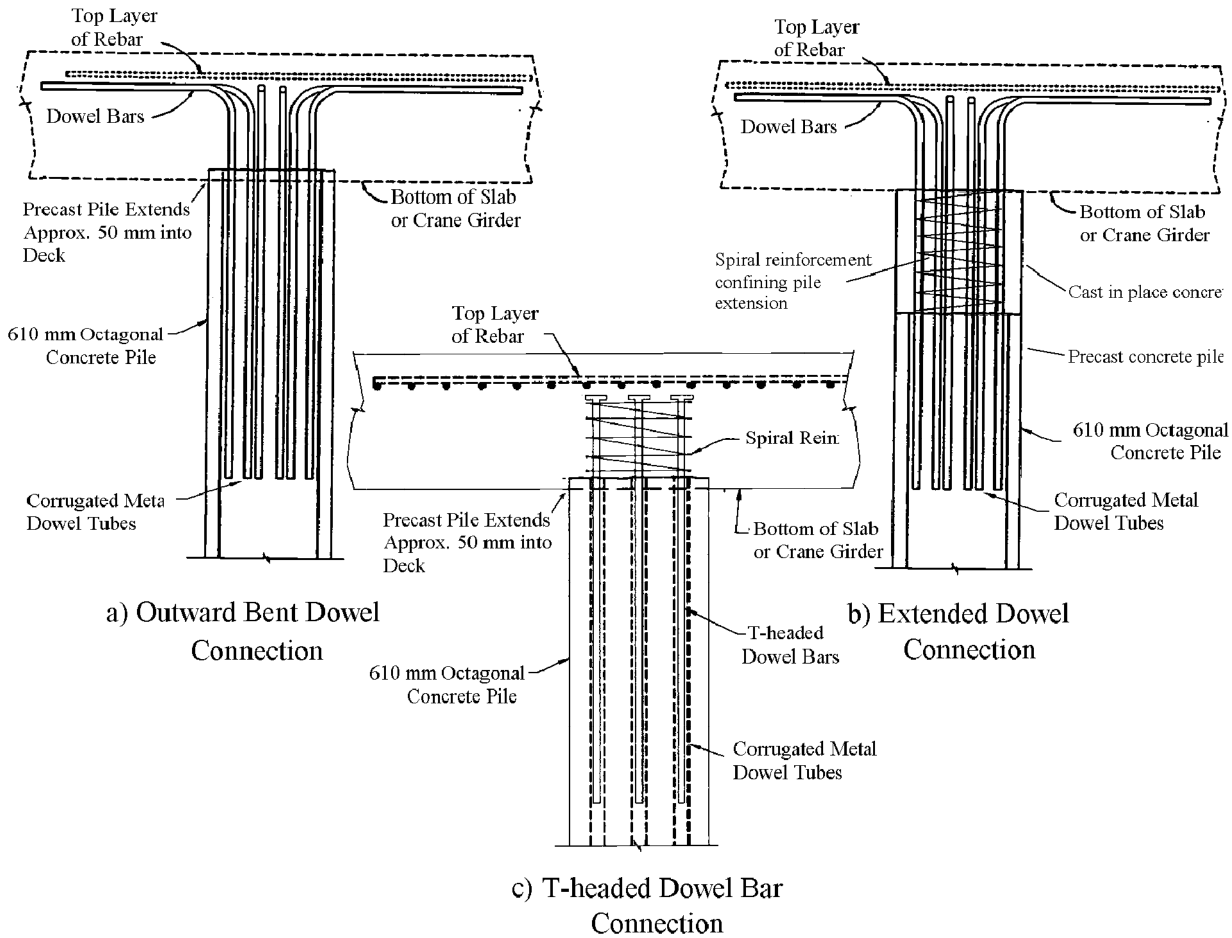

Figure 2. Typical US Pile-Wharf Connection Details, a) Outward Bent Dowel Connection, b) Extended Dowel Connection, and c) T-Headed Bar Connection

Steel H-piles, hollow tubes, and concrete filled tubular piles have sometimes been used as batter piles to provide lateral resistance as depicted in Fig. 1b. Vertical precast concrete piles still support most of the gravity load with these steel batter pile systems. Batter piles are preferred by some engineers, because they resist lateral loads easily and economically. However, steel batter piles are clearly in the minority for seismic design, and they are prohibited for some applications (Ferritto [2]), because concrete batter piles that were used in some older wharves performed poorly during past earthquakes (EERI [3]).

Limited past research has been performed on precast pile connections Pizzano [4] performed monotonic load tests on extended prestress strand connections, and the performance of these connections was quite variable. These connections are not commonly used today for seismic design of wharves, because the prestressing strands are sometimes nicked or cut while the concrete is crushed or the pile is driven. These nicks result in reduced ductility under seismic loading. Joen and Park [5] investigated the strength and ductility of pile connections with New Zealand details. These connections were vaguely similar to the outward bent dowel bar and the extended prestress strand connections, but they employed a significantly greater pile embedment into the wharf deck than used in US practice. These experiments developed the flexural strength of the pile and reasonable ductility, but they showed substantial deterioration in stiffness and resistance at large inelastic deformations. Sritharan and Priestley [6] tested one bond bar connection under inelastic cyclic deformation. The pile in this test was a reinforced concrete column rather than a precast pile as commonly used in design. This extended pile connection test did not include axial load, but the ductility from this test was very good with little deterioration in resistance.

EXPERIMENTAL INVESTIGATION

Eight precast concrete pile-wharf connections were tested (Graff [7], Soderstrom [8], Roeder et al. [9]) to evaluate their resistance, stiffness, and inelastic seismic performance. The test specimens simulated prototype connections from wharves at the Ports of Los Angeles and Oakland. The prototype structures had solid, spirally reinforced 610 mm octagonal prestressed concrete piles with corrugated ducts for dowels set in a 305 or 330 mm diameter circle. The test specimens were approximately 69% scale of the prototype connections. The 420 mm diameter octagonal piles were built at the ends of forming beds used for a large construction project in progress at that time. Eleven 12.5 mm diameter grade 270 prestressing strands with an applied prestress of 1400 MPa (75% gross ultimate tensile strength) were used. The piles had a 30.9 MPa concrete strength at release of the prestressing strands and a 68.1 MPa 21-day strength. Construction methods used for the test specimens simulated prototype construction. The deck concrete was a pea gravel mix which was designed to achieve a 41.4 MPa 28-day strength and to facilitate placement between the closely spaced bars.

Specimens 1,2,3,4, and 8 employed the outward bent dowel connection. Specimens 3, 4, and 8 had precast prestressed concrete piles, while Specimens 1 and 2 used reinforced concrete piles typical of the extended pile dowel connections. Specimen 5 employed the inward bent dowel connection, while Specimens 6 and 7 used the T-headed bar and bond bar connections, respectively. Lateral loads were applied with a $\pm$ 250 mm stroke MTS actuator with a load capacity of 370 and 245 kN in compression and tension, respectively. Lateral loading was applied as a displacement controlled cyclic load history that was based upon the ATC-24 protocol [10] with minor modifications for individual tests. Calculated deflections corresponding to first cracking, first yield, and plastic hinge formation were estimated and were used as benchmarks. Roller bearings permitted in-plane specimen deformation but restrained out-of-plane movement of the pile tip. Specimens 1, 2, and 3 were tested without axial load to provide a baseline for comparison of other tests, but Specimens 4-8 had axial load applied through a hydraulic jack, steel beam and travelling tie rod assembly. This axial load was approximately 10% of the maximum pile compressive load capacity and roughly equivalent to the dead weight of the prototype structure.

Strain gauges were attached to dowels in each connection to determine the transfer of force and moment from the pile to the deck assembly. Potentiomenters were used to measure deflections deformations, and rotations of the connections and the test specimens. Concrete cracks in the piles and deck sections were visually monitored and recorded throughout the test program.

EXPERIMENTAL RESULTS

The eight tests were completed, and the data was analyzed. Figure 3 shows typical corrected lateral load-deflection curves for Specimens 1, 3 and 4. Figure 3a shows a typical result for a prestressed pile outward bent dowel connection with axial load (Specimen 4). There is great deterioration of resistance for this test, since nearly all the lateral resistance is lost by the time a 9% drift deformation was achieved. This 9% drift appears to be quite large. However, most of the structural lateral resistance is provided by short piles, which require large drift angle for modest structural displacements. The secondary (P-Δ) moments and specimen damage at large deformations are the two primary reasons for this deterioration in resistance. Figure 3b shows a comparable curve for an identical prestressed pile connection (Specimen 3) without axial load. In this case, the resistance lost is due only to the specimen damage since no axial load was applied. Figure 3c shows the lateral load-deflection behavior for an extended pile outward bent dowel connection (Specimen 1). This specimen also has no axial load and no lost resistance due to P-Δ effects. Comparison of Figs. 3a, b and c shows that the prestressed pile connections and the presence of pile axial load contribute large deterioration in resistance over that noted with the extended reinforced concrete pile connection with no axial load.

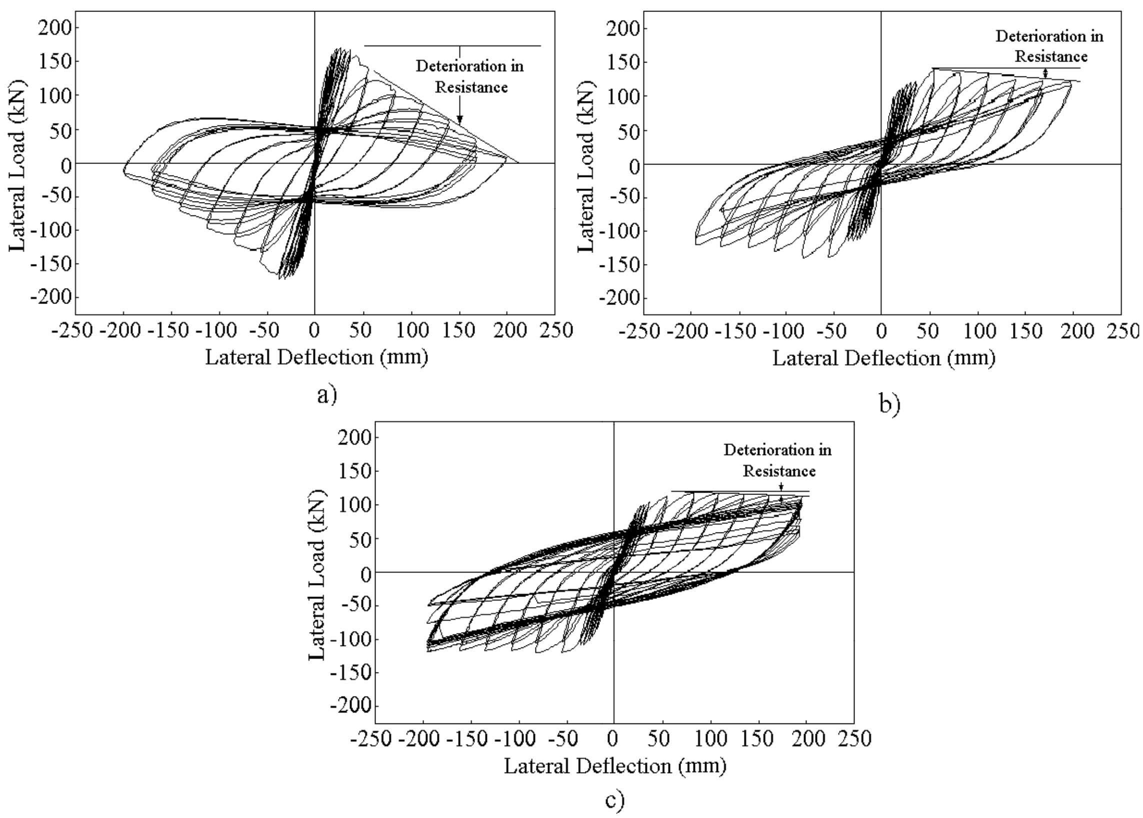

Figure 3. Corrected Pile Lateral Load vs Deflection; a) Specimen 4 - Prestressed Outward Bent Dowel Connection With Axial Load, b) Specimen 3 - Prestressed Outward Bent Dowel Connection Without Axial Load, c) Specimen 1 - Extended Pile Connection Without Axial Load

Figure 4 shows the moment-drift angle curves for the same test specimens. The full connection moment is included in these plots including the moment induced by P-Δ effects. As a result, the deterioration in resistance for these figures is entirely due to concrete spalling, cracking, debond of reinforcement, and specimen damage caused by the inelastic deformation and applied axial load. Figures 3c and 4c show the deterioration in resistance is quite small for the extended pile connection without axial load even at a 9% drift angle. Specimen 3 was a prestressed concrete pile connection without axial load (see Figs. 3b and 4b), and it showed significantly more reduction in resistance and specimen damage than the extended pile connection. Figure 4c shows that its moment resistance was reduced by approximately 8% at the 9% drift angle. Specimen 4 was an identical connection with axial load (see Fig. 4a). The axial load significantly increased deterioration and specimen damage and caused approximately 30% reduction in resistance at the 9% drift angle. Effective lateral resistance is reduced by an even greater amount at large deflections, because of P-Δ effects as seen in Fig. 3a. Comparison of Figs 3a and 4a show the magnitude of the P-Δ effect in reducing the effective lateral resistance.

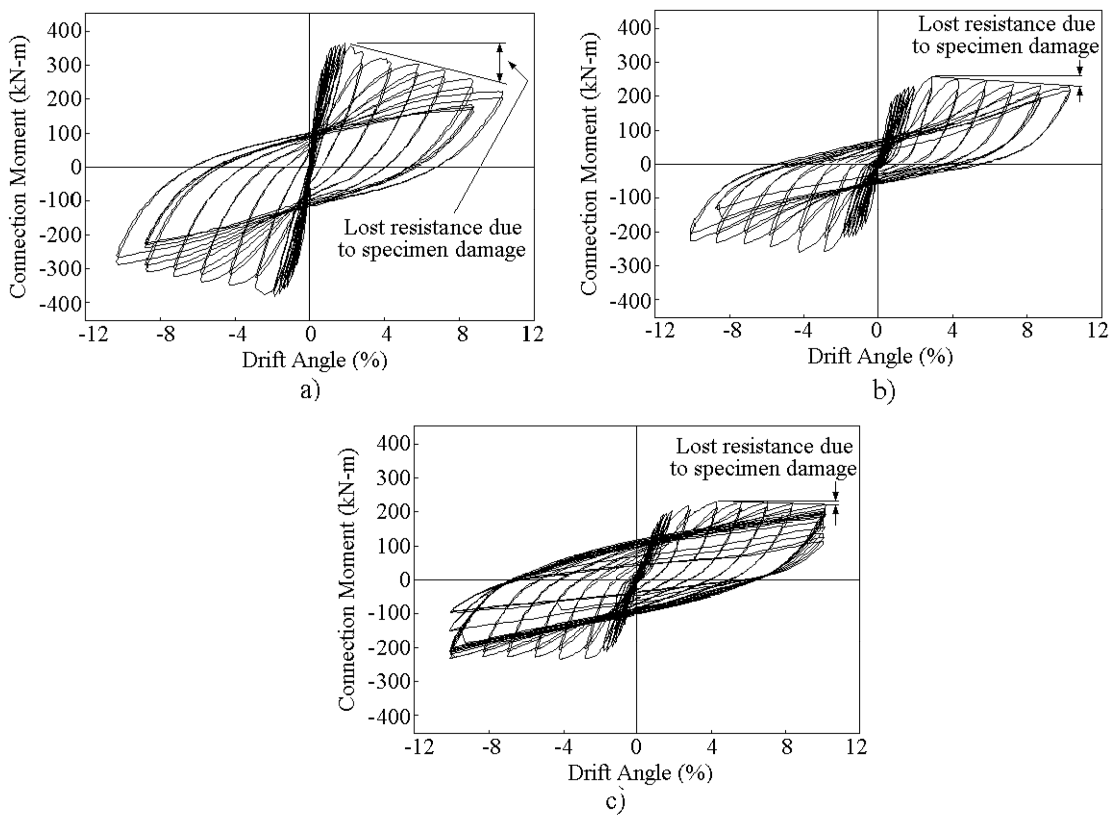

Figure 4. Moment vs Drift Angle Behavior; a) Specimen 4 - Prestressed Outward Bent Dowel Connection With Axial Load, b) Specimen 3 - Prestressed Outward Bent Dowel Connection Without Axial Load, c) Specimen 1 - Extended Pile Connection Without Axial Load

The experimental results (and comparison of the maximum resistances seen in Figs. 3b and 3c) show that prestressed pile connections are significantly stronger than extended reinforced concrete pile connections. This extra strength occurs, because the prestressed pile is reinforced by both the dowel bars and prestressing strands. The prestressing strands are not fully developed, but they provide some reinforcement. As a result, nearly all yield deformation in the precast pile connections occurs in the dowel bars within the deck section. This results in internal damage which is difficult to repair or detect after an earthquake. The pinching and concentrated damage occurs because the dowels yield in tension and accept only very small compressive forces after tensile yield elongation. This action causes the piles to rock on the deck interface. This rocking results in splitting and spalling of the edge of the pile. The addition of axial load to the pile further increased the moment resistance of the precast pile connections. Specimen 4 had 40% more moment resistance than identical Specimen 3, which was tested without axial load. The ACI [11] design procedure predicts increased moment resistance with increased axial compression, because compressive load acts within the compressive stress block and adds to the moment about the neutral axis. Although, axial load increased the maximum moment resistance of the connection, it also increased the edge bearing force and the resulting deterioration in resistance and concrete spalling noted for the precast pile connections.

The inward bent dowel, T-headed bar, and bond bar connections (Specimens 5, 2, and 7) attained similar deformations to those observed with the outward bent dowel connection, and the force-deflection and moment-rotation curves for these other connections were similar to Figs 3a and 4a, respectively. Connection damage due to large inelastic deformation and the degradation of resistance are also similar for these alternate connections. The results of this work shows that all connections:

- are strongly influenced by axial load,
- are expected to have different performance for extended pile connections than for the precast prestressed pile variations,
- exhibit significant deterioration in resistance at large deformations, and
- have similar pinched hysteresis characteristics for the lateral load-deflection and moment-drift angle behavior with the precast prestressed pile connection.

Connection stiffness has a significant impact upon wharf seismic performance and was monitored during this research. The precast pile connections were all stiffer than the extended pile connections, and connections with axial load were generally stiffer than connections without axial compression. The initial stiffness approached the uncracked stiffness of the pile, since the measurements were taken at small deformations where cracking was limited to the local area around the pile-deck interface. The addition of axial load reduced the amount of cracking noted at these small deformation levels. All specimens had significant deterioration in stiffness with increasing deformation levels, since they typically lost approximately 30% to 40% of their initial stiffness at drift angles smaller than 1%, and the specimens lost 70% to 80% of their initial stiffness at drift angles in the order of 10%.

PRACTICAL CONSEQUENCES OF RESEARCH RESULTS

The experiments show that the prestressed concrete pile connections develop large moment resistance and tolerate large inelastic deformations, but they sustain significant deterioration in resistance. The effective lateral resistance consumed by the P-Δ effects exacerbates this deterioration. This experimental information was used to analyze a prototype structure and determine the effect of this behavior on the behavior of prototype systems. A nonlinear model of a typical precast concrete pile wharf structure was developed using the two-dimensional non-linear analysis program, RUAUMOKO, which was developed by Carr [12]. This model included the full inelastic behavior of the pile and pile connection including the deterioration in resistance. The computer model was carefully calibrated to the experimental test results so that it included the proper stiffness, resistance and deterioration noted in experiments and provided a realistic model of prototype frame performance.

The prototype wharf for these analytical comparisons was Port of Los Angeles berths 308-309 and is illustrated in Fig. 5a. This structure typifies a number of other structures built on the west coast of the US in recent years. The prototype structure is a long wharf section with transverse pile frames spaced at 6.1m on center, and the deck width is 37.9 m. The deck thickness was 0.61 m thick through most sections but 0.9 m thick for sections adjacent to short piles that contribute most lateral resistance. Thicker deck sections were also used along two additional pile lines that provided crane rail support. Seven prestressed concrete piles were included in each pile frame, and additional piles between frames were provided on pile lines framing into the thicker wharf deck as illustrated in Fig. 5a. A plane frame computer model simulated the transverse response of this wharf. The modified bilinear Takeda hysteresis rule was used to model the inelastic behavior of the piles and pile-wharf connections. The connection of the vertical piles to the concrete wharf deck was modeled as fully restrained, but rigid end segments were employed between the centerline and the bottom surface of the deck. P-Δ effects were included in the analysis through geometric stiffness, but the gravity load on the wharf was limited to the self weight of the wharf.

The elastic pile properties were based upon the uncracked section, but a slight reduction was made in recognition of the local cracking that was expected near the pile-wharf connection and at the plastic hinge location under the soil. A bi-linear strain hardening ratio of 0.01 was used in the analysis, and some but not all analysis included the deterioration in resistance noted in the experimental study. The ultimate resistance of the piles and pile wharf connections were computed by normal ACI methods, since the experimental research showed ACI predictions were 11% to 15% smaller than the maximum resistance obtained in experiments. Stiffness proportional damping that was 5% of critical for the first mode of vibration was employed.

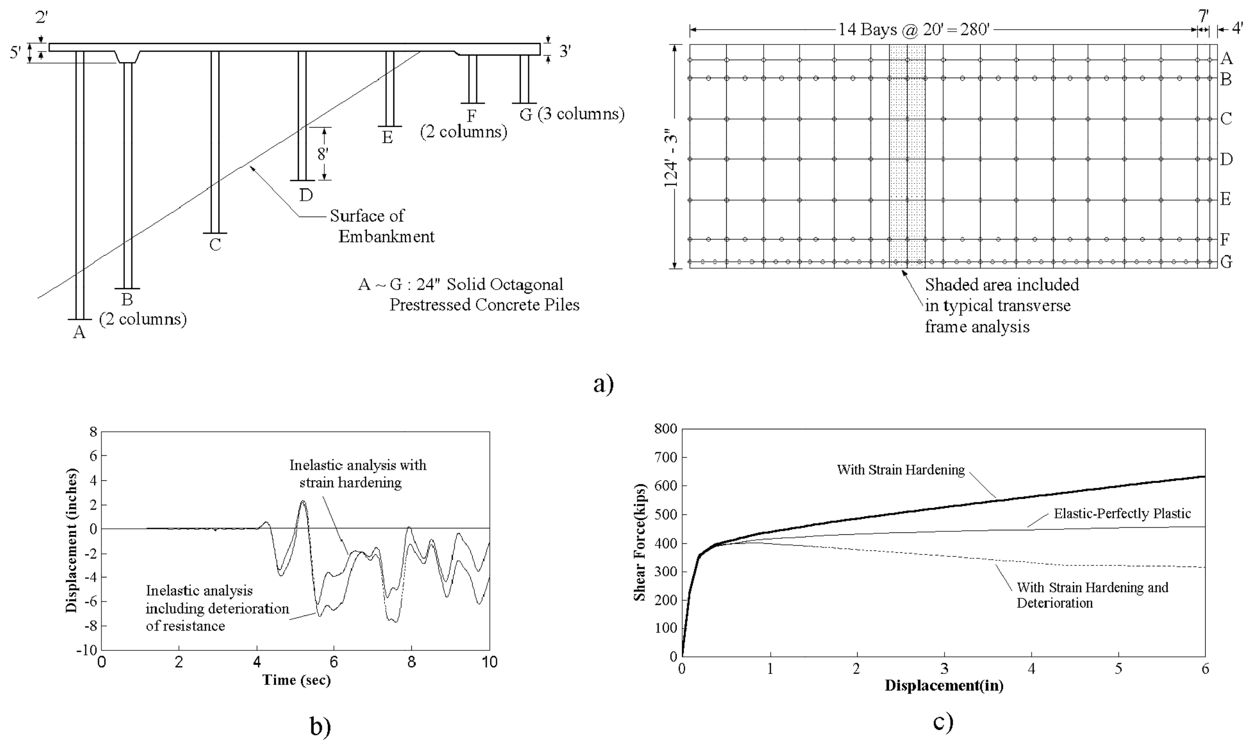

Figure 5. Typical Results of Prototype Analysis; a) Prototype Wharf, b) Inelastic Time-History, c) Inelastic Pushover Analysis

The prototype structure was stiff with a computed fundamental period of 0.22 sec. The lateral resistance of this transverse section based upon elasto-plastic analysis with nominal material properties shown in Fig. 5c was 34% of the structural weight. Inelastic time-history analyses were completed for several earthquake excitations. Figure 5b shows the computed inelastic response of the prototype wharf for the model with strain hardening and no strength deterioration and the same model including strength deterioration due to a Kobe acceleration record. This acceleration record is a near fault record measured during the 1995 Hyogoken-Nanbu earthquake, and it had a peak acceleration of approximately 0.8g. This figure shows that displacements were about 40% larger for the model with strength degradation than for the model with strain hardening only. This is a significant increase, because connection rotations are near the maximum tolerated in the connection experiments at these deformation levels. The experiments clearly demonstrated the strength deterioration included in these analyses, and they show that the deterioration increases dramatically at larger connection rotations. When scaling considerations are added to the reasoning, the performance of the prototype structure must be expected to experience a 0.12 radian connection rotation after the Kobe acceleration record. The condition of the prototype structure would clearly be unserviceable and would probably be irreparable after this event. Based upon the experimental results, it is unclear whether the piles would support the gravity loads after these large deformations.

RUAUMOKO is capable of doing pushover analyses if properly modeled. Figure 5c shows a comparison of the pushover resistance of the prototype wharf with elastic-perfectly plastic analysis, with the computer model employing strain hardening without deterioration in resistance, and with the computer model including deterioration of resistance. As noted earlier, the elastic perfectly plastic resistance of a single bay of the structure is approximately 34% of the dead weight of the structure. However, this resistance is developed only at very large deflections after the long piles develop their full plastic resistance. When strain hardening is employed, the post yield stiffness increase dramatically as shown in the figure, but the maximum resistance of the wharf section is only about 24% of the dead weight of the structures, when the connection deterioration is added to the model. The reduction in calculated resistance is very significant and may have an adverse effect on the structural response.

SUMMARY AND CONCLUSIONS

The seismic performance of moment-resisting precast concrete pile-wharf connections has been examined. Eight experiments were performed, and analyses were completed to illustrate the consequences of the experimental behavior on the prototype structural performance. Experiments evaluated outward bent dowel connections, inward bent dowel connections, T-headed dowel connections, bond bar connections, extended pile connections, and connections with and without axial load. The results of this work show that:

- Precast concrete pile connections are stronger than the extended pile connections but have greater deterioration of resistance and more severely pinched hysteretic behavior than extended pile connections.

- The axial load used in experiments was about 10% of the pile ultimate load capacity and the addition of this axial load increased the maximum resistance of the connection but produced rapid deterioration of this resistance.

- All tests specimens tolerated large inelastic deformations while maintaining the basic integrity and compressive load capacity of the connection.

- The bond bar connection and T-headed bar connections provided comparable performance to the more common outward bent dowel connection.

- Computer analysis of prototype wharf structures show that these port structures are relatively stiff and strong. The shortest piles provide the bulk of lateral strength and stiffness to the system. The maximum resistance due to pushover analysis was approximately 30% smaller than the elasto-plastic pushover analysis because of the deterioration in resistance noted with precast pile connections. Inelastic time history analyses showed that the deterioration in resistance caused significant increases in inelastic deformation demands for large earthquake acceleration records.

ACKNOWLEDGEMENTS

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