Seismic Analysis and Design of Berth 14 Extension
Balboa, Panama

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ABSTRACT

Berth 14 is located near the Pacific end of the Panama Canal and is part of a marginal wharf system built by the U.S. Army Corps of Engineers in the early 1900s. It consists of a hybrid concrete-steel superstructure supported on large and brittle concrete shafts of up to 2.4 meters (7.9 feet) in diameter.

This paper describes the challenges encountered in the construction of a finger pier extension 85 meters (279 feet) long by 50 meters (164 feet) wide to Berth 14. The extension was designed for repairable damage under a contingency level earthquake and minor damage and disruption to operations under an operating level earthquake.

A flexible structural system consisting of 700-millimeter (28-inch) octagonal precast, prestressed concrete plumb piles was chosen as the most practical and cost efficient solution to construct the extension. Careful detailing of a full force-transfer mechanism from the new structure into existing Berth 14 was required as part of the design. Potentially imposing large inertial forces on the drilled shafts of the existing berth—an initial concern—was proved to be irrelevant through analytical modeling of the connected new and existing structures.

The paper addresses the analytical tools and techniques employed to evaluate possible substructure alternatives as well as the seismic assessment of the existing Berth 14.

INTRODUCTION

Berth 14 is part of a marginal wharf system that includes three additional berths (Berths 12, 13, and 15) located near the Pacific entrance of the Panamá Canal, in Balboa, Panama. The port facility is owned and operated as a feeder vessel berth by Panama Ports Company (PPC). Currently, it supports Panamax-size ship-to-shore gantry cranes. The structure was built in the early 1900s by the U.S. Army Corps of Engineers and consists of a hybrid concrete-steel superstructure supported on a combination of large concrete shafts and gravity walls.

In 2007, BergerABAM was employed as the engineer-of-record by Intercoastal Marine Inc. under a design/build contract from PPC to design an extension of

Berth 14. The extension was 85 meters (279 feet) long by 50 meters (164 feet) wide. Requirements for this new finger pier-type structure included a two-level seismic design with the following performance objectives: (i) minor damage and minimal disruption to operations under an operating level earthquake, and (ii) repairable damage and life safety under a contingency level earthquake.

This paper describes the evaluation of alternatives and selection of an efficient structural system that minimizes project cost while keeping seismic risk of the new and existing structure at a low level.

DESCRIPTION OF EXISTING STRUCTURE

Figure 1 shows an overall surface features plan view of the existing structure and the new Berth 14 extension. Berth 14 is 225 meters (738 feet) long and 19 meters wide. Its bent spacing is 8.9 meters (29 feet) on the west side and 6.4 meters (21 feet) on the east side for about 102 meters (335 feet). Bent spacing at Berth 13 is approximately 7.7 meters (25 feet). The existing Berths 13/14 consist of hybrid concrete-steel superstructure supported on large concrete shafts of 1.8 to 2.4 meters (5.9 to 7.9 feet) in diameter reinforced with rails that do not project into the superstructure (Figure 2). The deck spans as a one-way slab in the transverse direction and it is supported by longitudinal steel joists about 1.0 meter (3.3 feet) in depth. The joists frame into transverse steel plates girders of about 2.0 meters (6.6 feet) in height that rest on the shafts. Both joists and girders are encased in reinforced concrete.

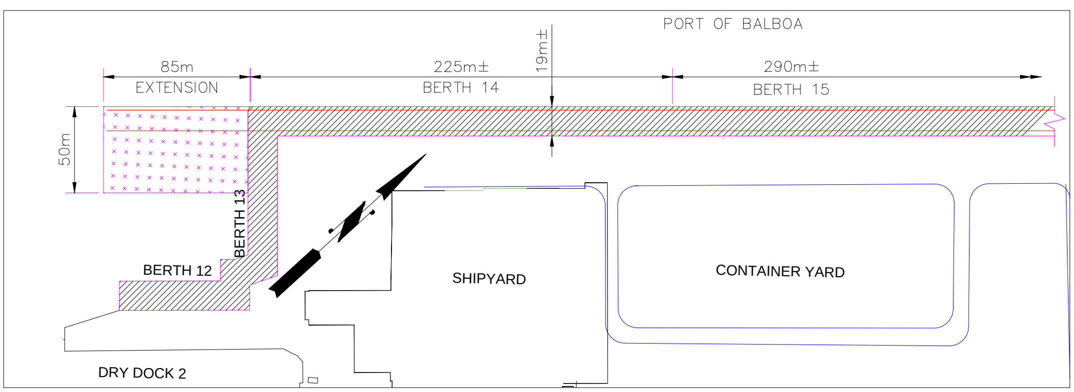

Figure 1. Overall surface features of existing structure and extension.

Following a design by BergerABAM, the original Berth 14 structure was upgraded in 2003 to support container cranes. The project involved the installation of precast, prestressed concrete crane beams along the existing pier to support the loads imposed by new gantry crane rails. The upgraded structure was made continuous through a series of cast-in-place (CIP) closures and a 430-millimeter (17-inch) surface topping with dowels bars drilled into the existing deck. A toe wall system was also installed to increase the berth depth of the wharf to -14.0 meters (-46 feet) (Figure 2).

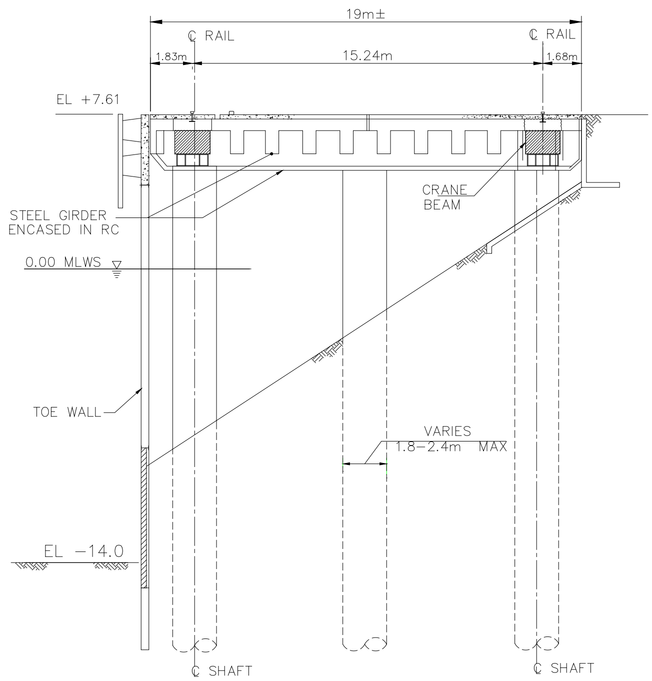

Figure 2. Berth 14 typical wharf section.

DESIGN CRITERIA FOR BERTH 14 EXTENSION

The scope of marine work included the construction of a new marginal wharf structure, 85 meters (279 feet) long by 50 meters (164 feet) wide, to the west of Berth 14 for deep water berthing of Panamax container vessels. With this extension, the total length of the Berths 14/15 wharf would be about 600 meters, which allows berthing of two Panamax vessels simultaneously.

Seismic design was performed for two ground motion levels. The first, an operating level earthquake intended to represent an event with a 50 percent probability of exceedance in 50 years. The second, a contingency level earthquake intended to represent an event with a 10 percent probability of exceedance in 50 years. Design requirements for the project accepted the occurrence of localized damage at the interface between the new and the existing structure; however, gantry crane derailment was unacceptable under the operating level earthquake.

Spectral acceleration parameters for the operating level and contingency level earthquakes are shown in Table 1. The magnitude of the operating level event was 60 percent of the contingency level event.

Table 1. Acceleration Spectra Parameters

Parameter	Operating Level Earthquake	Contingency Level Earthquake
A_a	0.09	0.15
A_v	0.09	0.15

The design acceleration spectrum listed in the project requirements was that of the Panamanian Building Code (REP 2004). Figure 3 shows the resulting contingency level design acceleration for a conservatively assumed soil type E in comparison to the spectrum obtained using Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS 2005). It is important to point out that beyond the constant acceleration region; the REP 2004 spectrum varies with the inverse of the period to the two thirds. For long periods, this is can be very conservative in relation to conventional design acceleration spectra. For a period of 3.0 seconds, for example, the base shear obtained from REP 2004 is 65 percent larger than that obtained with MOTEMS 2005.

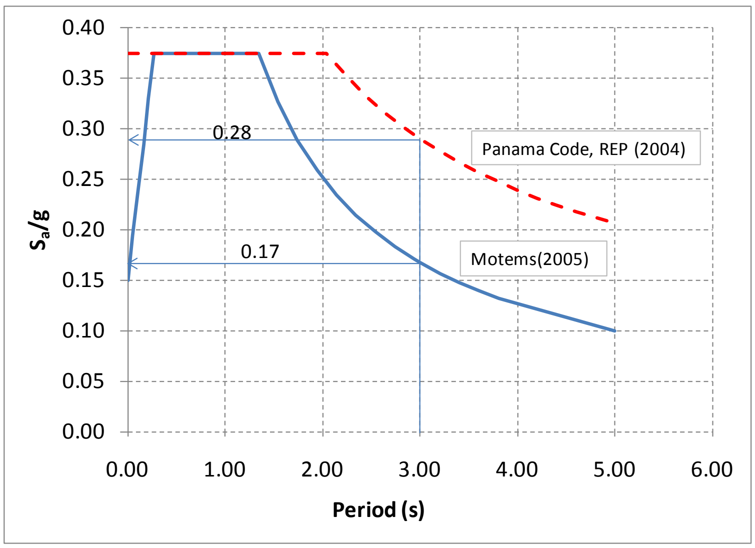

Figure 3. CLE design acceleration spectra.

BERTH 14 EXTENSION FRAMING

The proposed superstructure framing system (Figures 4 and 5) consisted of longitudinal pile caps that supported prismatic precast concrete panels spanning in the transverse direction of the structure. The panels and the pile caps were provided with sufficient transverse reinforcement projecting into a cast-in-place concrete topping to ensure composite behavior and diaphragm action of the superstructure as a whole. The width of the pile cap was directly proportional to the size of the piles/shafts used for the substructure of the extension. Figure 5 is a generic depiction of the three alternative substructure configurations that were evaluated.

Alternative 1. In this case, the substructure consisted of 700-millimeter (28-inch) octagonal plumb piles driven directly into the existing soil. This alternative constituted the base case for which the Berth 14 extension was evaluated as both a stand-alone structure and as a structure fully connected to existing Berth 14. The rationale for proposing a stand-alone extension was to prevent the transfer of inertial forces into the existing wharf during the design ground motion, given that the existing shafts were rather stiff and brittle.

Alternative 2. In this case, the substructure consisted of drilled shafts 1.5 meters (5 feet) in diameter and the extension was fully connected to the existing wharf. The choice of such large members to support the superstructure was made because the 85-meter (279-foot) extension had to match the large lateral stiffness of the existing wharf to minimize the transfer of inertial forces.

Alternative 3. In this case, the substructure consisted of 700-millimeter (28-inch) octagonal piles embedded into a rock dike and the extension was connected to the existing wharf. The intent of building a rock dike was once again to increase the lateral stiffness of the Berth 14 extension in order to better match that of the existing structure.

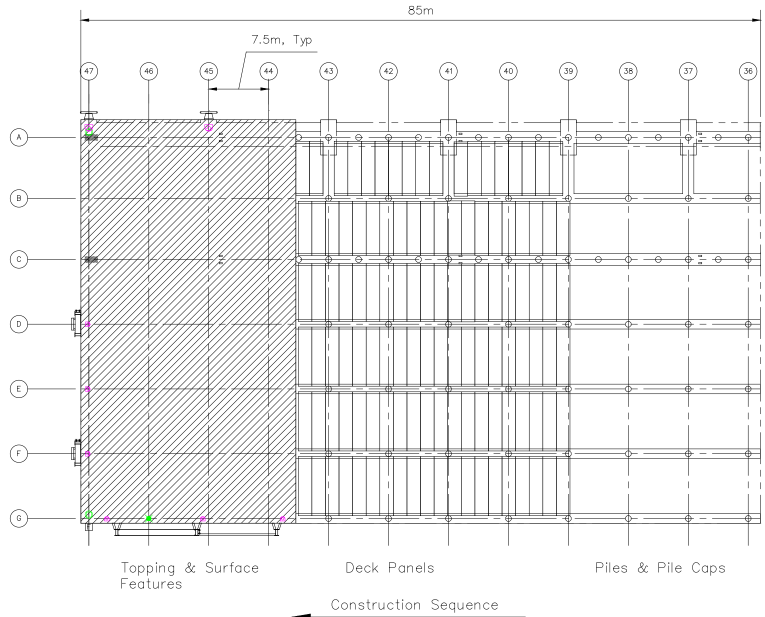

Figure 4. Berth 14 extension superstructure.

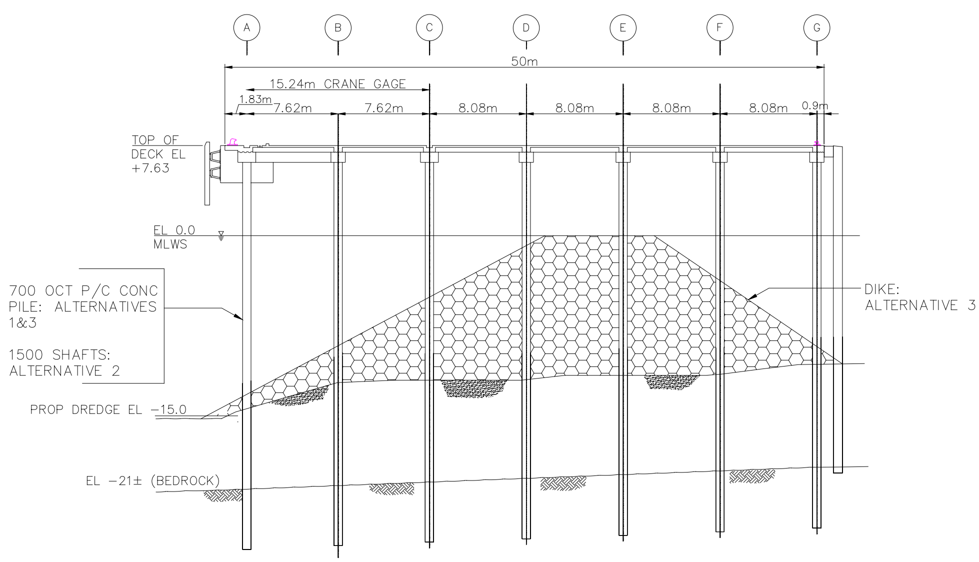

Figure 5. Berth 14 extension alternatives.

STAND-ALONE EXTENSION

The base case structure (Alternative 1), which consisted of 700-millimeter (28-inch) octagonal piles driven into the existing soil, was represented by a two-dimensional finite element model of a transverse bent. Soil properties were obtained from boring logs obtained at the site. The flexural length of every pile in the structural model was estimated based on the calculated lateral stiffness of the pile-soil system for given assumed displacements at the deck level. An iterative procedure was required to estimate the lateral stiffness that was consistent with the actual displacement demand calculated at the top of the piles for the design spectra. The computer program L-Pile®, which allows representing the soil as a series of nonlinear springs (p-y curves), was used for this purpose. Finite element modeling of the Berth 14 extension as a stand-alone was conducted using the computer program SAP2000®.

Push-over analysis of an individual bent involved calculating the moment-curvature relationships for the piles (reinforced with 24 grade 1,860 MPa strands of 12.7 millimeter [0.5 inch] diameter) and the pile-to-cap connection (consisting of eight #8 ASTM A615 bars) in order to define flexural hinges for the nonlinear structural system. Variations in the hinge properties associated to changes in the axial load were not considered in the analysis. Yielding curvature and length of plastic hinge were determined using provisions from MOTEMS 2005. The calculated lateral load-displacement response of a typical bent of the Berth 14 extension is shown in Figure 6. The base shear capacity of the base case stand-alone structure was found to be about 10 percent of its weight.

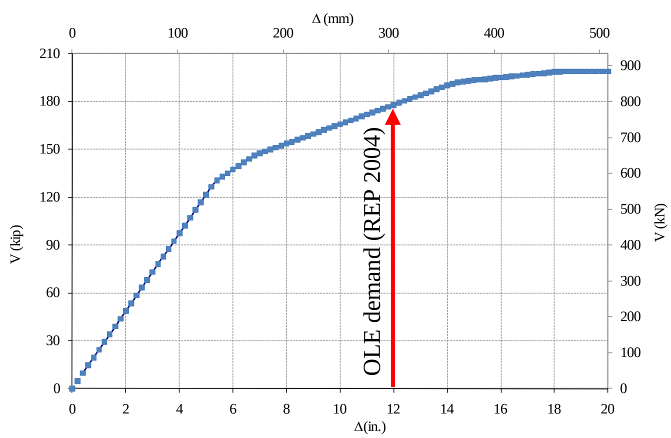

Figure 6. Lateral load displacement response for stand-alone structure.

The calculated fundamental period of the stand-alone extension was about 3.3 seconds. The linear dynamic transverse displacement demands for the operating level earthquake were estimated at 270 millimeters (11 inches) when using the spectrum from MOTEMS 2005, and 440 millimeters (17 inches) when using the spectrum from REP 2004. The nonlinear static procedure described in ATC-40 (1996) in combination with Figure 6 was also used to estimate the nonlinear displacements of the stand-alone structure. The demand was found to be about 300 millimeters (12 inches) for the operating level earthquake from MOTEMS 2005. No performance point, however, was found for the REP 2004 expression (indicating the inability of the structure to sustain the demand) because of the excessive flexibility and low base shear capacity of the stand-alone wharf extension.

EVALUATION OF ALTERNATIVES FOR SUBSTRUCTURE

When the need for continuous crane rails and a fully operational facility in the case of an operating level earthquake was considered, the estimated lateral displacement of a stand-alone structure was found to be unacceptable, and the new structure therefore had to be connected to the existing wharf.

Given no clear evidence in the field of the use of transverse reinforcement for the shafts, the mode of failure for these members was expected to be brittle shear. As a result, the structural evaluation of the existing structure for the alternatives under seismic actions is based solely on the inducted shear demand in relation to a conservative estimation of the shear capacity of the shafts.

The existing wharf and the extension were modeled as a series of shell elements supported on pairs of mutually perpendicular springs representing the effective lateral stiffness of each shaft/pile (Figure 7). The shell elements were selected to have the same flexural stiffness as the superstructure, while the lateral stiffness of each pile/shaft was obtained by using the program LPile® for average boring logs properties obtained at the site. A different set of lateral springs representing the soil and the piles/shafts that corresponded to the alternative substructure configuration defined in Figure 5 was calculated for the Berth 14 extension.

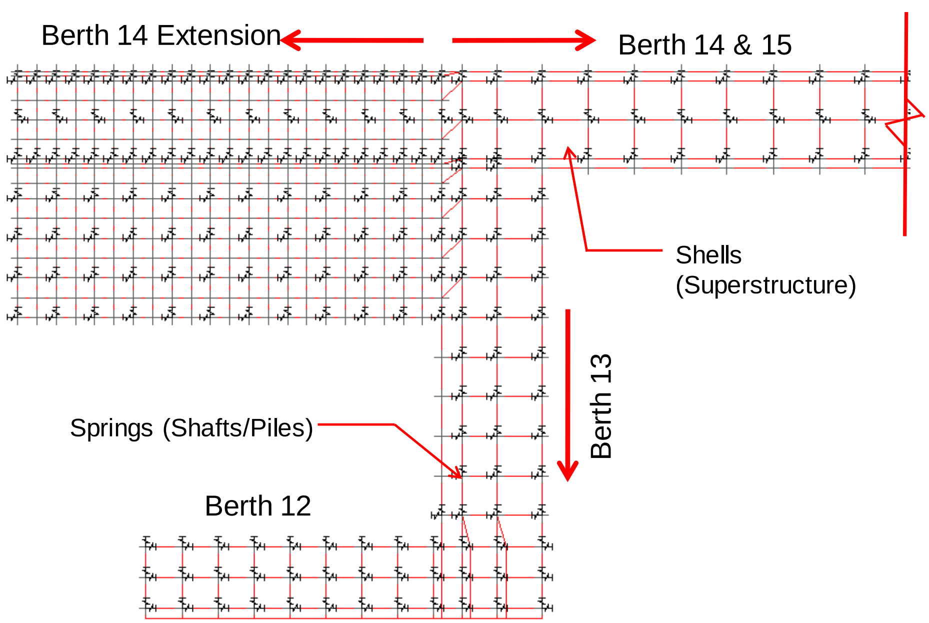

Figure 7. Overall structural model of existing structure and extension.

In the case of the extension supported on 700 millimeter (28-inch) octagonal piles and no dike (Alternative 2), the calculated unit shear stress on each shaft of the existing structure was as shown in Figure 8 for a 100 percent and 30 percent orthogonal combination of the REP 2004 contingency level design acceleration spectrum. The unit shear stress was calculated as the resultant spring reaction divided by the shaft transverse area. A linear dynamic analysis was selected in order to obtain upper bound shear demands on the existing shafts.

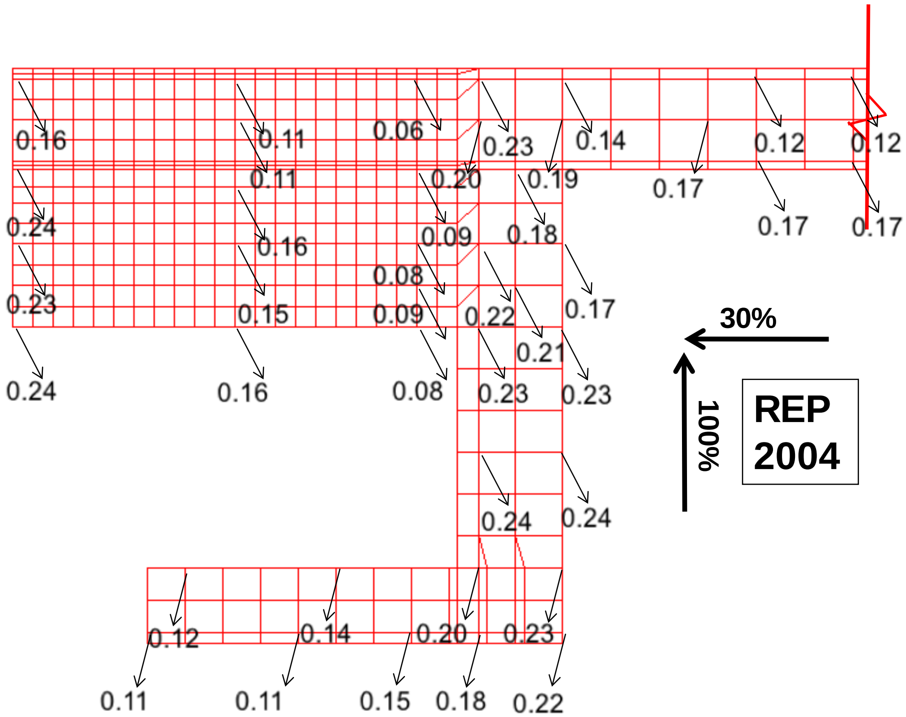

Figure 8. Calculated unit shear demand on existing shafts (linear dynamic analysis) for Alternative 1 (in MPa).

Maximum shear stress demands on the shafts of the existing structure are summarized in Table 2 for the three alternatives. It is observed that shear demands for Alternatives 2 and 3 are slightly smaller because, in these cases, the relatively stiffer extension structures limit the amount of inertial forces transferred to the existing Berth 14.

However, given that the expected unit shear strength of the shafts can conservatively be taken as 0.62 MPa (90 psi) for an assumed concrete compressive strength of 14 MPa (2,000 psi), shear failure of the existing shafts is unlikely to occur in all the alternatives. Therefore, it is apparent that precast prestressed piles driven directly into the existing soil (Alternative 1) render significant savings when compared to the other options. When compared with Alternative 2, for example, the savings amount to 4,700 cubic meters (6,100 cubic yards) of placed substructure and 400 cubic meters (523 cubic yards) of concrete for pile caps. When compared with Alternative 3, the savings amount to over 20,000 cubic meters (26,159 cubic yards) of placed rock dike. The selection of Alternative 1 for the extension does not represent any significant increases, therefore, in the seismic risk of the existing wharf as compared to Alternatives 2 and 3.

Table 2. Maximum shear demand on shafts of existing structure for connected Berth 14 extension under CLE

Extension Alternative (Connected to Existing Wharf)	Maximum Unit Shear on Shafts of Existing Structure, MPa (psi)	
	REP 2004	MOTEMS 2005
700 octagonal piles, no dike	0.24 (35)	0.14 (20)
1.5-meter (5.0 feet) shaft, no dike	0.23 (33)	0.13 (19)
700 octagonal piles with dike	0.21 (30)	0.12 (17)

CONNECTION DESIGN

An exaggerated depiction of the deflected shape of the wharf system under excitation in the transverse direction is shown in Figure 9 for Alternative 1. Because of the significant lateral stiffness of the existing Berth 14 structure, the extension supported on 700-millimeter (28-inch) octagonal piles driven into the existing soil essentially behaves as a cantilever deep beam fixed against rotation at the connection. A considerable amount of chord reinforcement was required at the ends of the connection to transfer the moment imposed by inertial effects. The south portion of the connection required more reinforcement because of corner effects. Reinforcement was also provided to transfer shear from the new flexible structure to the existing stiff structure. The reinforcement required did not need to be the sum of the amount required for shear friction transfer and tension chord action, but the greater of the two as stated in Section 11.7 of ACI 318-05.

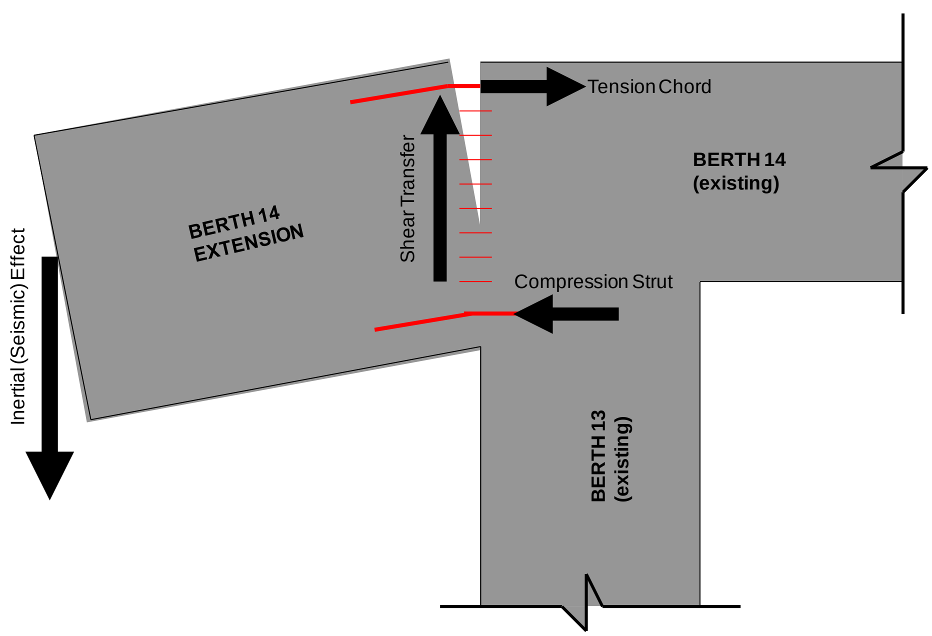

Figure 9. Connection design existing structure-to-extension.

CONSTRUCTION

The Berth 14 extension was built during the second semester of 2007 and first quarter of 2008. Because the underlying soil was rather stiff, 700-millimeter (28-inch) solid octagonal piles were first drilled to guarantee lateral support and then driven to refusal in order to achieve the desired bearing capacity. Supercone fenders and bollards were provided in the north face for berthing and mooring of Panamax vessels. A fender piles system and cleats were also provided on the south face for berthing and mooring of barges.

SUMMARY

Berth 14 is part of a wharf system that is supported on large and brittle concrete shafts up to 2.4 meters (7.9 feet) in diameter. An extension, 85 meters (279 feet) long by 50 meters (164 feet) wide, was designed to allow simultaneous servicing of two Panamax vessels at the existing Berths 14/15. A freestanding structure was found to be rather flexible and undesirable when considering the need for continuous crane rails. Options considered for the extension's substructure included building a dike and using drilled shafts, but a flexible system consisting of 700-millimeter (28-inch) octagonal precast, prestressed concrete plumb piles was chosen as the most practical and economical solution. The selected plumb pile system, referred as to Alternative 1 in this paper, was fully connected to the existing Berth 14 structure. Potentially imposing large inertial forces on the drilled shafts of the existing berth—an initial concern—was proved to be irrelevant through analytical modeling. Shear demands on the existing shafts were found to be less than half the shear capacity of the members and, thus, brittle failure under the design seismic event would be unlikely to occur.

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