Seven Key Words

- Maritime port planning and operations
- Container handling
- Solid bulk handling
- Precast deck system
- Seismic design
- Capacity protection deck design
- Top-down construction system

SEISMIC DESIGN AND CONSTRUCTION OF PILE-SUPPORTED CONCRETE WHARVES FOR CONTAINER AND BULK-HANDLING TERMINALS

By

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ABSTRACT

The paper describes the seismic design and construction of two adjacent wharves in greenfield terminals off the Pacific coast of Colombia. The wharves include two quays totaling 850 meters and two individual access trestles serving container-handling operations and bulk and breakbulk cargo-handling (coal exports/grain imports) operations, respectively.

The projects started with the intent of providing waterfront infrastructure capable of handling modern post-Panamax ship-to-shore (STS) quay cranes, mobile harbor cranes, and operations of bulk-handling equipment in a remote and high-seismic area of Colombia.

The design adopted a modular and repeatable open-wharf system consisting of high-capacity steel pipe piles supporting a high-capacity precast concrete deck system. Due to heavy rainfall and the remoteness of the site, a deck system consisting primarily of precast concrete elements was implemented in order to delink construction progress and quality control with site constraints. Deck elements needed to have adequate weight and sufficient reinforcement to resist the 35 kPa operational and STS crane loads under service conditions; however, given the high-seismic activity in the region, the overall design also needed to limit seismically induced lateral deflection.

State-of-the-art performance-based and capacity protection seismic design and detailing for pile-supported wharf structures per ASCE/COPRI 61-14 were adopted for the design of the quay and the access trestles. A key component of design was the development of an innovative precast concrete pile plug providing a practical connection between the steel piles and the concrete superstructure. The plugs were designed to provide significant inelastic rotation capacity without penalizing the deck design. The paper will elaborate on important serviceability and seismic design considerations and explain how these challenges were overcome in design and construction. A significant portion of success in meeting the aggressive schedule was attributed to the innovative construction methods adopted in the project. A linear top-down construction approach was adopted wherein previously installed piles were used to install future piles and deck elements. Due to this, precast element design details had to be made compatible with the top-down system.

Construction of both the wharves was completed in late 2016, and they are currently in operation.

INTRODUCTION

The remote Aguadulce peninsula off the Pacific coast of Colombia now hosts one of largest marine terminal complexes in Latin America. The complex includes the 30-hectare Sociedad Puerto Industrial de Aguadulce (SPIA) container terminal and the 4-hectare Boscoal bulk-handling terminal. The construction of the entire marine complex was divided up into multiple contracts; both the container wharf and bulk-handling wharf construction contracts were awarded to design-build (D-B) teams with BergerABAM as prime designer. Both the wharves were constructed by a consortium consisting of Soletanche Bachy Cimas, Conconcreto, and Soletanche Bachy International. The projects were realized after a period of intense value engineering (VE) evaluations by the designer that included evaluation of multiple alternatives. It is to be noted that the configuration of both the wharves, including location and orientation, was defined in previous studies.

The marine structures for the container- and bulk-handling terminals consist of offshore quays connected to the uplands with individual access trestles. The SPIA container terminal consists of a T-shaped pile-supported wharf comprising a 600-meter-long quay connected to a 160-meter-long access trestle and a 25-meter-long platform. The wharf is designed to support super post-Panamax gantry cranes capable of loading 23-wide 12,500-TEU (twenty-foot equivalent unit) container vessels. The wharf design also accounted for berthing of small 300-TEU feeder vessels. The marine structures for the Boscoal bulk-handling terminal is an L-shaped pile-supported wharf, comprising a 250-meter-long quay connected to

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a 186-meter-long access trestle and a 15-meter-long platform. The wharf was designed to support Handymax bulk-handling vessels and conveyor belt supports for coal exports and grain imports.

The site is located in one of the highest reported seismically active regions in the world and experiences heavy rainfall all year long with tidal fluctuations of up to 5 meters. Due to the remoteness of the site and the tight cost and schedule constraints, the D-B team adopted an innovative precast (PC) wharf deck system supported on all driven steel plumb pile substructure system.

To accelerate construction, the D-B contractor for both the projects decided to build the wharves using a top-down construction system. This linear construction approach relies on previously installed steel pipe piles as supporting elements of a platform that rapidly installs future piles and PC deck elements and then moves forward to continue with the construction. One of the big drivers of the accelerated schedule was the fact that the design for both the wharves was made very similar despite it serving two different operations; i.e., container handling and solid bulk handling. This was due to the versatile and modular design that allowed repeatability to the maximum extent possible.

This paper describes the structural analysis and design/construction process of the wharf with emphasis on the seismic design of the wharves. The paper also summarizes how the different PC concrete elements forming the wharf deck system were conceptualized, designed, detailed, erected, and interconnected.

LAYOUT AND FRAMING

Figures 1, 2, 3, 4, and 5 present the layout and typical cross sections of the container- and bulk-handling wharves, respectively. Table 1 presents salient features of the container- and bulk-handling wharves. The site is characterized by the presence of thick layers of soft marine sediments overlying relatively stiff strata of clay and mudstone (Mallorquín formation). From the available laboratory testing, the mudstone showed evidence of weathering as we head onshore. The boreholes showed the presence of mudstone at elevations between -35.0 to -40.0 meters mean sea level (MSL) along the quay, overlaid by 10 to 20 meters of soft (CL, ML type) soil. Across the quay width, the thickness of the soft overburden decreased towards the land. A combination of soil conditions and schedule led to the selection of ***driven open-ended plumb steel pipe piles*** as the preferred piling option for the project. The piles were predominantly friction piles with some contribution from end bearing. To prevent premature plugging of piles while driving, a decision was made early in the project to use driving shoes. For corrosion protection, piles were provided with a polyethylene coating extending 1 meter below mudline.

The quay and trestle structures consist of a concrete deck at Elevation +5.05 meters MSL supported by steel pipe piles. Pictures 2 and 3 indicate the typical quay framing for both the wharves. The trestles in both the container- and bulk-handling wharves consisted of two pile bents. Bents were spaced at 7.5 meters in the longitudinal direction, with no intermediate pile(s) between bents along crane beam grids.

The deck for both the wharves implemented a predominantly ***PC system composed of PC capped pile plugs (champagne-cork type) inserted in pipe piles; PC transverse beams, PC longitudinal crane beams and PC fender beams positioned over pile plug caps, and interconnected via cast-in-place (CIP) closure pours; PC pretensioned deck panels spanning from bent to bent; and a CIP topping.***

For both the container- and bulk-handling wharves, the quay was separated from the trestle by means of expansion joints designed and detailed for operational and seismic loading cases considering movement in similar and opposite directions.

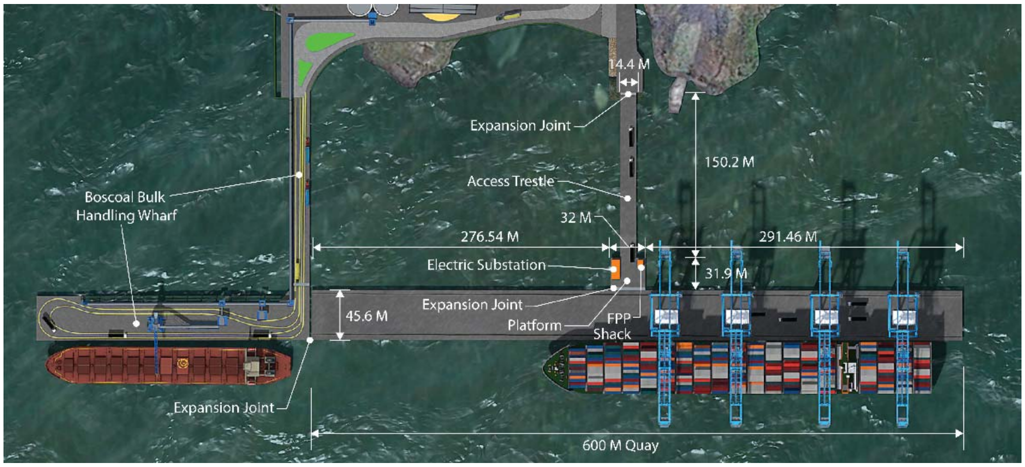


Figure 1. SPIA Container Wharf and Boscoal Bulk-Handling Wharf Layout

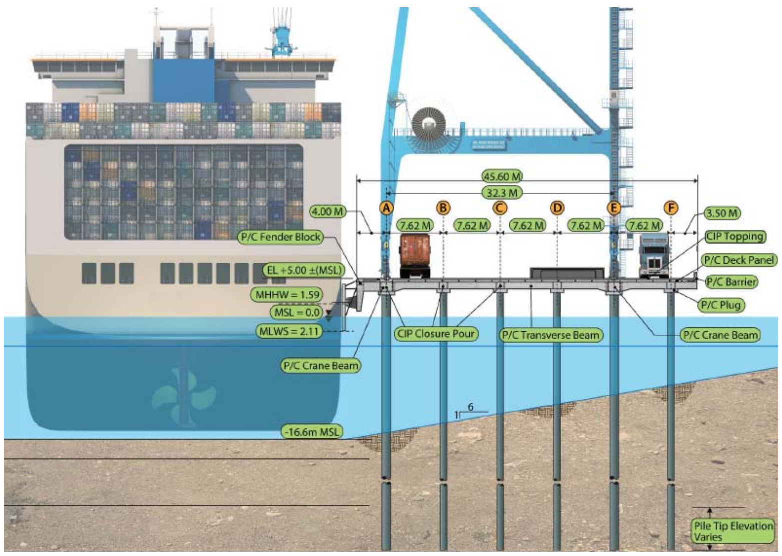


Figure 2. Container Quay Cross Section

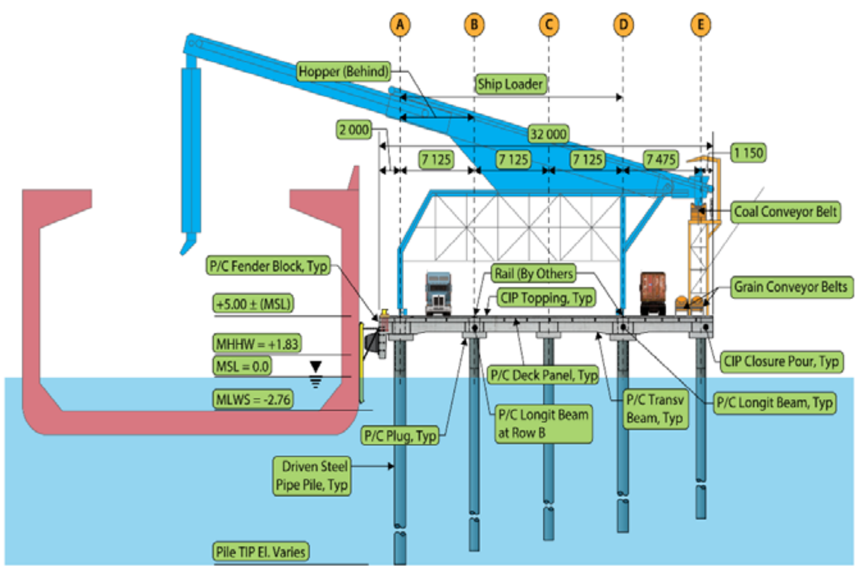


Figure 3. Bulk-Handling Quay Cross Section

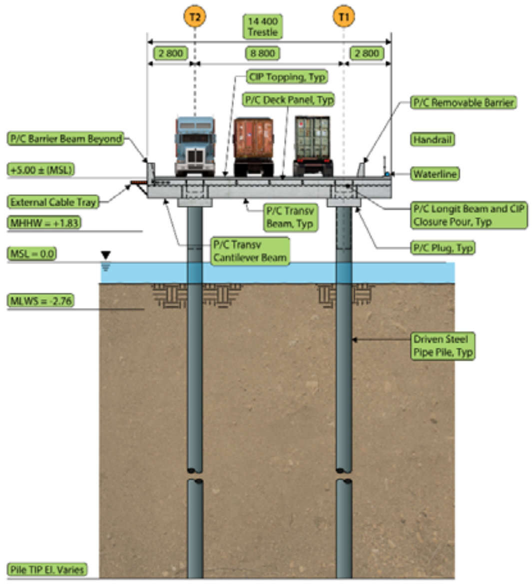


Figure 4. Container Trestle Cross Section

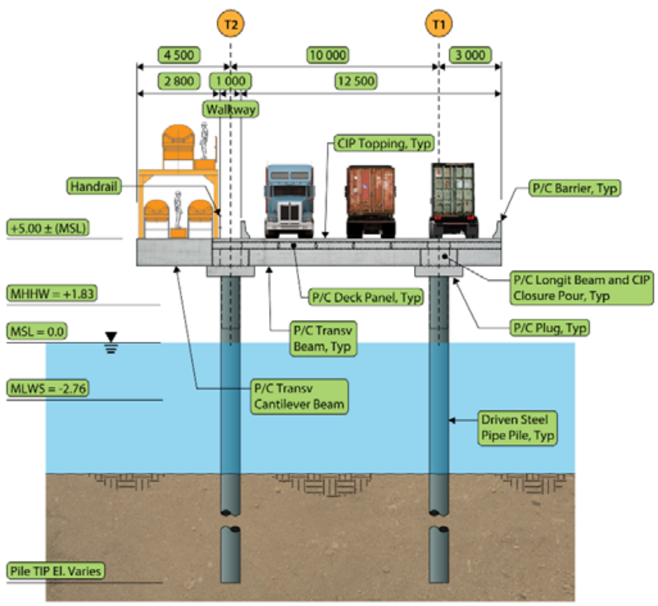


Figure 5. Bulk-Handling Trestle Cross Section

Parameter	Container Wharf	Bulk-Handling Wharf
Quay Dimensions	600 m x 45.6 m	250 m x 40 m (max)
Platform Dimensions	32 m x 32 m	15 m x 30 m (max)
Trestle Dimensions	150.15 m x 14.4 m	185 m x 17.5 m
Dredge Depth	-16.6 m, 1:3 slope	-15.0 m

Table 1: Key Layout Parameters of Container and Bulk Handling Wharves

OPERATIONAL LOADS

Container Wharf

The container wharf design, as well as the framing for the quay portion, was dictated by an owner-specified Basis of Design (BOD) and design, respectively. In addition to self-weight, the deck elements were designed for a uniformly distributed live load of 3.5 tons per square meter and operational crane wheel loads of about 70 tons per meter. A 1.5–meter-wide safety zone was defined at each crane beam row. The controlling operational load case for the trestle deck design was the passing of an unloaded rubber-tired gantry (RTG) crane, representing the case of RTGs being transferred from the wharf to the container yard. The container wharf was also designed to resist lateral berthing and mooring loads from servicing a 12,500-TEU 150,000-DWT (dead weight tonnage) post-Panamax vessel.

Bulk Handling Wharf

The design criteria of the bulk handling wharf were developed by the D-B team in conjunction with the owner. In addition to self-weight, the deck elements were designed for: 1) uniformly distributed live load of 2.0 tons per square meter; 2) operational loads from the shiploader of 28.13 tons (waterside, three wheels per corner); 3) 32.6 tons (landside, two wheels per corner); 4) conveyor belts for coal/cement exports (15 tons every 7.5 meters); and 5) grain imports (4.6 tons every 6.0 meters). In addition, the wharf had to be designed for an LHM 420 Mobile Harbor Crane (MHC) operating anywhere over the quay deck except the cantilever areas and a transiting MHC over the trestle deck. The bulk-handling wharf was also designed to resist lateral berthing and mooring loads from servicing an 80,000-DWT bulk-handling carrier.

SEISMIC DESIGN CONSIDERATIONS

Seismic design was an important component of the D-B team's responsibility for the project because the wharves are located in a high seismic region. The following explains some of the components.

Multilevel Seismic Design

The design had to provide adequate deformation capacity and strength in piles, deck, and pile-deck connections for two design level earthquakes: the Operational Level Earthquake (OLE) with a return period of 72 years and the Contingency Level Earthquake (CLE) with a return period of 475 years. The BOD called for CLE acceleration spectra constructed using A_a=0.45g and A_v=0.45g per Colombian Code NSR-10. Amplified spectral accelerations for the clayey site are shown in Figure 3. Spectral acceleration ordinates for OLE correspond to the damage threshold event prescribed by NSR-10. In general, CLE-based effects controlled design of the primary structural elements. ASCE/COPRI 61-14 also calls for checking the structure for a third event called Design Event (DE) that has a return period for 2475 years. However, the design team decided to adopt a "less stiff" design without sacrificing operational performance – this resulted in design for DE not being a consideration because for periods of vibration greater than 0.6 second, the structure experiences the same acceleration for both CLE and DE. Figure 6 presents the seismic spectra used in design.

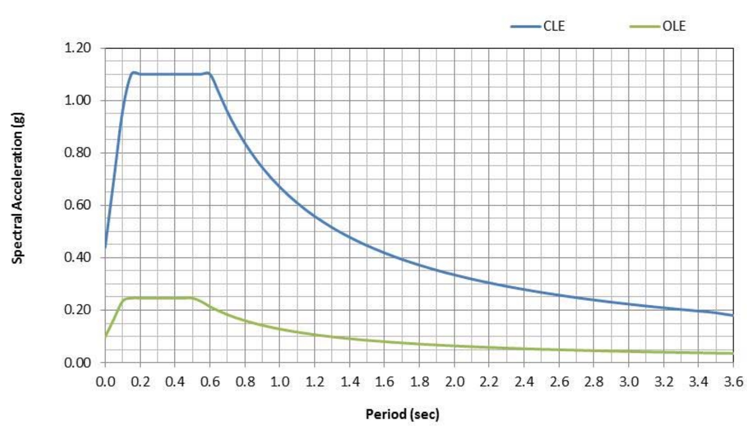


Figure 6. Spectral Accelerations for OLE and CLE

Seismic Weights

A key consideration in design was to limit the seismic weights of the structure as it has an impact on the seismically induced deflections and hence strains in critical members. Earthquake loads were combined with dead and live loads assuming the full dead load and 10 percent of the live load for both the wharves. The same percentage of live load was assumed for the definition of the seismic mass in the dynamic analysis. The container wharf was essentially an “offshore quay” and had a trestle connecting it to land. Due to the limited width of the quay, stacking loaded containers on the quay was deemed an inefficient and ineffective operation and hence the 10 percent value of live load contribution was justified. For the bulk-handling wharf, the most critical component was to include the self-weight of the conveyor belts and hoppers in the seismic mass.

Wharf Seismic Design Philosophy

As in typical horizontal construction for marine/waterfront structures, seismic design followed the “weak column-strong beam” design principle. Capacity protection principles were applied for the shear design of piles, shear design of pile-deck connections, and the shear and flexural design of the deck elements. For the design of capacity-protected members and actions, the calculated demand was based on 125 percent of the calculated plastic strength of the yielding member, which was the pile-deck connection.

Seismic Strains

For practical purposes, the upper end of the steel pipe piles was designed as a confined reinforced concrete (RC) element, with the ability to develop a hinge, with ductility provided by the spiral provided in the PC pile plug, benefitting by confinement provided by the encasing steel pile shell. Pile plug dowels were ASTM A706 steel. Strain limits in dowels complied with ASCE/COPRI 61-14 requirements. The pile-deck connections were detailed per ACI 318-14. Shear design of piles considered the overstrength capacity of the pile-deck connection. The overstrength moment demands at top (deck soffit) and bottom (in-ground hinge) of the pile were calculated from moment-curvature analysis using expected material properties specified by ASCE/COPRI 61-14. The moment-curvature modeling of the plug end of the piles accounted for the impact of potential plug cover spalling. At the in-ground hinge end, the shear capacity of the pile was calculated per AISC Load and Resistance Factor Design (LRFD). P-Delta effects due to seismic loading were considered.

Deck Capacity Protection

Capacity-protection design of the deck was challenging because of the large magnitude of seismic moments in piles applied over an optimized deck with only crane beams in the longitudinal direction. The problem was accentuated by the presence of large diameter piles along crane and longitudinal beams. Due to these being the stiffest elements of the substructure system, these piles attracted a larger portion of the seismic moments. Strictly speaking, full capacity protection of the deck implied it had to resist the sum of seismic moments (factored by 1.25) from all the piles all the way across without undergoing damage.

The sum of pile moments per bent will be resisted by the deck across areas tributary to each pile, with the main tensile contribution coming from the crane beam reinforcement and outside crane beam zones from the top deck reinforcement and bottom deck panel bars. The latter were extended and terminated in 90 degree hooks to enable proper tension force development during earthquake reversals. Refer to Figure 7 for a conceptual idealization of capacity protection design of deck.

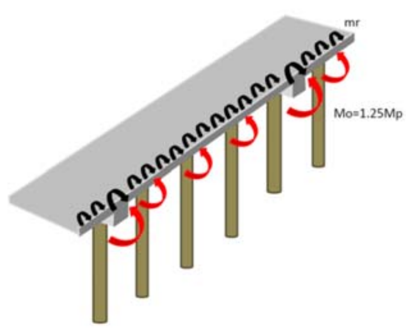


Figure 7. Deck Capacity Protection Design Concept

SUBSTRUCTURE DESIGN

All piles for both the container and bulk-handling wharves had to develop necessary axial and lateral capacities. Because the wharf framing consisted of an all plumb-pile system and the under-wharf slope was very gradual, the design had to make sure that the piles penetrated sufficiently into the weathered mudstone to develop full pile fixity and capacity for operational conditions and provide sufficient ductility for seismic conditions. The D-B team decided to adopt API 5L steel pipe piles for the wharves and adopted a 60-ksi yield strength pipe pile material in order to limit deflections within the elastic regime of the pipe material.

Parameter	Container-Handling Wharf	Bulk-Handling Wharf
Pile Type	Open-Ended Tip-Reinforced Driven Plumb Steel Pipe Pile API 5L Grade 60 ksi	Open-Ended Tip-Reinforced Driven Plumb Steel Pipe Pile API 5L Grade 60 ksi
Quay Working Axial Compression Demand	750 Tons (Waterside Crane) 560 Tons (Landside Crane) 310 Tons (Internal)	310 Tons (All)
Quay Pile Size	1219 mm x 25.4 mm, 914 mm x 19 mm	1067 mm x 25.4 mm, 914 mm x 19 mm
Quay Pile Quantity	486 piles	176 piles
Platform Working Axial Compression Demand	200 Tons	200 Tons
Platform Pile Size	914 mm x 19 mm	914 mm x 19 mm
Platform Pile Quantity	20 piles	7 piles
Trestle Working Axial Compression Demand	200 Tons	200 Tons
Trestle Pile Size	914 mm x 19 mm	914 mm x 19 mm
Trestle Pile Quantity	40 piles	50 piles

Table 2: Key Pile Design Parameters of Container- and Bulk-Handling Wharves

Table 2 summarizes critical pile axial compression loads under service conditions. Due to the owner-specified framing for the container wharf, which did not include intermediate piles under the long-span crane beams, the critical crane beam piles required high capacity. In addition, the offshore container wharf piles had to be designed for a future dredge depth of -16.6 meters. On the other hand, the reasonably modest shiploader loads for the bulk-handling wharf resulted in significantly lower pile axial capacities. Anticipated dredge depth for the bulk-handling wharf was limited to -15.0 meters; therefore, the design team was able to optimize the size of piles. See Figure 8, schematic detail of the driven pile.

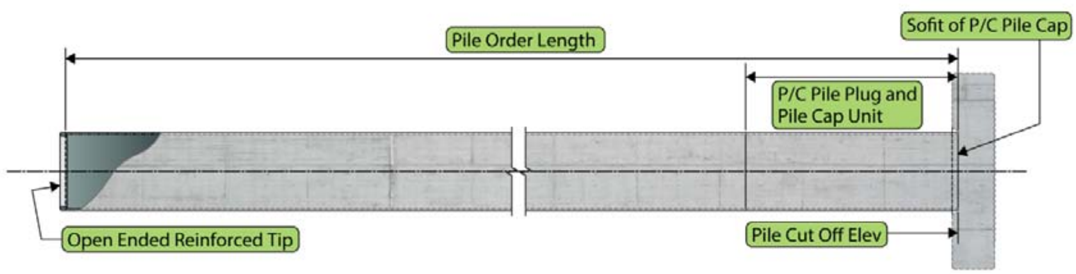


Figure 8. Driven Open-Ended Tip-Reinforced Plumb Steel Pipe Pile

Geotechnical Considerations

The container wharf piles were the first production piles for the marine projects. Due to the variability at the beginning of the job and the varying, yet high, magnitude axial load capacity requirements for the container quay piles, the D-B team decided to adopt the criterion based on

- Providing a pile tip elevation at or below the estimated depth of fixity
- Driving the pile to a specific resistance criteria defined by a specified blow count for a given penetration

However, for the bulk-handling quay, the D-B team decided to drive the piles to grade based on an estimated pile length computed based on providing full fixity at the bottom. The construction of the bulk-handling wharf piles also had the advantage of information gained from installing the container-handling wharf piles.

Structural Considerations

Slenderness effects on axial and bending moment capacity of piles under gravity loads had to be first considered appropriately given the wharf consisted of an all plumb-pile system. For load cases involving operational lateral loads due to berthing or mooring of vessels, analysis and design involved the final configuration of the deck. For seismic analyses, the D-B team had two considerations.

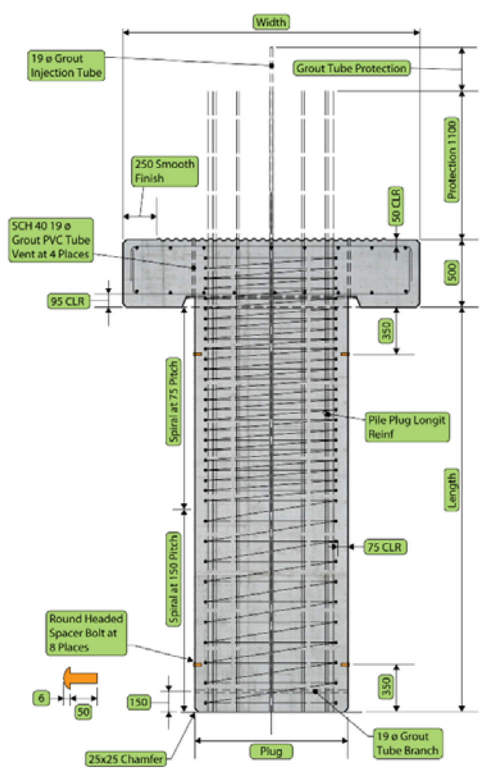
- Minimizing pile top moments for the “flexible” quay piles
- Limiting pile shell strains in the “flexible” quay piles and “stiff” trestle piles to ASCE/COPRI 61-14 recommended seismic strains with the intent of minimizing the possibility of global and local buckling

SUBSTRUCTURE TO SUPERSTRUCTURE CONNECTION DESIGN

A precast reinforced plug connection between the steel pipe piles and the PC superstructure was conceived by BergerABAM and implemented by the contractor team for the project. This is the first instance in which such a system has been implemented on a major scale in marine construction. The PC pile plug was designed and detailed to provide performance equivalent to its traditional CIP counterpart that is identified by ASCE/COPRI 61-14 as a ductile design detail. The PC capped pile plug includes a rectangular reinforced pile cap cast integrally with a cylindrical reinforced plug, the dimensions of which are defined by the inner diameter of the piles. The PC plug transfers all vertical loads to the pile through the cap that was detailed to provide direct bearing over the pile shell. The annulus between the PC pile plug and the steel pile was filled with a cementitious grout carefully selected to minimize shrinkage. The basic concept behind the PC pile plug for lateral load transfer is that it only needs to contact the steel casing at two points to develop a couple that can transfer the moment from the pile top to the deck. The contact points were ensured by the tight-fit size of the plug and overall behavior of pile-deck system when subjected to lateral loads. Load transfer through the PC plug was provided by a seismically detailed connection consisting of longitudinal and transverse confining reinforcement, which is not very different from its CIP plug counterpart. Figure 9 presents details of the PC plug and a typical moment-curvature curve for the same. Note that a stiffness reduction factor of 0.9 was considered for the PC plugs in design to account for the innovativeness of the system.

Parameter	Container Wharf	Bulk-Handling Wharf
Plug Size	1135 mm, 845 mm	985 mm, 845 mm
Plug Reinforcement	24#10, 18#10	20#10, 16#10

Table 3: Key Pile Plug Design Parameters of Container and Bulk Handling Wharves



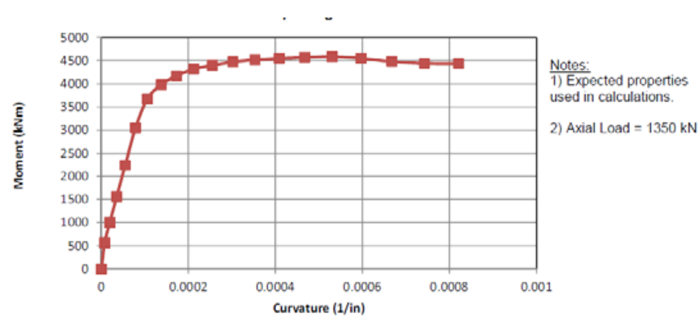


Figure 9. Precast Pile Plug Details

SUPERSTRUCTURE DESIGN

The design team adopted a predominantly precast deck system consisting of precast reinforced transverse and crane/longitudinal beams, precast pretensioned deck panels, and CIP reinforced closure pours and topping. The precast beams and deck panels had projecting top and bottom mild steel reinforcing to provide strength during construction/installation, as well as seismic conditions. The beams framed into seismically detailed CIP closure pours that provided strength, confinement, and continuity to the entire system. In order to provide necessary early and long-term strengths, as well as marine performance, a marine concrete mix consisting of innocuous aggregates, low in permeability and chlorides and rich in cement, was provided. The concrete mix typically had a minimum 28-day compressive strength of 42 MPa. For providing desired ductility, ASTM A706 Grade 60 ksi reinforcing steel was used for the beams. ASTM A416 Grade 270 ksi was used for the pretensioned strands.

Though the owner-specified BOD for the container wharf deck did not include any serviceability requirements, the D-B team decided to adopt a crack-control design philosophy given the design life and marine environment. The same philosophy was adopted for the bulk-handling wharf deck. This was based on our experience that marine structure deck design is typically controlled by meeting service rather than strength design requirements. Structural performance of the structure under service loads was verified through control of cracking and deflections in precast deck elements. Maximum allowable width of flexural cracks at the surface of structural concrete elements under service loads was limited to values presented in Table 4 below. Precast pretensioned concrete deck panels were designed so that any net tension under normal service load conditions did not exceed the limits stipulated in ACI 318. Crack widths in reinforced concrete members were then verified per the recommendations of AASHTO LRFD 2012. Maximum deflection in longitudinal deck elements under normal uniformly distributed service live load was limited to L/500 typically and L/300 for cantilever members.

Non-prestressed concrete elements (beams, topping)	Bottom face	$w \leq 0.25$ mm
	Top face	$w \leq 0.25$ mm
Precast pretensioned concrete deck panels	Bottom face	max $f_{tension} \leq$ ACI 318 limit (normal service loads)

Table 4: Service Design Criteria for Container- and Bulk-Handling Wharf Decks

The deck components had to be designed accounting for the following construction sequence.
1. Beams simply supported on capped pile plugs
2. Beams made continuous through closure pours at joints
3. Self-weight of deck panels on transverse beams
4. Weight of wet topping over continuous deck panels
5. Full design loads applied on the final configuration of the deck

Structural Considerations

1. Precast Reinforced Crane/Longitudinal Beams
   The container quay crane beam vertical load design was controlled by serviceability requirements. These elements were designed to resist the imposed crane loads given the lack of intermediate pile in container quay and yet maintain a reasonable stress level in steel reinforcement for crack control considerations consistent with marine construction practice. The shiploader and internal longitudinal beams in the bulk-handling quay were designed to transfer the operational vertical loads. The beams also needed to have adequate projecting reinforcement to meet the seismic capacity protection requirements.

2. Precast Reinforced Transverse Beams
   The precast transverse beams had to be designed to resist the dead loads from self-weight, as well as weight of deck panels and topping. In order to mitigate cracking, the D-B team developed a construction scheme that minimized loading the bare precast beams before the ends were integrated. The beams also had projecting reinforcement to meet the seismic capacity protection requirements.

3. CIP Reinforced Closure Pour
   The CIP reinforced closure pours included a series of vertical and horizontal stirrups detailed to provide adequate confinement and shear capacity. The closure pour also served to provide space for developing the capacity of the projecting flexural reinforcement.

4. Precast Prestressed Deck Panels
   The deck consisted of precast pretensioned deck panels placed longitudinally. Due to the high magnitude of pretensioning needed for resisting deck operational loads, the panels had top mild steel reinforcing to minimize cracking during the strand stressing process. In order to provide sufficient longitudinal deck capacity protection, the panels had projecting bottom reinforcement hooked into the closure pour.

5. CIP Reinforced Topping
   The deck panels were topped with a bidirectionally reinforced concrete topping. The reinforcing in the topping was designed for not only operational loads but also seismic deck capacity protection.

Figure 10 presents a schematic detail of the precast beams and the reinforcing in the CIP closure pours at the end of beams.

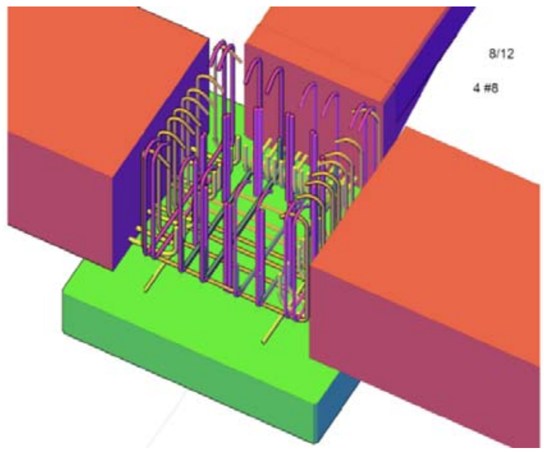


Figure 10. Precast Pile Plug Details

SEISMIC ANALYSES AND DESIGN METHODOLOGY

Seismic load effects were analyzed through displacement-based procedures using non-linear pushover techniques with soil properties derived from the geotechnical investigations. The results were verified with traditional linear response spectra modal analysis. The linear response spectra analyses provided upper bound estimates of displacements that helped in "bracketing" the structural performance. The non-linear pushover analyses incorporated the following features:

1. Full-length structural model with appropriate bent spacing and pile locations
2. Steel pipe piles built out of "expected properties" of API Grade X60 base limit lateral mud and soft rock P-y, skin friction T-z, and end bearing Q-z springs to model lateral and axial stiffness provided by mud and soft rock layers for the two pile types along the length
3. Nonlinear axial-moment interaction hinge (P-M hinge) and plastic hinge lengths for pile section above the estimated fixity points to simulate in-ground hinging effects on all piles
4. Pile-to-cap connection modeled as frame members with stiffness modifier of 0.35 per Reference 4 and built out of "expected properties" of concrete, including design longitudinal reinforcing bars and transverse spacing made of "expected properties" of ASTM A706
5. Nonlinear axial-moment interaction hinge (P-M hinge) and plastic hinge lengths of defined on the plug at the pile-to-deck connection to simulate pile top hinging on all piles
6. Concrete transverse beam section modeled as frame member with stiffness modifier of 0.35
7. Concrete longitudinal beam section modeled as frame member with stiffness modifier of 0.35
8. Concrete deck simulating the 350-mm PC panel and 150-mm CIP topping modeled as shell elements everywhere except over the longitudinal beam section with stiffness modifier of 0.35
9. Pile caps modeled as point loads acting on top of the piles
10. Dead load of all components and 10 percent of live load (1.5 kPa) is incorporated as seismic mass and in period calculations

See Figures 11, 12, and 13 for typical pile springs adopted in seismic analyses and snapshots of the full 3-D finite element model for the container quay and trestle. Note that all the modeling was done on the commercially available software SAP2000 and was verified through hand-checks using spreadsheets. Consistent with ASCE 61/COPRI 61-14 guidelines, analyses were performed for three values of springs – a base value, a lower bound value (less stiff), and an upper bound value (more stiff). Figure 14 presents a typical pushover curve for the structure with the anticipated performance point for the container quay. Table 5 presents typical analyses results for the container quay assuming baseline spring stiffness. In general, the seismically induced forces, deflections and strains were more onerous for the container quay when compared to the bulk-handling quay given the greater unsupported length, higher seismic mass and live load.

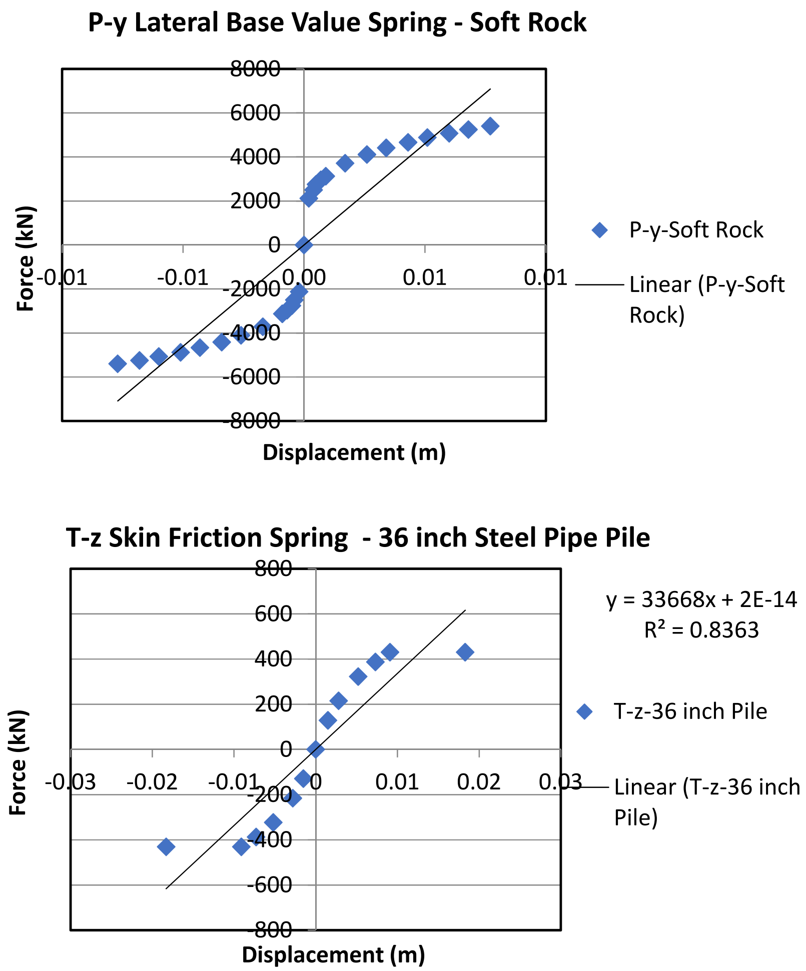


Figure 11. Typical Pile Springs

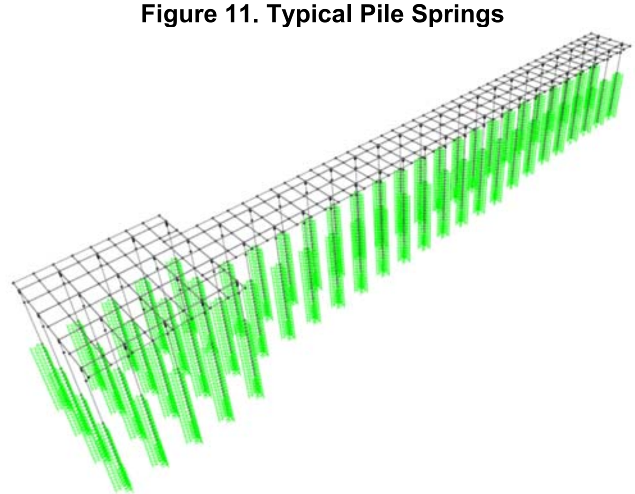


Figure 12. Full Model for Container Trestle and Platform

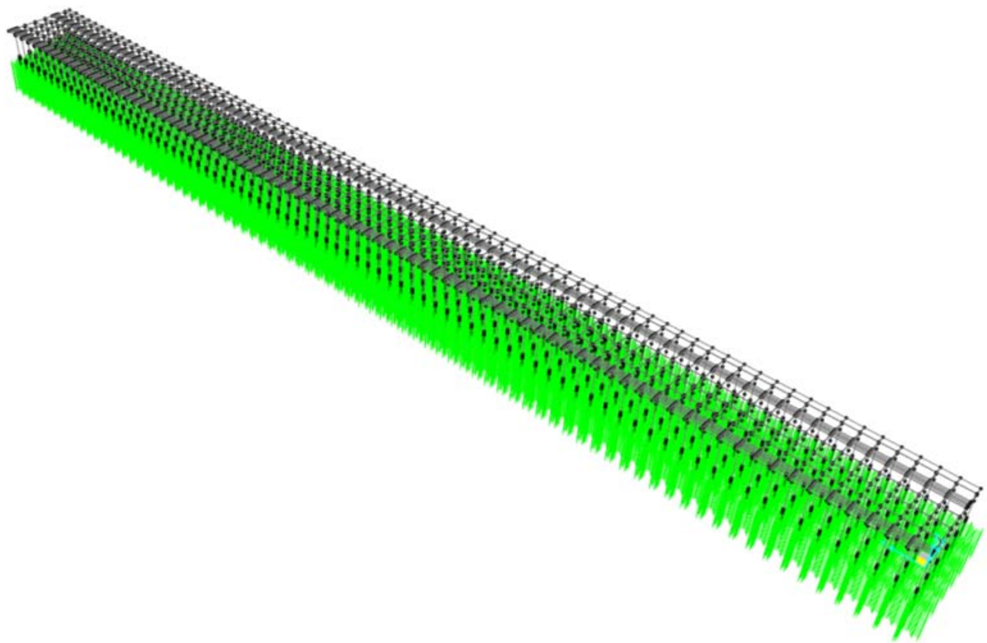


Figure 13. Full Model for Container Quay

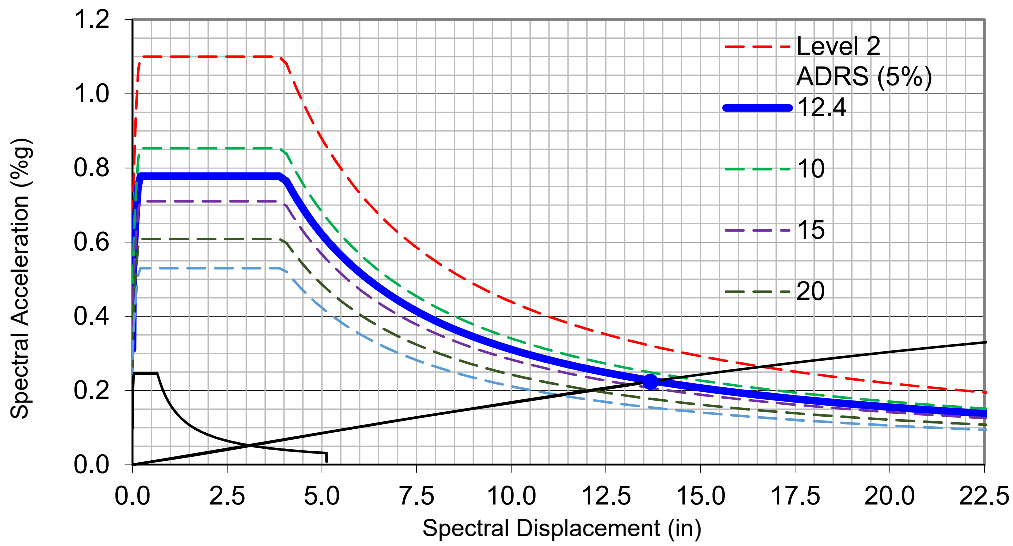


Figure 14. Performance Point Example - Container Quay Transverse Direction

Parameter	Analysis Result
Seismic Mass	Approx. 667,250 kN (150,000 kips)
Performance Point for OLE transverse to quay (x-direction)	Approx. 70 mm (2.8 inches)
Performance Point for OLE parallel to quay (y-direction)	Approx. 75 mm (3.08 inches)
Performance Point for CLE transverse to quay (x-direction)	Approx. 335 mm (13.28 inches)
Performance Point for CLE parallel to quay (y-direction)	Approx. 355 mm (14.08 inches)

Table 5: Service Design Criteria for Container- and Bulk-Handling Wharf Decks

CONSTRUCTION

For both the quays and the trestle for the bulk-handling wharf, the contractor used a top-down construction system to install the piles and deck. The methodology applies a linear construction approach that uses previously driven and cut off steel pipe piles as supporting elements for the "piling platform" (two-bents wide) that installs future piles and PC pile plugs followed by a "deck-works platform" (two-bents wide) that installs the PC deck components. The latter is supported on PC pile plugs previously installed in piles driven and cut off. Once the PC pile plugs were installed, the deck-works crane installed the PC beams over the pile plugs, cast the closure pours at beam intersections, installed pretensioned precast deck panels, and cast topping concrete. PC elements were supplied via floating barges. The interaction between the piling and deck-works platforms required coordination of PC deck elements to be installed per movement. The sequence of construction for the container quay is shown in Figure 15 whereas sequence of construction for the bulk-handling wharf is shown in Figure 16.

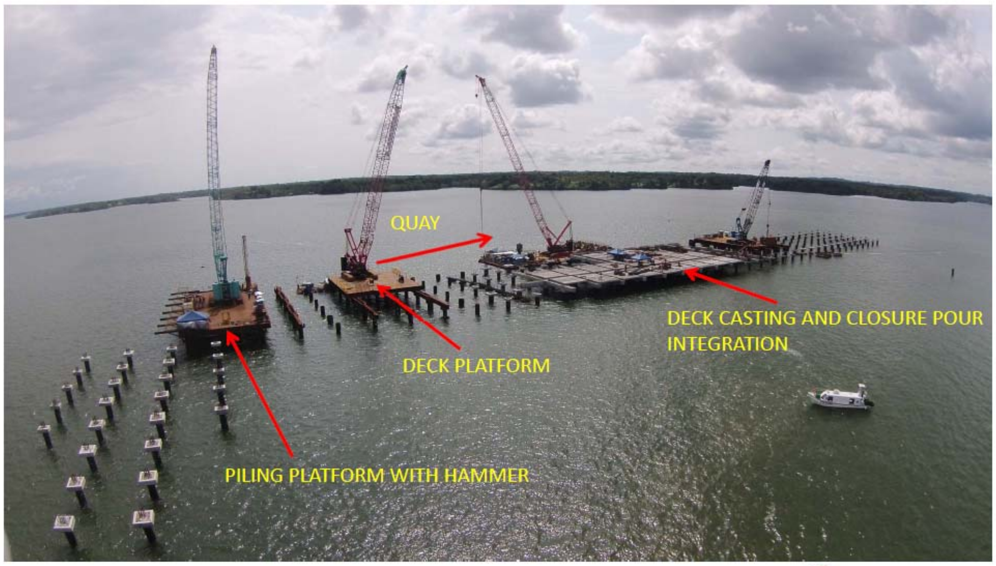


Figure 15. Top-Down Container Quay Construction

The trestle piles for the container quay were installed differently. Trestle piles near the abutment were installed with a crane operating from a temporary fill embankment whereas piles located near the platform were installed with the same crane over floating equipment. See Figure 17.

In terms of production, the piling platform managed to install up to six piles (one bent for the container quay) in a 24-hour-long shift. Dismantling and resetting of the platform took two extra days. Figure 18 shows the installation of a PC-capped pile plug. All PC elements, including capped pile plugs, crane beams, transverse beams, fender beams, and deck panels, were fabricated near Medellín. PC elements were trucked to a staging yard in Buenaventura and then barged over to the peninsula. Erection of fender beams was particularly challenging because of weight and asymmetric nature of these elements. Special lifting and temporary strapping elements had to be designed and installed to provide stable support for their Stage 1 erection prior to integration with adjacent crane and transverse beams. See Figure 19 for photographs indicating sequential deck construction.

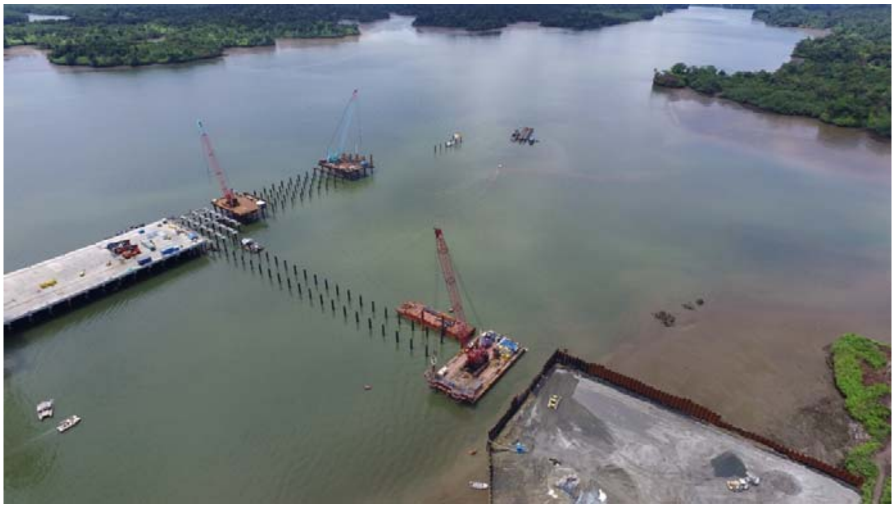


Figure 16. Bulk-Handling Wharf Construction

Figure 17. Container Trestle Construction

Figure 18. PC Pile Plug Installation

Figure 19. Sequential Deck Construction

CONCLUSIONS

The design and construction of the container- and bulk-handling wharves in Aguadulce, Colombia, represent a prime example of extraordinary coordination between the D-B team members. Despite challenging site and environmental conditions, tricky design situations, and a highly compressed schedule, both the wharves were constructed in record time. In fact, wharf construction preceded the upland yard construction by a significant margin, which was inconceivable when the project was being conceptualized. The design adopts the state-of-the-art recommendations for seismic performance as envisioned by ASCE/COPRI 14 and implements a displacement-based design approach that does not penalize the structure despite it being located in a region of high seismicity. The design also maximized the use of precast elements that not only provided necessary quality for marine performance but also provided the contractor with a way to minimize site logistics and construction. A modular yet versatile approach allowed the wharves with different uses to adopt a consistent design that further reduced construction time. Figure 20 presents an aerial view of the completed projects.

Figure 20. Completed Container- and Bulk-Handling Wharves

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REFERENCES

1. Carlos E. Ospina, PhD, PE; Jyotirmoy Sircar, PE; and Viswanath K. Kumar, PE, SE, “Container Wharf with Innovative Precast Deck in High Seismicity Area,” ASCE Ports 2016
2. “Seismic Design of Piers and Wharves (61-14),” American Society of Civil Engineers
3. “The Port of Los Angeles Code for Seismic Design, Upgrade, and Repair of Container Wharves,” City of Los Angeles Harbor Department, May 2010
4. “Building Code Requirements for Structural Concrete, ACI 318-08,” American Concrete Institute
5. AASHTO 6th Edition (2012 with 2013 and 2014 revisions) LRFD Bridge Design and Specifications Manual