Development and Qualification of a Floating Pier for the U.S. Navy Fleet

Robert F. Zueck, PhD, PE[1] and Markus Wernli, PhD, PE[2]

[1] Research Structural Engineer; CI62, Naval Facilities Engineering Service Center, 1100 – 23rd Avenue, Port Hueneme, CA 93043; PH (805) 982-1210; email: robert.zueck@navy.mil

[2] Project Manager; BergerABAM, 33301 Ninth Avenue South, Suite 300, Federal Way, WA 980030; PH (206) 431-2300; email: wernli@abam.com

Abstract

The U.S. Naval Facilities Command plans to deploy a floating modular hybrid pier (MHP) to berth most major Navy ship classes. Developed to replace deteriorating pile-supported piers, the MHP is made up of floating modules that can be assembled into any length of pier, and later disassembled and relocated separately or as a unit in another home port. This paper summarizes the development, testing, and evaluation of the MHP. The paper discusses the features of the pier that allow its reconfiguring for specific applications and introduces the most likely configurations for particular vessel support goals and mooring requirements. The paper also summarizes some of the key analyses performed to mitigate technical and functional risks.

Introduction

Measuring 1,300 feet (396 meters) long and 88 feet (27 meters) wide, the modular hybrid pier (MHP) concept shown in Figure 1 consists of four identical modules. For rigid post-tensioned connectivity, the cross-sectional geometry must remain constant between modules.

Figure 1. A concept for relocateable Modular Hybrid Pier.

Compared to a single-deck pier, the three levels of the MHP increase its efficiency:

- The bottom compartments are individually sealed for stable flotation.
- The middle (service) deck is for routing utilities to moored ships.
- The top (operations) deck is for cargo/personnel transfer and ship maintenance.

Separate bridge ramps connect the service and operations decks to shore. Instead of thousands of piles driven deep into the seafloor, water buoyancy supports the MHP vertically, as shown in Figure 2. Because it floats, the MHP avoids vertical loads from wave, tidal, storm surge, seafloor settlement, or sea-level rise and also avoids most of the mooring, fendering, and utility connection issues associated with tidal motion and changing water levels much like a modern yacht marina.

Figure 2. Sectional view through the modular hybrid pier.

The MHP concept shown has four vertical founding shafts along the pier's centerline to restrain horizontal motion that would result from wind, wave, current, and berthing. A minimum of two shafts provide the required horizontal resistance to normal low-frequency loads. The horizontal loads of the MHP are transferred to the founding shafts through rubber fenders, referred to as founding fenders, that comply with higher frequency seismic energy, thus naturally isolating the MHP from earthquakes. With a spread mooring replacing each shaft, the MHP could even be founded in very deep water.

Combining functional flexibility with durable construction, the MHP is a good example of a sustainable structure. It remains largely maintenance-free for 100 years, twice the life of a traditional fixed pier (Springston, 2004). Built in a certified fabrication yard, quality should be significantly higher. Built of pre-stressed and post-tensioned concrete panels with advanced corrosion protection, structural durability should also be significantly higher (Lanier et al, 2005). Built off site using much less embodied energy and generating much less pollution with many fewer seafloor piles, environmental impacts should be significantly less (Wernli and Springston, 2007). With a salvage value and minimal effort to relocate, the MHP should have a total life cycle cost significantly less than for a traditional fixed pier (Wernli and Zueck, 2008).

MHP Configuration

The U.S. Naval Facilities Command studied the piers at the naval bases in San Diego and Norfolk that are likely candidates for replacement in the near future. The study concluded that the piers slated for replacement can be accommodated by MHP configurations in three lengths (as shown in Figure 3) without exceeding the original pier footprints.

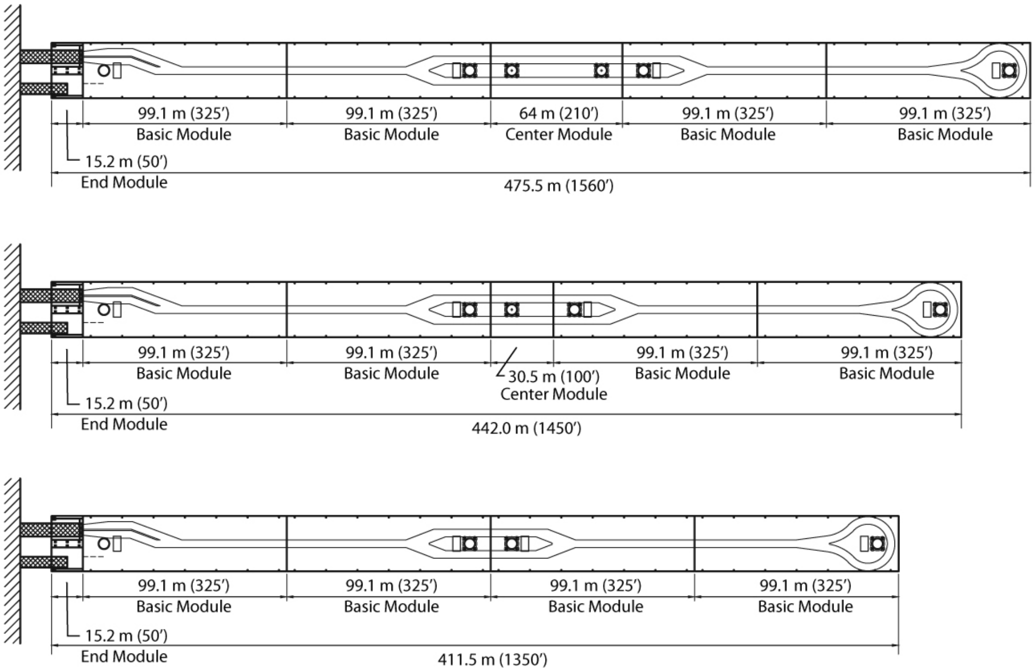

Figure 3. Typical pier configurations for different pier length using a variable length center module.

The overall goal was to define a typical configuration of modules that could be used for all of the pier lengths identified. The solution was to compose the piers of several modules of three types that could be configured to fit all pier lengths: a base module, an end module, and a center module. The base modules, which are 325 feet (99.1 meters) long, are the core building blocks of an MHP. They house all the utility hookups and generators. Four of these base modules, along with a 50-foot-long (15.2 meter) specialized end module to accommodate the access ramps, make up the shortest pier (1,350 feet or 411.5 meters) now being considered. Replacements for longer piers are made up of four basic modules and an end module plus a center module. For the 1,450-foot (442-meter) pier, the center module is 100 feet (30.5 meters) long. For the 1,560-foot (475.5-meter) pier, the center module is 210 feet (64 meters) long. The length of the MHP depends on its location, the length of the pier it will replace, and the mix of vessels that will berth at the pier.

Because ramp landings need to be designed to suit each specific site, rather than incorporating ramp supports and shore utility connections into the basic module, a separate end module was designed that accommodates these features. Making the end module a separate unit and accommodating all length variations in center modules allows greatest standardization of the basic module. Standardization allows reusing the individual modules and permits for repetitive fabrication, which is key to economy in precast production.

The design of the modules uses identical (or at least very similar) precast pieces as much as possible and minimizes the number of different pieces. For maximum economy, the arrangement of bulkheads in a module is as identical from one module to another as is practicable. For instance, relative to the end of the module the moonpool is in the same position in the basic module and the center module. This characteristic allows the use of identical precast panels and simplifies the connection of one module to another. Workmen will have to learn fabrication and assembly only once for all types of MHPs.

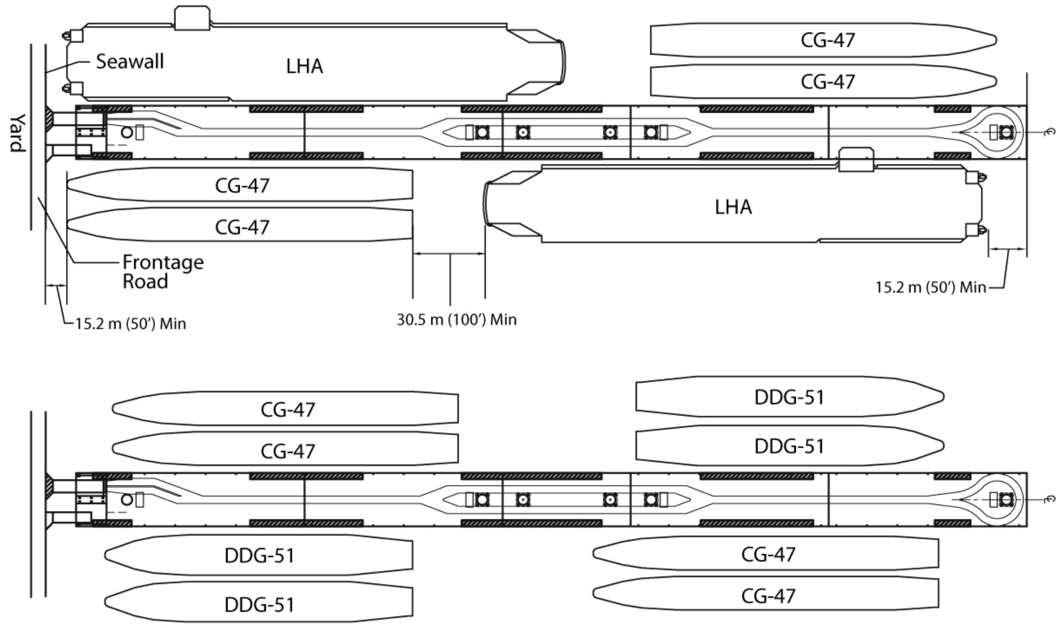

Figure 4. Typical maximum vessel nesting configurations for a pier 1,560 feet (475.5 meters) long, with larger amphibious vessels (top) and combatant vessels (bottom).

The MHP is designed to allow nesting of up to two surface combatants at all berthing locations. Only one ship per berthing location (no nesting) will be allowed for large vessels such as amphibious vessels (Figure 4). Per Unified Facilities Criteria 4-159-03, the basic design assumption for the MHP mooring is that berthed vessels will leave the MHP before an approaching large tidal surge, hurricane, or typhoon. Larger vessels leave the pier if the expended wind velocity exceeds 50 knots (25.7 m/s), thus mooring forces become manageable as the mooring of larger vessels typically drives the design.

The utilities are designed for cold-ironing all berthed vessels that are expected to be served primarily at the MHP and to allow servicing larger but fewer alternative vessels. The utilities required for the MHP will be coordinated through each basic module. Because the basic modules can be connected by either end to the adjacent pontoon, the utility conduit and piping will be identical on both sides of the pontoon. Bollards spaced according to Navy standards will be mounted on the edge of the operations deck. Ideally, all utilities will be hooked up at the service deck level to leave the operations deck uncluttered.

Modularizing and standardizing utilities is important in controlling capital and maintenance costs. Therefore, to the maximum extent possible, utilities are designed to the following principles.

- Use the minimum number of different components and the same pipe splicing spool elements.
- Use the same brand, size, and capacity where multiple units of equipment are needed.
- Arrange utility outlets and valves the same with the same fixtures for each location in each system.
- Configure hoses and cables to maximize interchangeability.
- Use components that have a good use history with the Navy.

Concept and Component Qualification

The MHP includes several innovative designs as part of its key components. They include durable marine concrete panels, holistic cathodic protection, post-tensioning concrete module connections, modularized pier hardware, reconfigurable utility lines, secure access ramps, and efficient mechanized ship mooring hardware. Several numerical models and physical tests qualified the performance of each innovative component and the overall pier concept.

The large-scale test bed with key characteristics of the full-scale MHP built in Tacoma was the most significant example (Figure 5). The test bed was subjected to a series of functional and structural tests to qualify each innovative component and the overall concept.

Figure 5. Test bed in place in San Diego, California.

Verification of Desired Floating Pontoon Performance

The test bed consisted of two short pontoon modules, floated and post-tensioned rigidly together to form a 100-foot (30-meter) long, 50-foot (15-meter) wide double deck pier. Made of post-tensioned concrete walls and prestressed concrete planks overlain with post-tensioned cast-in-place concrete decks, the fabrication of each pontoon included modern unconventional materials and panel tilt-up assembly (Lanier et al, 2005). Instrumented for seaworthiness, the test bed was towed over 1,200 miles (1,900 km) to San Diego. Measured data was used to calibrate numerical hydrodynamic models to assure stable towing in the open ocean for the full-scale MHP.

The basic MHP pontoon was analyzed extensively with the latest in finite element methods for all key design loads. For example, nonlinear tensioned membrane effects were included in the deck punching resistance to large crane outrigger loads.

The top deck of the test bed was load tested with a very large crane outrigger load near an outside window. At this location, the resulting membrane load distorts and rotates a beam across the window as the load travels down the pontoon wall into the water. As shown in Figure 6, several vertical rods (and strain gauges) measured deflections in the upper deck (and in the wall around the window).

Up to a safe maximum test load of 500 kips (2224 kN), the deck behaved in a linear manner up to this design capacity (Bogage et al, 2007). A nonlinear finite element analysis further estimated an ultimate load capacity of 1,872 kips (8327 kN).

Figure 6. Upper deck capacity test on test bed.

The MHP test bed is equipped with current flux and voltage potential sensors to characterize corrosion behavior and monitor protection of electrically isolated post-tensioning hardware, other concrete reinforcement, and the founding shafts. Each shaft has an upper stainless steel and lower regular steel section for the wet/dry and fully submerged corrosion zones, respectively. Corrosion behavior was compared to boundary element simulations and improved with better cathodic protection.

Verification of Pier Founding Performance

Figure 7 shows how founding shafts maintain the horizontal position of the MHP. Initial installation of the founding shaft consists of driving piles, fitting a pile cap form, lowering a reinforcement cage into the form, setting the lower section of the shaft, and pouring tremie concrete. Final installation consists of floating the pontoons in place, setting the upper section of the shaft, connecting both sections of the shaft, and installing four rubber founding fenders (shown as purple squares) around the shaft.

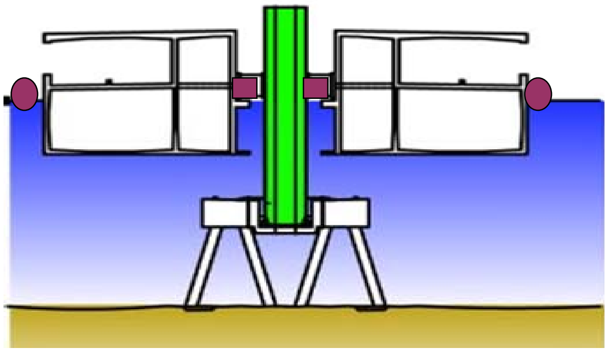

Figure 7. Horizontal founding system on MHP test bed.

To explore temporary, high-load behavior, short-term tests were performed on the fenders of the test bed (Lee et al, 2008). Hydraulic actuators applied compressive displacements to the fenders for multiple cycles. Uniaxial test data showed that the measured axial load-deformation relationship at low deformation levels is similar to that obtained from the fender manufacturer. Strength degradation occurred during high-displacement testing. Bi-axial test data showed that lateral forces significantly decreased the axial fender capacity. Friction between fenders and the mooring shaft was significant, although lower once sliding was initiated.

The fenders on the test bed were also subjected to long-term tests to study medium-load creep behavior and friction during tidal cycles (Lee et al, 2008). By using two weight blocks and a pulley system, a load was sustained on one fender for a prolonged period of time. A fender at 60% of design load capacity was tested. During the very first vertical tide cycle, the fender buckled horizontally as shown in Figure 8.

Figure 8. Fender of test bed failing long-term test in first tide cycle.

After chain restraints were installed to limit the amount of horizontal movement, all four fenders were tested to 25% and 60% of design load capacity. Although the fenders did not fail, the chain restraints caused more non-compliant frictional sliding than desired. Fender creep under sustained loading was minor.

The fenders should be stiff enough to resist low-frequency wind, wave, tidal, and berthing forces, but flexible enough to isolate the MHP from higher frequency seismic energy. Improved designs for the founding fender and its earthquake isolation ability are currently being studied for high cyclonic and high earthquake sites.

A numerical AQWA model of the floating test bed, as shown in Figure 9, was used to study the fluid forces and motion on each body of the MHP. Bodies 1 through 4 are the floating pontoon, the founding shaft, the bridge ramp, and the quay wall, respectively. Body 5 is a simple steel pile that roughly represents a second founding shaft and keeps the test bed from yawing out of position.

AQWA uses linearized potential theory to represent multi-body fluid flow hydrodynamics combined with nonlinear structural theory to represent multi-body interactions such as geometric articulation, mooring line tightening, fender contact, load-bearing friction, and fender buckling. The floating motion performance of the MHP will be analyzed further for the desired operational and survival design criteria.

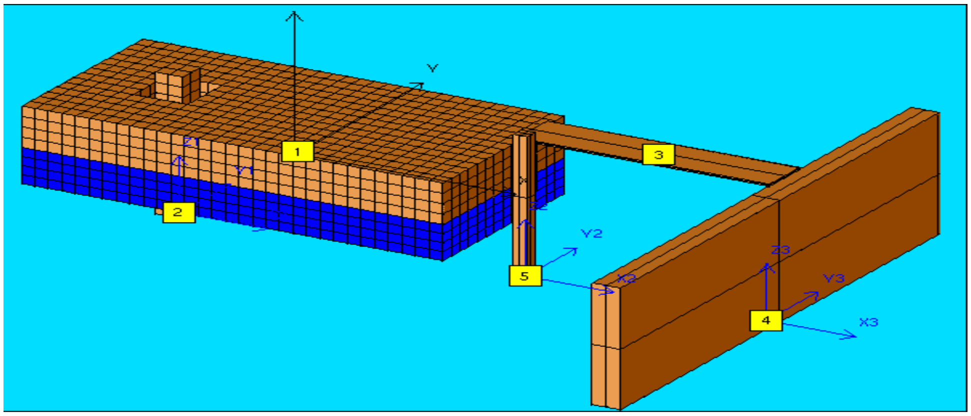

Figure 9. Hydrodynamic model with nonlinear structural components.

Sea level rise, land settlement, cyclonic storm surge, tsunami, harbor seiche, module towing, ship collision, seismic loading, and severe storm metocean loading are all possible risk factors for MHP survivability. Passing and berthing ships, operational loads, and normal metocean loading are all risk factors for how the pier performs and if there are any restrictions on pier operations.

Verification of Vessel Mooring Performance

Alternative methods of ship mooring are being considered for the MHP. For example, the fenders for mooring a vessel to a floating pier do not need to float. Ship mooring performance and related safe crane operation will be analyzed using AQWA hydrodynamic/structural models.

The effects of large-scale flow events, such as a passing ship, a harbor seiche, and long period swell, on the MHP and its client moored ship have already been studied. Closely imitating scaled physical modeling in a towing tank, these flow-field simulations used a special Chimera, Reynolds-Averaged Navier-Stokes-based viscous flow solver fully coupled with a three-dimensional ship motion tracer (Huang and Chen, 2003). Simulation results were governed by the overall geometry of the basin and relative ship layouts, not by the type of pier. As such, ship motion relative to a floating pier is generally either the same or less than that relative to a fixed pier.

The mooring bollards on the test bed consist of concrete-filled steel pipes welded to a base plate. Four bolts secure the base plate to a steel reaction plate underneath the deck. Using a wire rope wrapped around the bollard, a quasi-static load up to the maximum service load of 200 kips (890 kN) was applied to the bollard, as shown in Figure 10. No damage was observed in the measured linear behavior (Bogage et al, 2007). A nonlinear finite element analysis further estimated an ultimate load capacity of 1,000 kips (4450 kN), a load that yields the anchor bolts.

Figure 10. Bollard test on test bed.

Conclusion

As an alternative to the traditional pile-supported fixed berthing pier, the modular hybrid pier (MHP) is ready for deployment as a general use Navy pier. At many potential sites, the MHP has more structural efficiency, higher durability, lower environmental impact, and better sustainable functionality than a traditional fixed pier. Buildable off site, the MHP is a relocatable, reconfigurable floating structure that adapts to sea level rise, has higher quality with better material utilization, and provides better operational functionality.

With a construction cost equal to a fixed pier and with 100 years of maintenance-free life, the total life cycle cost of an MHP should be significantly less than that for a traditional fixed pier. Better founding fenders are being investigated for sites with very high cyclonic and earthquake risk. Providing reconfigurable utilities with higher capacities and diversity in modular form is also still being investigated, particularly for unconventional future Navy ship classes.

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