New Technologies Proven in Precast Concrete Modular Floating Pier for U.S. Navy

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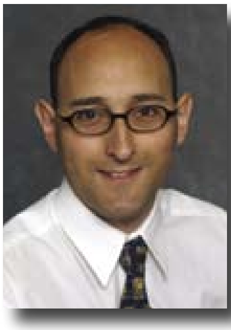

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Representing a breakthrough in naval vessel berthing infrastructure, a test bed structure for a large-scale modular hybrid floating pier was designed with state-of-the-art precast/prestressed concrete technology and a number of material and design innovations. In 2004, the $5 million 15.2 × 30.5 × 8.8 m (50 × 100 × 29 ft) test structure was fabricated, erected, and open-ocean towed to its final destination in San Diego, California, as proof of concept for a future $45 million, 400 m (1300 ft) long double-deck floating pier for the U.S. Navy. The Modular Hybrid Pier was conceived as a replacement for obsolete and deteriorating naval berthing facilities. Designed for 100 years of repair-free service, the pier will provide a high level of support services to a variety of vessel classes and facilitate a rapid upgrade of vessel utilities with the advance of fleet support system technologies. More than 25 government, university, and private entities collaborated to develop this groundbreaking concept in precast concrete pier infrastructure.

An innovative and efficient concept for a modular hybrid floating pier for the U.S. Naval fleet was first conceived in 1998 by a development team that included the Naval Facilities Engineering Service Center (NFESC) in California and BERGER/ABAM Engineers Inc. of Federal Way, Washington. The Modular Hybrid Pier (MHP) ushers in a new class of military ship mooring facility that incorporates state-of-the-art materials and the highest level of

Fig. 1. Floating precast concrete modular pier test bed on a 1770 km (1100 mile) open-ocean transport to its final destination at a naval base in San Diego, California, September 2004. *(U.S. Navy photo. Photographer: Erick Huang.)*

operational system technologies for all classes of naval vessels (see Figs. 1 to 4). Constructed with state-of-the-art post-tensioning reinforcement and post-tensioning systems, high strength lightweight concrete with corrosion-resistant steel reinforcement, and qualitative fault diagnostics and sensing, the MHP is designed to dramatically reduce the repair costs of traditional docking facilities by up to 80 percent and deliver a service life of 100 years.

In addition to operational flexibility and a significant reduction in maintenance costs, the MHP takes maximum advantage of high performance lightweight concrete (HPLWC) and high strength corrosion-resistant steels to maximize its service life while offering an initial cost that is comparable with conventional steel reinforced concrete pier construction. Sponsored by the Office of Naval Research (ONR) under its program for Total Ownership Cost Reduction, requirements for new major combatant vessels of the 21st century shaped the modular pier's geometry and structure, enabling the MHP to meet evolving berthing and shore-side support needs for the U.S. Naval fleet.

U.S. NAVY DEVELOPS NEW TECHNOLOGIES

NAVFAC is leading a consortium in the development, testing, and evaluation of concepts and materials technology for a new generation of berthing piers. Leading this advance in naval infrastructure technology is NFESC, located in Port Hueneme, California. NFESC contracted with BERGER/ABAM Engineers in 1998 to develop the MHP concept and provide test support.

Integrated Product Team

The MHP concept was further advanced by the guidance of an Integrated Product Team (IPT) that was composed of leading experts experienced in port operations, public works, construction materials, systems modeling, testing, and pertinent technical disciplines in various fields.

Because NFESC develops new technologies for use in Navy infrastructure, much of NFESC's activity and funding is focused on research and development—specifically, project implementation to prove out appropriate new technologies that can be reliably incorporated in typical design/bid/build and design/build procurements in a low risk manner. Products or processes that have problems in implementation or operation in the production environment can represent significant cost or maintenance risks that NFESC seeks to avoid by the evaluation work it performs.

The IPT's approach as implemented by NAVFAC took a proven systems development method (used by the Department of Defense for acquisition of complex weapons, ships, and aircraft) and effectively applied it to development of an innovative naval facility concept. IPT methodology is a structured approach for soliciting multidiscipline input in the form of requirements and concerns that are then either systematically included in the project design criteria or become the subject of special studies to determine, for example, the validity of a stated concern.

Naval Infrastructure and Mission Performance

Fiscal concerns and mission performance were the forces that impelled the

Fig. 2. Isometric rendering provides a visualization of the completed, full-scale modular hybrid pier (MHP) in operation.

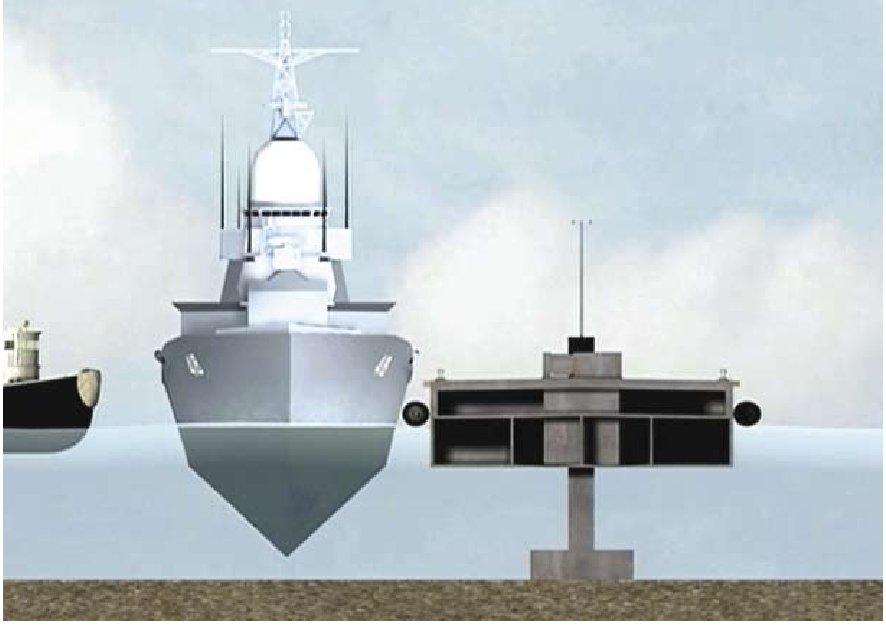


Fig. 3. Sectional view provides perspective of MHP in service with vessel moored at pier.

Navy to seek state-of-the-art technologies. U.S. Navy waterfront structures represent a significant capital investment and constitute a disproportionate amount of the cost of real property maintenance because of the harsh marine environment in which they are located. The Navy will spend about $70 million in the 2005 fiscal year on repair for aging piers and wharves. There is also a significant backlog of naval pier repair projects that require funding to increase readiness.

The Navy typically budgets for construction of about four piers or wharfs annually to replace or modernize its waterfront infrastructure. The Navy owns 145 berthing piers and wharves of a size equivalent to a two- to four-module MHP; of these structures, 59 percent are over 50 years old—nearing the end of their service life. Based on these fiscal and military imperatives, naval waterfront structures present an excellent rationale and opportunity for implementing new technologies. In this article, the authors describe the concept, design, innovations, production, construction, project challenges, and future plans for the MHP.

MHP CONCEPT AND RATIONALE

NFESC developed the MHP concept to offer vastly improved design alternatives to traditional pile-supported berthing structures.[1-6] The purpose of the MHP project is to provide the following advantages over conventional docking facilities:

1. Repair-free service life of 5 to 100 years.
2. Functional flexibility to accommodate, or berth, a range of Navy surface combatant vessels that have different demands for utilities and access.
3. Mobility to allow the Navy to move or reconfigure a pier as base mission changes dictate. Production and fabrication of the MHP off-site ensures reliable quality control, pier mobility, lower costs, minimal disruption to naval station operations, and reduction of adverse environmental impacts to marine ecosystems.

As a result of these challenging requisites, the modular hybrid floating pier concept needed to be virtually independent of on-site parameters, such as harbor soil conditions, daily tidal fluctuations, seismic forces, and climatic conditions. A major feature of the pier is that the use of high quality plant-cast precast concrete would be key to attaining the exceptionally long life for this marine structure.

The MHP concept is based on using four individual, standardized, double-decked floating pier modules structurally joined together to create a single structure. The MHP test bed was constructed and prepared for towing at a cost of $2.7 million; this is the value of the package provided by the precaster. Installation on site will involve another $2.3 million for a total cost of $5 million. The test bed prototype structure is 15.2 m wide, 30.5 m long, and 8.8 m deep (50 × 100 × 29 ft).

A full-scale pier production version would cost $45 million and would typically be composed of four 99 × 27 m (325 × 88 ft) modules joined together (while afloat) to form a 396 × 27 m (1300 × 88 ft) production berthing pier—although modules can be added or subtracted to adapt to changing homeport requirements. Approximately $25 million of the total production structure cost would be the precast concrete contract. The production version is configured to provide 10,590 m^2 (114,000 sq ft) of operations deck space, 5760 m^2 (62,000 sq ft) of service deck space, vessel berthing provisions, and all utilities to service a wide range of combatant vessel classes. The size and configuration of the operations deck will allow semi-trucks and trailers to enter the pier, unload, and turn around on the pier prior to exiting.

Off-site construction means these new pier modules can be fabricated in one or more precasting facilities located near a drydock facility; this means the MHP can be assembled anywhere along the coast, towed to any Navy harbor site, and joined in specified configurations. Off-site fabrications afford the significant advantage of minimal service interruption to an existing naval base, as facility disruption is limited to the time required to demolish the old pier and install the mooring for the new MHP.

Modules are designed to be disassembled and reassembled for relocation to ensure future optimization of regional infrastructures assets. MHP mobility reduces the risk that the Navy may have to abandon and reconstruct valuable pier assets if a shift in homeport assignments occurs.

In addition to its inherent mobility, the MHP concept provides additional practical benefits. Previous pier designs were of fixed height, which meant large diameter camels to provide stand-off of the ship hull and superstructure from the pier and complex brows (platforms) for ship access from the dock at any tide condition. Conventional naval piers are typically supported by more than 700 bearing piles, driven into what is usually poor and uncertain foundation material. Conversely, the flexible MHP design does not require the driving of hundreds of piles for pier substructure support. The ability of the MHP to maintain a constant elevation with its berthed ships simplifies cargo and supply transfer, mooring line handling, vessel fendering, and utility cable and hose routing from the pier to the vessel.

Part of the rationale that generated the MHP concept was the elimination of costly construction and maintenance of support and fender piles of conventional docking facilities. With the floating modular design, floating foam-filled fenders are positioned along the MHP's exterior walls to interface with the ship's hull, and internal fenders at mooring shafts absorb impact energy from vessel mooring, thereby providing optimum flexibility in the range of ship classes that can be berthed and serviced (see Fig. 3).

The MHP's elevation fluctuates with the tide, maintaining a constant relative distance, or standoff, from ship decks to the pier deck. This reduces dockside labor spent in tending bows, mooring lines, and utility cables. As ships can be berthed at less standoff, there is no risk that flared hulls or ship appendages will contact the pier as the tide drops.

The MHP itself is moored by two to four steel shafts founded in underwater pile dolphins. Each dolphin consists of a pile cap into which the mooring shaft is embedded, typically at the elevation of the sea floor, and 8 to 15 piles depending on local geotechnical conditions. The number of moorings and their foundation detail design depends on site-specific geology and environmental loads; mooring shaft foundation design is the only portion of the MHP that is "site adapted." Buckling rubber fenders located at the centerline of mooring wells in each floating module absorbs energy and limits pier longitudinal and lateral motion. The mooring design also isolates the MHP from potential seafloor seismic ground motion; therefore, it can be sited in areas of high seismicity without incurring costs for seismic structural strengthening.

The full-scale MHP is designed to berth up to eight destroyers at one time. Naval vessels are moored two deep with four ships on each side of the pier. Destroyers are typically 165 m long × 17 m wide (560 × 55 ft). The pier is also designed to handle large Navy surface combatants and amphibious ships with a typical size of 253 m long × 40 m wide (830 × 132 ft). A variety of different combinations of berthed vessels were used to determine utility configurations and utility system capacities to ensure that the full range of possible vessel berthing configurations could be accommodated.

MHP modules are double-decked for efficient ship support. Ship berthing, resupply, and intermediate maintenance are conducted on the topmost, or operations, deck. Ship support utility services (potable water, power, sewerage, communications, and air) are on the lower service deck. Efficient vessel support reduces costs associated with

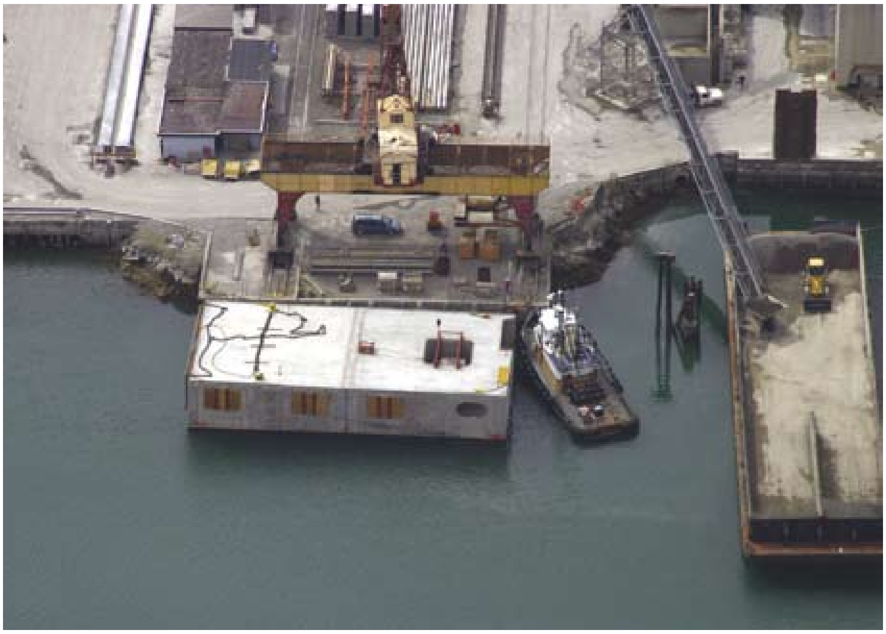


Fig. 4. MHP at Concrete Technology Corporation's Tacoma, Washington, facility provides good perspective of 15.2 × 30.5 × 8.8 m (50 × 100 × 29 ft) dimensions of the test bed.

ship berthing, repair, and maintenance. This arrangement leaves the operations deck uncluttered for operation of multiple 127 metric tonne (140 ton) mobile cranes. Utilities, all surface mounted in a large dedicated utility corridor, are readily accessible for maintenance and eventual change-out to meet new ship requirements. The life-cycle savings for each floating pier structure is projected to be on the order of $15 million.

DESIGN PHASES AND STANDARDS

Phase I of the MHP concept development in 1999 included consideration of:

1. Fixed versus floating pier;
2. Use of composite materials;
3. Durability issues;
4. Functional and structural configurations;
5. Mooring configurations;
6. Cost considerations; and
7. Wall panel concept validation.

The Phase II predesign in 2001 included development of:

1. Operational and structural criteria;
2. Preliminary floating module design;
3. Mooring and access ramp design;
4. Criteria for utilities; and
5. Cost estimates.

During the Phase III test bed module creation in 2004, NAVFAC IPT analyzed the following risk reduction issues:

1. Durability and corrosion, including high durability concrete, mooring, utilities, and appurtenances;
2. Constructibility factors, including tolerances and quality control; and
3. Service performance with modeling and simulation for load response, motion, and fatigue.

The objective of the MHP test bed design, construction, and testing program was to demonstrate 75- to 100-year durability, constructibility, structural and hydrodynamic performance, acceptable ramp motion, and utility flexibility.

Panel Design

The exterior precast concrete wall plates of the structure are designed to resist local hydrostatic forces, and the pier as a whole acts as a girder to resist global wave bending, lateral vessel berthing forces, and lateral forces resulting from design wind on the berthed vessels and the pier itself. The exterior wall plates are also designed to resist the forces associated with pneumatic fender reactions located at the waterline at any longitudinal location along the hull.

NFESC considered several durable materials for the design of the modules, including lightweight concrete with a high fly ash content, carbon fiber reinforced polymer (CFRP) reinforcement, stainless steel reinforcement, and epoxy-coated reinforcement. The modules are compartmentalized, whose hulls are made of bidirectional post-tensioned lightweight precast concrete panels (see Figs. 5 to 9). The

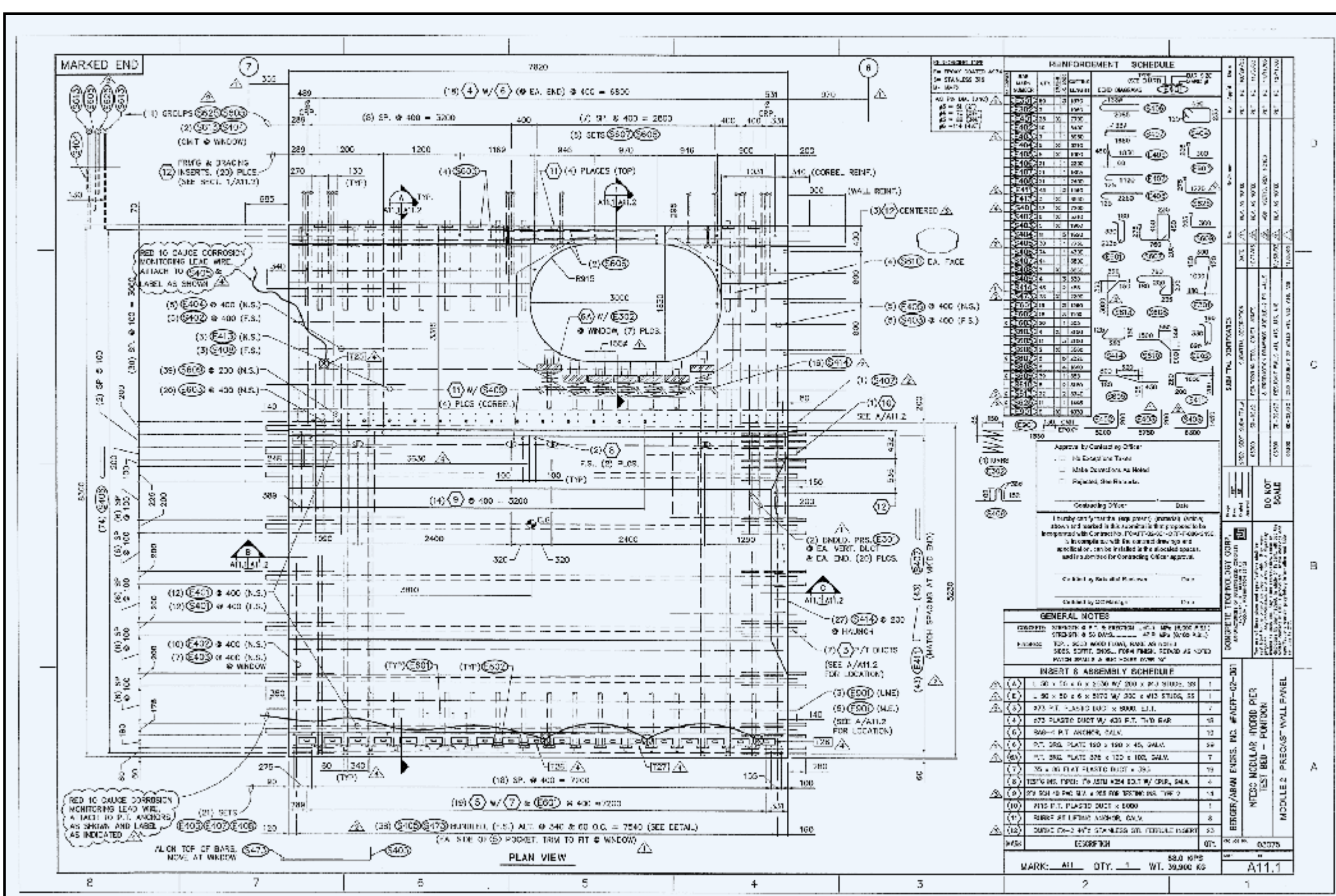


Fig. 5. Plan drawing of Module 2 precast concrete wall panel.

panels were manufactured at a PCI-certified precast concrete manufacturing facility. It was important that the panels achieve a very high and consistent product quality, tight construction tolerances, and uniform surfaces.

Panel post-tensioning functioned as the principal reinforcement to resist local stresses from hydrostatic pressure, as well as the global membrane forces from bending of the entire structurally continuous multi-module hull. Under full service loads, the module panels maintain a compression zone under bending or decompression stresses at any given section cut. In this way, the panels retain their water-tightness by ensuring that no through-cracks develop.

Limited tensile stresses were allowed in the panel section tensile zone, requiring rigorous service design criteria on maximum tensile strain. Because of this criterion, tensile stresses typically governed the design of the panels. Supplemental grid reinforcement was added close to the panel surface to control cracking and provide resistance from local overloading. Because of the relatively small hydrostatic forces, the thickness of the precast concrete panels was mainly a function of the space required to accommodate the post-tensioning and grid reinforcement with sufficient concrete cover.

MHP Benefits

The following benefits and advantages are an inherent part of the MHP design:

1. Standardization of modules used from one pier project to the next;
2. Faster and higher quality construction;
3. Minimal maintenance over the life of the structure;
4. Efficient ship support for a wide variety of vessels;
5. Design flexibility and functional adaptability to accommodate new vessel technology;
6. Minimal adverse environmental impact due to over-water construction;
7. Ability to relocate in the event of homeport mission change;
8. Less standoff needed to accommodate flared hull clearance, thus reducing the necessary lift radius for cranes;
9. Multiple crane operation and berthing can occur at the same time;
10. Unobstructed operations deck allows more efficient vessel supply and maintenance;
11. Space for utilities growth to accommodate changing vessel needs;
12. Seismic forces isolated to full-scale mooring design;
13. Impact energy absorbing fenders that can be located anywhere on the perimeter of the MHP;
14. Watertight precast concrete compartments to enhance damage stability;
15. Single steel mooring shafts that allow vertical movement while restraining lateral and longitudinal motions;
16. Repair pier capacity equal to that of larger double decked fixed piers; and

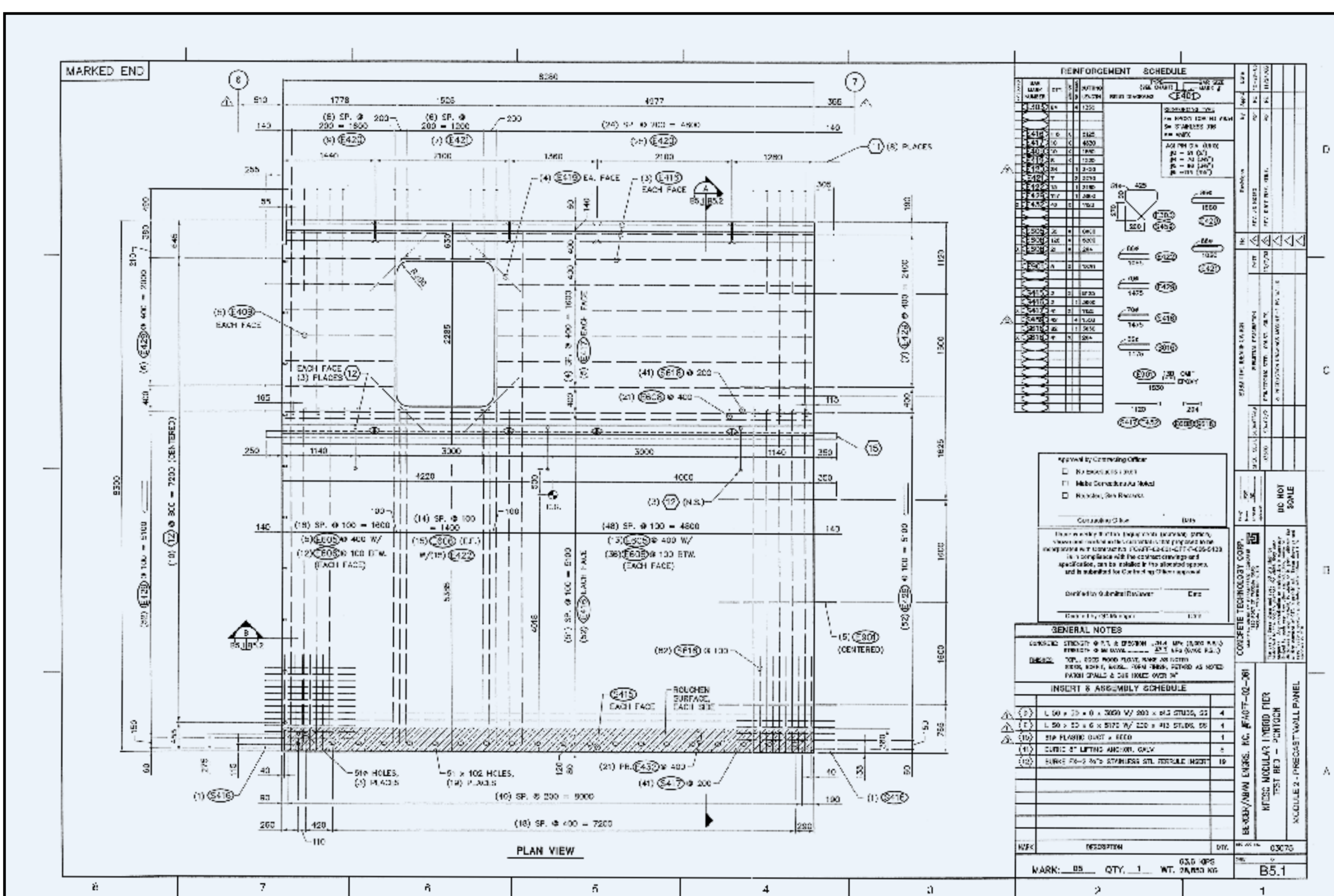


Fig. 6. Plan view of Module 2 precast concrete wall panel.

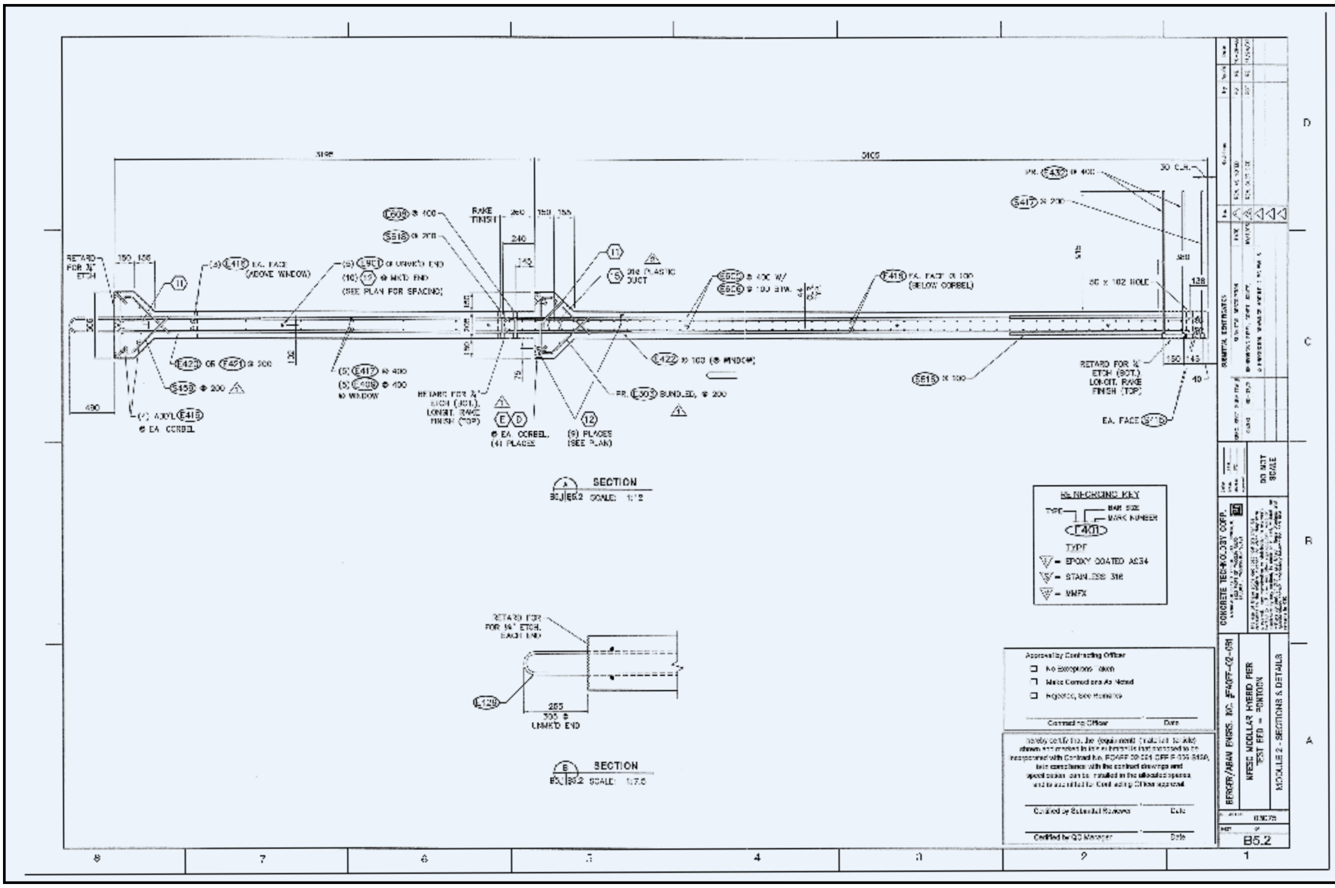


Fig. 7. Section and detail drawing of Module 2 precast concrete wall panel.

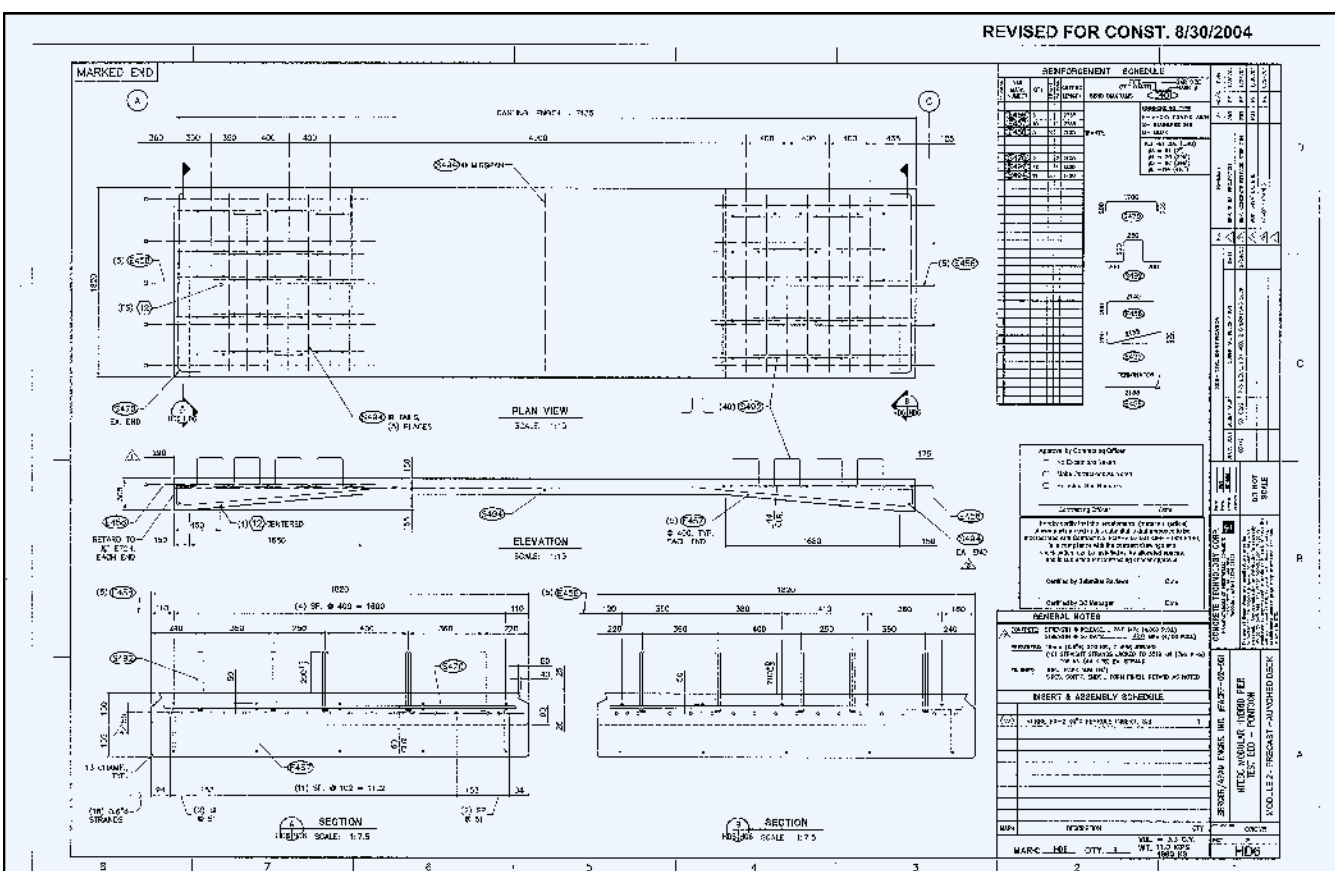


Fig. 8. Plan and sectional drawings of Module 2 precast concrete haunched deck.

17. State-of-the-art utility galleries directly accessible for routine maintenance.

Design Codes and Standardization

The design of the MHP test bed was based on the provisions of ACI 318-02 and ACI 357R-84.[7,8] Both codes together, however, were not sufficient to serve as a basis for design of the floating pier. Therefore, a project-specific basis of design was established that complements the codes for requirements regarding allowable stresses to achieve watertightness (no through-cracks) and durability.

The modified PCI *Manual for Quality Control for Structural Precast Concrete*[9] was developed by the design team, with permission of PCI, and tailored to include additional items that were specific to the MHP project. This became the quality control manual for the production of the MHP test bed.

There were standardization issues in testing the electrically isolated post-tensioning tendons. The test methods for verifying electrical isolation of these tendons were refined during the MHP project and will likely be refined further on future projects using this technology. Encapsulated and electrically isolated tendons are an emerging technology and will need standardization in the near future.

The decision to use MMFX-2 reinforcing steel was made after a Navy and consultant review of a number of conflicting research reports on the performance of this material. In the end, it was determined that the use and evaluation of this material was a good investment and would provide valuable information to guide future Navy decisions about wider use of this material for marine applications.

Mooring Design

The possible magnitude of a seismic seiche was considered in the development of the mooring system. It was found that the seiche for the locations considered was significantly less in terms of water elevation change that was the storm surge criteria for U.S. east coast locations subject to hurricane storms. The storm surge is handled by adding length to the mooring shafts and designing the shaft and shaft supports for the higher moments associated with the longer shaft length.

Note that tsunami effects were not considered in the initial conceptual design; however, the effects of extreme storm tidal surge on the facility would be similar to that of a tsunami. The response of the MHP and berthed ships to long period waves propagating within San Diego Bay is being modeled by NFESC and Texas A&M University.

The mooring approach for the MHP incorporates large Trellex fenders that attenuate the loads from berthing ships as they are transferred from the vessel fendering system at the perimeter of the MHP through the deck diaphragms and into the mooring shafts. The maximum likely displacement associated with a design earthquake was determined (for a 2500-year return event in Southern California) at 765 mm (30 in.); Trellex fenders located between the stationary mooring shafts and the MHP floating structure that provide a near constant reaction force over a 765 mm (30 in.) excursion were selected for use.

The result of this approach is that the facility is essentially isolated from the effects of strong seismic movements. Thus, an MHP designed for a non-seismic area can remain structurally unchanged when moved into a seismic area; this is one of the important benefits of the concept.

MATERIAL AND DESIGN INNOVATIONS

100-Year Service Life

For this project, the quality of the HSLWC had to be sufficient to ensure 100 years of pier service life. The HSLWC used manufactured lightweight aggregate, a high fly ash content, corrosion-resistant MMFX-2 and stainless steel reinforcement, and a post-tensioned superstructure.

The concrete mixture had to meet critical technical specifications: lightweight aggregate; 25 to 40 percent ASTM C 618 Class F fly ash (by mass of cementitious materials); a *w/cm* of 0.28; a concrete compressive strength of 28 MPa (4000 psi) at 16 hours and 48 MPa (6960 psi) at 56 days; splitting tensile strength of 4 MPa (580 psi) at 28 days; a modulus of elasticity of 19,700 MPa (2860 ksi) at 28 days; a prestress loss not greater than 23 percent; no shrinkage cracking; ease of concrete pumping; and durability based on testing and durability modeling results.

Low permeability to chloride ions was set at less than 1500 coulombs per ASTM C 1202 (actual rapid chloride permeability values from production: 845 coulombs at 60 days and 490 coulombs at 180 days). Local normal weight fine sand was used in the HSLWC mix, with expansion less than 0.08 percent in 14 days when tested ac-

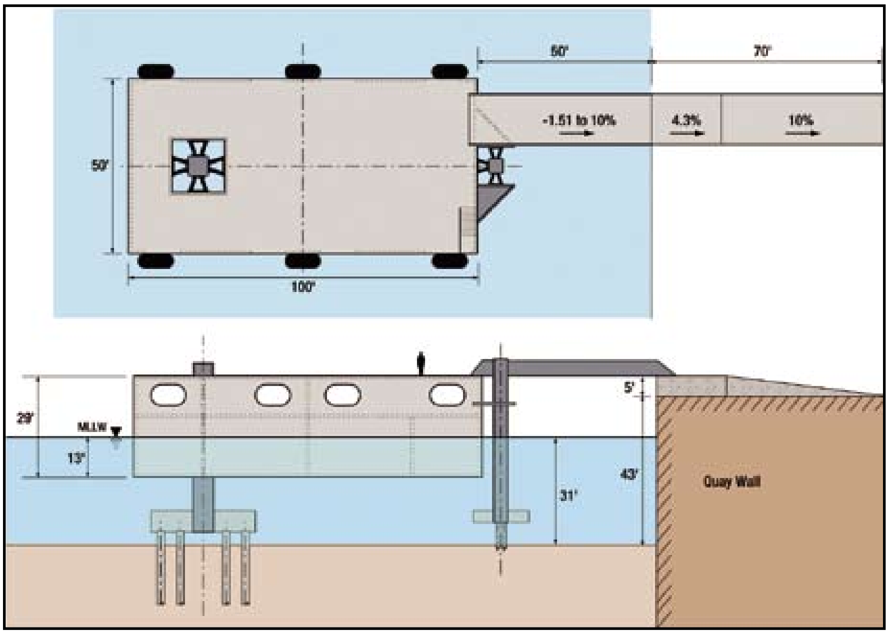


Fig. 9. Plan and section isometric views of the test bed illustrate the general dimensions and orientation of the MHP to dockside and the steel mooring shaft.

Fig. 10. Manufactured lightweight aggregate was used in a durable concrete mix that attained an average compressive strength of more than 50 MPa (7.5 ksi) after 56 days.

cording to ASTM C 1260. Maximum unit weight for the concrete was 1954 kg/m^3 (122 lb per cu ft).

The HSLWC mixture was designed to be durable and adequate for the saline marine environment. The concrete was required to be high slump and to be able to flow without segregation around the reinforcement, with little external vibratory compaction. The lightweight aggregate, normal weight sand, fly ash, and additives were used to increase flowability and cohesion, and the maximum aggregate size was limited to 16 mm (5/8 in.). The concrete reached an average strength of more than 50 MPa (7.5 ksi) after 56 days (see Fig. 10).

These technical parameters for the concrete mixture were achieved in fabrication and testing of large prestressed concrete panels manufactured by Clark Pacific Inc., Fontana, California; Coreslab Inc., Perris, California; and Bellingham Marine, Inc., Bellingham, Washington. Two west coast lightweight aggregates—Realite, a product of TXI, Boulder, Colorado, and Utelight, a product of Utelight Corporation, Coalville, Utah—and an East Coast aggregate, Stalite, a product of Carolina Stalite Company, Salsbury, North Carolina, were used in the panels. The panels produced by Clark Pacific, Inc., using Stalite aggregate, met all structural and durability performance requirements. The resulting HSLWC mixture was highly impermeable to chloride ions and highly resistant to alkali-silica reactivity (ASR), affordable, and extremely durable.

MMFX-2, Stainless Steel Reinforcement, and Corrosion Resistance

At the time of selection of the corrosion-resistant reinforcement material in 2002, all composite reinforcement arrangements considered appeared to be at least three times more expensive than a stainless steel grid (see Reference 10). Furthermore, there were some practical hurdles to overcome in order to apply CFRP reinforcement in the MHP, such as how to detail connections and splices.

Fig. 11. External panel reinforcement shows arrangement of corrosion-resistant metals selected to achieve 100-year repair-free service life of HSLWC: (Type 316) stainless steel and fusion-bonded epoxy-coated steel.

The preferred reinforcement material was stainless steel due to its cost advantage at a similar corrosion protection level compared with CFRP. During the design phase of the MHP test bed, however, it was recognized that the reinforcement ratio was much higher than anticipated. This was in part because of the increased demand on mild steel reinforcement after increasing the concrete cover requirement (thus reducing the effective structural depth for the reinforcement) and also because of the high demand for splicing and connection reinforcing steel typical for such a modular construction process with small panel sizes used in the MHP test bed.

It was found that the cost premium for having a structure exclusively reinforced with stainless steel reinforcement was unacceptable. The resultant design compromise was to use stainless steel reinforcement only at concrete surfaces that were subject to salt water, including all external hull surfaces and decks. The remainder of the structure was to be built with the less expensive epoxy-coated steel reinforcing bars. This model-supported, selective approach would lead to savings of about $1.6 million in a prototype (full-scale) pier compared with use of all Type 316 stainless steel reinforcement.

In an additional effort to reduce costs, it was decided to build half of the structure (Module 1) using MMFX-2 reinforcement in combination with conventional post-tensioning. This decision resulted in a somewhat reduced structural durability for the marine application, and a reduced service life demand of 75 years. The 2002 unit prices for the different reinforcing bars considered, excluding handling, installation, and markups, were as follows:

- Stainless steel: $4.50/kg ($2.04/lb)
- Epoxy-coated steel: $1.34/kg ($0.61/lb)
- MMFX-2: $1.34/kg ($0.61/lb)

MMFX-2 has a carbon content of 0.05 to 0.09 percent, a chromium content of 8.5 to 10 percent, and a corrosion-resistant microstructure. MMFX-2 steel has an ultimate tensile strength of 1034 MPa (150 ksi) and provides some economic advantage from the overall use of less steel. MMFX-2, however, requires more concrete cover than stainless steel—about 45 mm (1.8 in.)—to attain the threshold service life of 100 years (see the section on "Modeling" for rationale in choosing reinforcing materials for the project). This project represents the largest marine application to date of MMFX microcomposite reinforcing steel.

Two alternative steel reinforcement systems were evaluated for use in the MHP test bed: selective use of Type 316 stainless steel for outer mats with 25 mm (1 in.) of concrete cover, and fusion-bonded epoxy-coated (ASTM A934) steel for inner mats with 38 mm (1½ in.) of concrete cover. The epoxy coating ensures against creation of galvanic macrocells where bars of two dissimilar steels overlap. The second system of reinforcement was the use of MMFX-2 steel, a product of MMFX Steel Corporation, Charlotte, North Carolina (a subsidiary of MMFX Technologies, Irvine, California), for all the non-tensioned steel.

Although MMFX-2 reinforcement required more concrete cover, its use simplified the precast concrete panel setup and saved about $2.8 million in a prototype pier compared with all Type 316 stainless steel reinforcement. Each of the two corrosion-resistant reinforcement strategies was evaluated in the MHP test bed so that either could be incorporated in a prototype structure. Test Bed Module 1 was constructed with selective use of Type 316 stainless steel reinforcement and fusion-bonded epoxy-coated reinforcing bars (see Fig. 11). Test Bed Module 2 was constructed solely with MMFX-2 reinforcement. The MHP test bed reinforcing steel and post-tensioning systems are instrumented for monitoring long-term corrosion performance.

Post-tensioning provides the primary reinforcement and places module concrete in compression. This limits formation of cracks that would accelerate chloride intrusion. Tendons and anchors have 51 to 127 mm (2 to 5 in.) of concrete cover, depending on location. Supplemental non-tensioned reinforcement provides strength for precast panel handling during fabrication and for local service loads. The non-tensioned reinforcement had a minimum concrete cover between 25 and 45 mm (1.0 and 1.8 in.), depending on the steel type to reduce the weight of the floating modules. Given the relatively slight concrete cover and durability objectives, the supplemental reinforcement elements need to have a high corrosion threshold and low rate of corrosion.

Electrically Isolated PT System

The electrically isolated PT system for the test bed was supplied by VSL International. Encapsulated and electrically isolated tendons were developed and tested in Switzerland in the early 1990s. These tendons can be connected through a lead wire to enable impedance measurements that give insight into the tendon's initial quality after construction and its durability over time. The technology has been applied mainly on bridge and retaining wall structures in Europe and has been standardized by the Swiss Railways. The evaluation process for impedance measurements is very specific for each tendon type, and each product needs to be separately tested to define the performance requirements. If a high electrical isolation standard is to be achieved, the use of encapsulated and electrically isolated tendons can burden the contractor with a rigorous quality control on the tendon installation. The problem is that only the impedance measurement of the stressed, grouted, and cured tendon gives the true value of the achieved performance, and at that point in construction, any needed repairs would be very difficult and expensive. The practical goal, therefore, would be to negotiate the expected passing rate of tendons to meet the performance requirements with the contractor; a passing rate of more than 90 percent would be desirable.

However, since this technology was not a common practice at the time of the MHP test bed construction, there was concern that a contractor would add a high risk premium before committing to such a requirement. For this reason, and because of the small number of electrically isolated tendons, the requirement of a passing rate was omitted for the MHP test bed construction (see Fig. 12). Data were collected to provide experience on actual impedance values that could be attained with the post-tensioning systems used.

Fig. 12. The second module used a combination of encapsulated post-tensioning tendons and anchors and encapsulated, electrically isolated tendons.

MODELING PROGRAM

Concrete Cover for Corrosion Protection

Long-term behavior of HSLWC exposed to seawater was predicted using a numerical model called STADIUM (software for modeling, transport, and degradation in unsaturated materials).[11-13] STADIUM predicts ionic transport in unsaturated porous media, and it accounts for the effects of dissolution/precipitation reactions on the transport mechanisms. Outputs from STADIUM include a time-phased prediction of chloride/hydroxide ion migration and of expansive compounds that form from the reaction of seawater with the concrete constituents.

The STADIUM model predicted chloride concentration with depth and time and chemical reactions within the concrete with time that could cause deleterious expansion and cracking, and provided the rationale for the eventual selection of reinforcing materials and associated values of concrete cover. STADIUM predictions were compared with chloride corrosion thresholds and corrosion rates to estimate time to steel corrosion and concrete cracking, relative to the desired service life. It was concluded that uncoated conventional black steel reinforcement would not provide the necessary time to initiation of concrete cracking to provide the planned 100-year service life.

The decision on material selection—MMFX-2 (ASTM A1035), fusion-bonded epoxy-coated (ASTM A934M) steel, and Type 316 Grade 520 stainless steel (ASTM A955M)—was based on economics. Although Type 316 stainless steel provided the best corrosion performance, it was deemed to be cost prohibitive as the sole reinforcement material for the project.

During its development, STADIUM was validated with laboratory test results and by NFESC,[13] and later by NFESC prior to use of STADIUM in the MHP project. Samples were also taken to establish the current condition of a floating boat dock that had been exposed to marine conditions in the Pacific Ocean since its construction in 1978 in the Port of Seattle, Washington. The current measured condition (chloride content, concrete decomposition) was compared with STADIUM prediction of condition derived from input of known concrete qualities at time of construction.

TESTING AND INSTRUMENTATION

Structural testing provisions in the MHP test bed included built-in reaction fixtures, mooring module interaction, exterior bulkhead performance (simulated mooring loads), and embedded strain monitoring in the MHP test bed keel. Durability monitoring included reinforcing bar corrosion, post-tensioning electrical isolation, and mooring system corrosion.

Corrosion-resistant reinforcement for Module 1 included MMFX-2 reinforcing bars, bare steel post-tensioning anchors, and galvanized steel tendon ducts. Module 2 included stainless steel reinforcement, fusion-bonded epoxy-coated reinforcing bars, galvanized and encapsulated post-tensioning anchors, and plastic tendon ducts.

The MHP test bed was instrumented with concrete strain gauges to monitor the stress changes in selected concrete panels and with corrosion initiation instrumentation on different areas of various reinforcement and post-tensioning types. The instrumentation will be monitored by NFESC on a regular basis over the next decade. Early feedback from the instrumentation will be used to make modifications to the design of the prototype MHP.

The test bed contains strain sensors (vibration wire sensors) in the keel slab and wires to reinforcing steel and post-tensioning anchors in selected areas of all walls. In addition, all encapsulated and electrically isolated tendons are provided with a lead wire. The wiring of the reinforcement and anchor heads permits the Navy to measure changes of the differential electrical potential between the steel and a testing anode. This instrumentation configuration allows monitoring of both the onset and the speed of corrosion over time. The MHP monitoring is expected to be conducted over several years.

The test bed is also equipped with all of the structural inserts necessary to allow the Navy to conduct structural testing while the test bed is afloat. Potential structural testing includes a crane outrigger load of 1512 kN (340 kips) on the deck, a maximum fender load of 1415 kN (318 kips) on the external wall, a 1547 kN (348 kips) lateral load on the primary mooring assembly, and an 890 kN (200 kips) load on the bollard.

Production Testing of CFRP Grid Reinforced Concrete Panels

Initial consideration of the use of CFRP reinforcement allowed less concrete cover than normal. This reduction in cover decreased the panel thickness and weight of the draft of the structure. A typical marine structure would be designed with 75 mm (3 in.) of concrete cover. In the preliminary MHP conceptual design, however, the concrete cover was reduced to 13 mm (0.5 in.), a reduction of 83 percent. A panel thickness as small as 200 mm (8 in.)

Table 1. Cost comparison of different reinforcement grids (in 2001 dollars).

Material	Grid size in. (mm)	Stiffness ratio[1]	Strength ratio[2]	Grid cost \$/sq ft (\$/m^2)
Black steel grid Grade 60	W4–4/4 (Ø5.7–50/50)	1	1	0.30 (3.00)
Stainless steel grid (SS316, SS2205)	W4-4/4 (Ø5.7–50/50)	1	1.25 to 1.5	2.50 (27.00)
GFRP reinforcement bars (glassforms)	Ø0.3–6/6 (Ø8–150/150)	0.90	4.3	8.60 (94.00)
CFRP fine grid (NEFMAC)	C6–2/2 (C6–50/50)	0.69	4.1	6.80 (73.00)
CFRP coarse grid (NEFMAC)	C6–2/2 (C6–50/50)	1.23	7.5	11.20 (121.00)
CFRP reinforcement bars (Reichold C-rod)	Ø0.375–6/6 (Ø9.5–15–/150)	1.11	8.7	12.00 (129.00)

Note: [1] × 3480 kip/ft (× 50.7 MN/m); [2] × 7.2 kip/ft (× 105 kN/m).

was achievable and still accommodated all the layers of reinforcement.

A prototype panel was designed using a fine CFRP grid reinforcement with minimum concrete cover. The bar spacing of the grid was minimized to improve crack control. As the CFRP grid reinforcement was expected to prove effective as crack control reinforcement, this meant that larger reinforcement tensile strains could be permissible at service levels to better use the high strength of the composite material and to increase the efficiency of the design.

The prototype panels—designed using a fine CFRP grid reinforcement with minimum concrete cover—were tested at the University of Wyoming at Laramie.[10] The structural testing program showed that the composite grid reinforcement can increase the ultimate strength of the panel by 30 percent compared to precast concrete panels reinforced with conventional steel welded wire fabric. Crack widths could be kept below 0.25 mm (0.01 in.) at a load level up to 60 percent of the panel's ultimate load, while the composite material reached strains of more than 0.2 percent.

Although the current provisions of ACI 357R[8] for offshore concrete structures allows a maximum strain of 0.06 percent in the mild steel during service load to limit cracking, a maximum design strain of the CFRP reinforcement of 0.2 percent could be acceptable if the CFRP reinforcement has proven adequate durability in a marine environment. Therefore, the precast panel prototype would allow reinforcement strains more than three times higher than the ACI 357R allowable value. This approach could potentially increase the service load level of the precast concrete panels by a factor of two and, for this reason, increase the efficiency of the module's hull panels.

Constructibility testing of the CFRP grid material and the self-consolidating (SCC) lightweight concrete mix was also performed on 11 pretensioned panel specimens using varying reinforcement grade and mesh size, prestressing levels, and concrete cover. The grid material selected for use in the specimens was a CFRP grid with the brand name NEFMAC (see Table 1). Based on previous experience with the SCC lightweight concrete in the panel test program, time and resources were not spent on developing a suitable prequalified SCC lightweight concrete for use in the MHP test bed.

As the project moved forward, NFESC materials engineers reviewed chloride concentration at depth-versus-time (from the STADIUM concrete durability model that used as input concrete constitutive, permeability, and porosity data obtained by testing cylinders of the actual concrete mix to be used in the MHP). The chloride concentration-versus-time data were compared with chloride corrosion thresholds for Type 316 stainless steel, fusion-bonded epoxy-coated steel and MMFX-2 steel that were determined by studies of the Federal Highway Administration, Texas A&M University, South Dakota Department of Transportation, and others.[14-17] From this approach, it was determined that to achieve a 100-year service life, the following minimum concrete cover was necessary for the different reinforcing materials used with the MHP concrete when adjacent to a surface exposed to seawater:

- Stainless steel reinforcement: 30 mm (1.18 in.)
- Fusion-bonded epoxy-coated steel: 50 mm (2 in.)
- MMFX-2 steel: 44 mm (1.75 in.)

As the panel thicknesses had already been set at this time, design of the MHP test bed exterior plate element reinforcement was revised to accommodate the larger cover without increasing the panel thickness. This resulted in the requirement for more mild steel reinforcement than optimal—had it been possible to increase the thickness of the plate elements. For the full-scale prototype MHP, the panel thickness will be increased somewhat so that the mild steel reinforcement can be used more efficiently.

SCHEDULE AND COSTS

The contract to consider concepts that could be used to dramatically improve Navy pier design was awarded by Naval Facilities Engineering Contracts Office, Port Hueneme, California, in 1998. A variety of concepts were considered during an intensive nine-month effort that involved input from Navy engineers and consultants that serve the marine industry. Once the floating pier concept was identified and selected from other considered alternatives as the best approach to pursue, concept confirmation testing, material selection testing, and operational configuration design proceeded in parallel over a 24-month period (see Fig. 13).

Following the development of a suitable operational configuration, the MHP test bed structure was designed and a construction contract awarded for

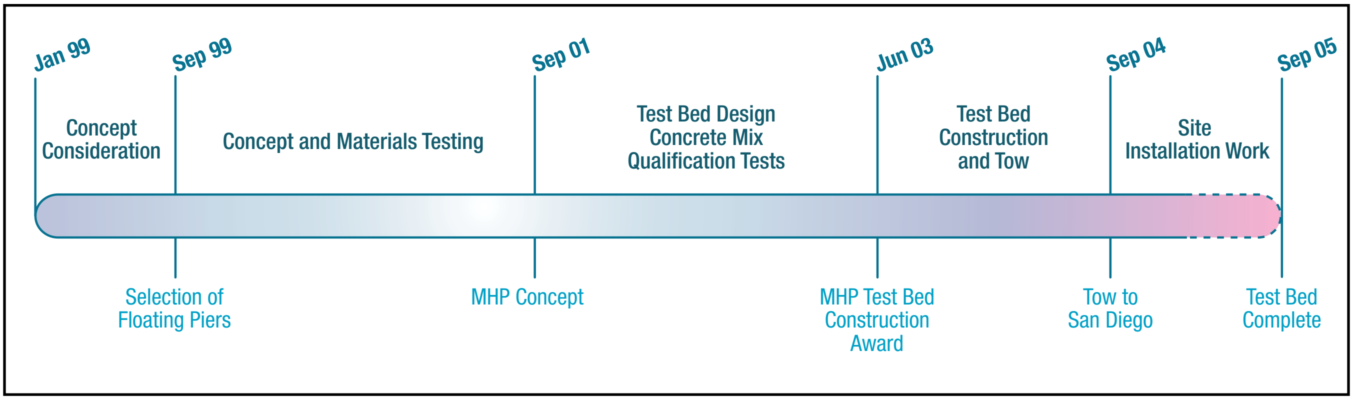


Fig. 13. MHP project timeline.

Fig. 14. Erection at CTC precasting facility showing hoisting of precast concrete wall panel.

Fig. 15. Partial erection of MHP precast concrete wall panels at CTC Tacoma, Washington, graving dock facility.

this facility in June 2003. This contract award was preceded by a concrete mix design/panel test program to qualify the lightweight concrete panel production mix through the input of three different PCI producer member companies.

The MHP test bed was completed and towed to San Diego in September 2004. It is currently being installed on its test mooring at Naval Station San Diego by Marathon Construction Corp., San Diego, California, under contract to NAVFAC Southwest Division; work is expected to be completed in the fall of 2005. In less than six years after the program was initiated, the construction of the floating pier test bed was being delivered via open-ocean tow to its final destination.

PRODUCTION AND ERECTION

Both modules for the MHP project were fabricated and outfitted for towing at Concrete Technology Corporation's (CTC) Tacoma, Washington, production facility (see Figs. 14 to 19) at a total cost of $2.7 million; the cost of the precast concrete components alone was $900,000. According to CTC, the paramount challenge of the MHP project for the U.S. Navy was that very little redundancy in precast concrete production was afforded the precaster. Because the intent of the test bed was to build most of the details that would later be required in the full-scale production version of the MHP, almost every precast piece was unique.

CTC's original schedule called for a completion date of April 30, 2004, but was later extended to the end of August 2004 due to the complexity of the production. All of the production elements

Table 2. Precast concrete inventory for MHP test bed.

Number	Floating pier test bed component	Size, m (ft)	Maximum weight, kg (lb)
12	Longitudinal exterior panels, biaxially prestressed	8.6 × 8.6 (28.2 × 28.2)	39,000 (86,000)
8	Transverse end panels, biaxially prestressed	5.4 × 7.0 (17.7 × 22.9)	23,800 (52,500)
4	Transverse internal panels, reinforced	7.0 × 8.6 (22.9 × 28.2)	28,800 (63,500)
4	Interior longitudinal panels, reinforced	varies × 7.0 (varies × 28.2)	28,800 (63,500)
4	Mooring moon pool panels, reinforced	4.3 × 8.6 (14.0 × 28.2)	14,750 (32,500)
30	Service deck panels, axially prestressed	1.8 × 7.2 (6.0 × 23.6)	3310 (7300)
28	Operations deck panels, axially prestressed	1.8 × 7.5 (6.0 × 24.5)	3310 (7300)
8	Keel plates, cast-in-place, biaxially prestressed	—	—
2	Operation deck cast-in-place toppings, biaxially prestressed	—	—

were different in some way. The use of many different materials and numerous complex construction details, intended to reflect all of the daunting production aspects of a full-scale structure in the much smaller prototype test bed, magnified the complexity of the project for the precaster (see Tables 2 and 3).

The different materials required were multiple post-tensioning tendon types, including the following:

- Bar tendons of differing lengths;
- Strand tendons of six different types, including flat four-strand tendons and round six-, seven-, and twelve-strand tendons with differing duct types, anchorages and detailing; and
- Monostrands.

Post-tensioning tendons ranged from the typical type using galvanized ducting and black steel anchors to electrically isolated tendons using plastic ducts, special installation detailing, galvanized anchors, and electrical isolation monitoring wires.

Specifications initially required that casting of the exterior panels exposed to seawater should not have steel support chairs (in close proximity to the exterior formed surface) for the reinforcing steel and bar post-tensioning, as there was concern about the chairs causing seawater ingress into the panel. Several approaches for suspending the reinforcement and post-tensioning tendons from above the form were developed to accomplish this objective. None of the approaches provided the necessary positioning tolerance for the reinforcement; thus, after several panel castings, the decision was made to use high strength concrete support chairs.

Four-strand flat tendons were used

Fig. 16. Hoisting of precast concrete deck panel.

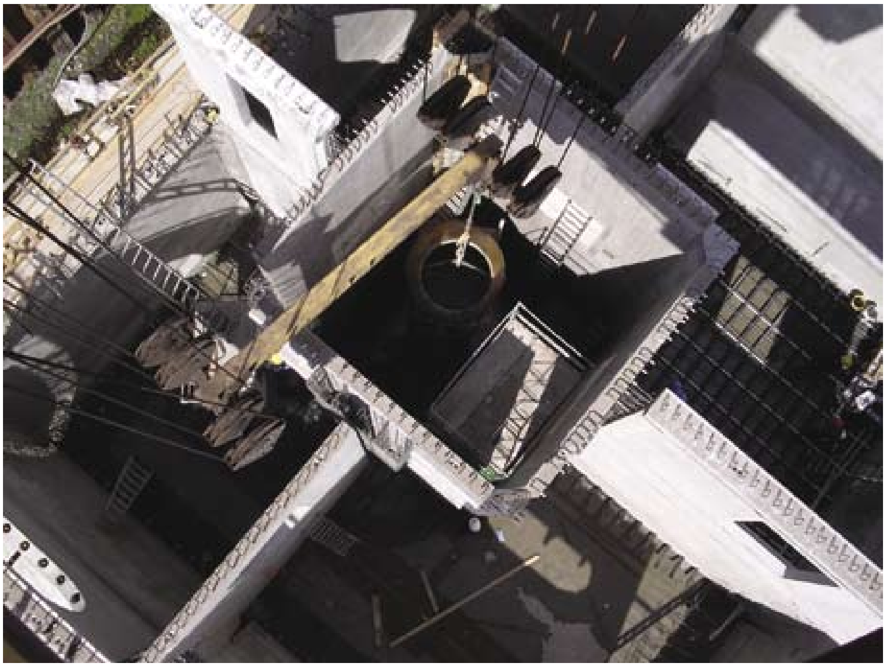


Fig. 17. Overhead view of MHP precast concrete construction with walls in place.

Table 3. Precast concrete inventory for MHP.

Number	Production floating pier components	Size, m (ft)
80	Longitudinal exterior panels, biaxially prestressed	9.9 × 8.6 (32.4 × 28.2)
64	Longitudinal interior panels, axially prestressed	9.9 × 8.6 (32.4 × 28.2)
24	Longitudinal interior panels, axially prestressed	9.9 × 5.4 (32.4 × 17.7)
16	Full height transverse end panels, axially prestressed	6.2 × 8.6 (20.3 × 28.2)
16	Reduced height transverse end panels, axially prestressed	7.2 × 5.4 (23.8 × 17.7)
24	Full height transverse interior panels, reinforced	6.2 × 8.6 (20.3 × 28.2)
72	Transverse interior panels, reinforced	7.2 × 5.4 (23.8 × 17.7)
16	Mooring moon pool panels, axially prestressed	6.1 × 8.6 (20.0 × 28.2)
984	Operations deck panels, axially prestressed	5.9 × 1.9 (19.4 × 6.3)
328	Service deck panels, axially prestressed	5.9 × 1.9 (19.4 × 6.3)

Fig. 18. MHP module shown under construction at CTC in Tacoma, Washington, with the Blair Waterway (an extension of Commencement Bay) in the background.

in the MHP keel, service deck, and operations deck. When the anchors for these tendons arrived on site, they were found to be significantly larger than assumed in the design. A similar situation occurred with the anchors for the vertical bar tendons in the exterior walls and with the seven-strand double encapsulated tendon anchors in the end walls of the MHP. As a result, it was necessary to redesign the reinforcement in these affected areas to accommodate the larger size of these anchors.

The encapsulated post-tensioning tendon systems had plastic tendon ducts that were larger in outside diameter than typical galvanized steel ducts for the same number of strands in a tendon. In addition to the tendon ducts being nominally larger, the duct coupler fittings for these tendons were even larger. The specific location of the plastic duct splices had to be carefully planned to ensure that there was sufficient space in the plate element to accommodate the duct splice as well as the required reinforcement and still achieve the specified cover tolerances.

Table 4. HSLWC mix design.*

Material	Weight, kg/m³ (lb/cu yd)	Supplier
Type I/II cement	390 (658)	Lehigh Northwest Cement Ltd.
Fly ash	142 (240)	I.S.G. Resources
Sand	706 (1190)	Glacier Northwest
16 mm (5/8 in.) expanded shale and clay (lightweight aggregate)	567 (955)	TXI Inc.
Water	157 (265)	
WRDA-64 water reducer		W. R. Grace
Adva Cast superplasticizer		W. R. Grace
Daravair 1000 air entrainer (air content = 5.5 percent)		W. R. Grace
Unit weight	1954 (3295)	

*56-day compressive strength of 42 MPa (6100 psi) required by specification; actual 56-day compressive strengths ranged from 48 to 62 MPa (7000 to 9000 psi).

Concrete Mix Design

As described above, the concrete mix used for the MHP test bed was a 42 MPa (6100 psi) design with Type F fly ash (25 percent minimum cement replacement) and lightweight aggregate (see Table 4). The fly ash improves durability by reducing the potential for ASR of the normal weight fine aggregate and by decreasing the concrete's permeability to chlorides. NFESC conducted a series of test panel evaluations with three PCI member precast concrete producers.[23] The lightweight concrete mixtures met the design requirements for density, strength, and permeability.

A series of 3.0 × 3.7 m (9.8 × 12 ft) haunched prestressed concrete panels were produced by each of the three precast producers using the mix that each developed independently. At first, most of the panels developed small hairline cracks parallel to the strands. The concrete mix, detensioning process, and curing methods were adjusted to mitigate the cracking problem. NFESC conducted cyclic tests to failure to characterize and validate the panels' response to punching shear loads that would be produced by the outriggers of mobile cranes operating on a prototype MHP. The results of these test mix designs and test panel production were provided to the contractor selected for the MHP test bed construction as guidance for the production mix design.

The concrete's high fly ash content increased the risk of plastic shrinkage cracking. The panel testing program reduced this risk, but rigorous quality control procedures were necessary for all concrete mixing, placing, and curing operations. A mock-up test of a set of precast concrete panels helped to qualify the contractor's concrete production rates and placing procedures, and established the acceptance criteria for the concrete in the field.

The use of lightweight concrete also made the concrete quality control more difficult as the moisture control of the aggregate was retrospective. The moisture content of the aggregate was controlled by hygrometers in the storage silo that were periodically calibrated by measuring the true moisture content (by weighing and baking aggregate samples). The humidity calibration could only be applied to the preceding batch, since the current batch was placed by the time the measurements were available. This sequencing caused a delayed tune-up and adjustment of the concrete fabrication until the desired consistency of the concrete was achieved.

For outdoor production, the concrete mixture was sensitive to weather conditions and required the careful placing and curing efforts to follow strict guidelines, derived from ACI recommendations for hot and cold weather concreting.[24,25] It was important to avoid any water accumulation within the formwork as the concrete tended to segregate when it came in contact with water. Water from light rain or too much misting during wet curing tended to mix with the cement paste at the surface and caused scaling.

The contractor's placing and curing procedures were adjusted several times during the construction period. Outdoor concreting was ultimately performed under a protective tarp when there was any threat of rain. During the entire construction, only minor shrinkage cracking was observed. No shrinkage cracks required injection, and no precast panel was rejected because of concrete quality. Some concrete spalling and accidental bending of connection reinforcement occurred during the erection of the large panels. Several approaches to minimize this type of damage were evaluated, but it could not be completely avoided.

Questions were raised on the durability of the repairs made. These questions highlighted the need for more standardization and testing of durable repairs of concrete damage occurring during construction. Although field bending of reinforcing bars is not permitted in specifications, it is common practice that connection reinforcement, in particular, is necessarily bent in the field during placing of wall elements to interlace the steel between adjacent walls. Placement of coupler bars within tolerance often needs field adjustments. The three different types of reinforcement used in the MHP project made field bending even less desirable.

If epoxy-coated bars become damaged during bending, the bars lose some corrosion resistance. The stainless steel and MMFX bars are of high strength and, therefore, are very difficult to bend in the field. Nevertheless, it is unclear how much the ductility capacity of high strength reinforcing bars is reduced as a consequence of field bending. The construction processes and associated quality control efforts were extensively documented so that lessons learned from the construction of the floating pier test bed would be systematically available for the final design and construction of the full-sized prototype operational floating pier.

OCEAN TRANSPORT AND MHP MOBILITY

During a 12-day period in September 2004, the MHP was open-ocean towed from Tacoma, Washington, over 1770 km (1100 miles) to the Naval Station in San Diego, California, where mooring construction began and is expected to be completed in the fall of 2005 (see Fig. 20). The towing operation and the concerns of hauling such a large structure led to some interesting precautions (see the "Hydrodynamic Modeling and Simulation of MHP" sidebar on the following page).

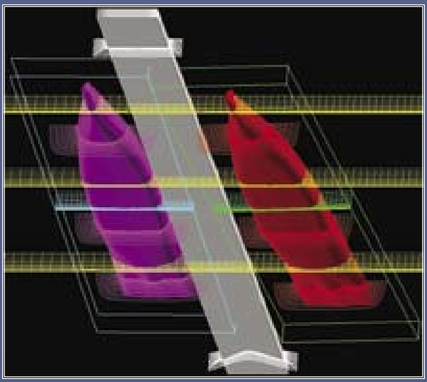
To ensure the seaworthiness of the MHP for open-ocean towing, careful control of concrete density and detailed weight takeoffs of reinforcing steel and attached and embedded hardware were required to ensure that the weights of the various elements were maintained within the limits developed during the design. Once the test bed structure was joined and launched, an inclining test was done by moving large weights to different positions on the deck and measuring the resulting trim angle to confirm the buoyant properties and center of gravity for use in the refined towing stability calculations. These calculations were very important for the test bed structure, because while the full-scale production version had 100 individual watertight compartments and was designed to remain fully operational with two compartments flooded,

Fig. 19. Completed test bed module during flooding of CTC's graving dock.

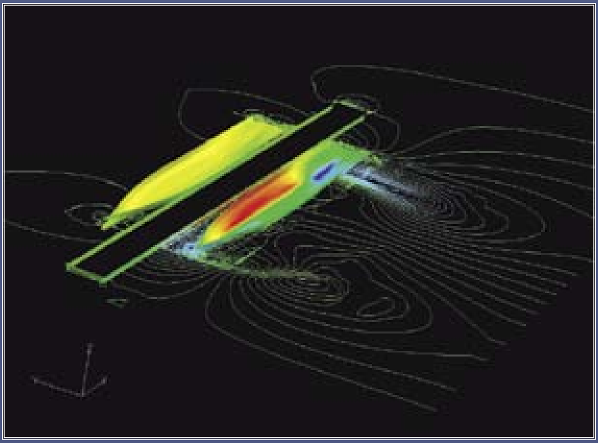
Hydrodynamic Modeling and Simulation of MHP

Advanced numerical modeling is being used to resolve operational issues to increase confidence that the floating MHP will meet U.S. Navy requirements.[18] Hydrodynamic performance issues identified by the Integrated Product Team (IPT) included the response of:

- MHP and berthed ships to ship berthing;
- MHP to impact from a large drifting ship;
- MHP and berthed ships to harbor oscillation; and
- MHP to hurricane level current, wave, and wind forces.



Extensive hydrodynamic, nonlinear modeling and simulation for the project is being conducted by NFESC and Texas A&M University.[19, 20] The modeling initially focused on evaluating the coupled hydrodynamic response of the MHP and a berthed vessel to the dynamic forces associated with a large vessel berthing at the MHP. One of the initial concerns was whether the motions and accelerations associated with a berthing vessel would result in constraints for mobile cranes operating on the deck of the MHP.



As expected, indications from the analyses are that cranes can operate on the floating MHP essentially the same as on a fixed pier and that berthing operations would not require operational constraints. Additional modeling has demonstrated the resistance of the pier mooring system to impact the pier from an uncontrolled drifting vessel. Modeling is in progress to evaluate pier response to long-period waves, such as harbor seiche (harbor oscillation from long period waves produced by seismic events or distant storms at sea).

The first two problems identified by the IPT were modeled using the Reynolds Averaged Navier Stokes (RANS) code[21] coupled with the Navy's six-degree-of-freedom Compound Ocean Structure Motion Analysis (COSMA) code.[22] RANS and COSMA were used to predict MHP motion during berthing of an LHD class vessel (amphibious assault ship). Parameters for water depth, fender stiffness, and vessel approach velocity were varied to determine the effects on MHP motion response. It was found that MHP acceleration during ship berthing is on the order of 0.12 m/sec^2 (0.04 ft/sec^2), producing only minimal dynamic loading on the boom of a mobile crane that is making a lift, verifying that the MHP was suitable for the operation of mobile cranes.

The Navy typically requires special certification for floating cranes or for mobile cranes that are used on floating barges. This is because hydrodynamic stability of the barge-mounted crane must be considered. The MHP, unlike a barge, is a massive, rigid structure that exhibits minimal list to the live load imposed by lifts made by the design 127 metric tonne (140 ton) cranes. Modeling and simulation is assisting the development of Navy policy for operation of cranes on a MHP. The NFESC is using STARDYNE, a finite element modeling program, to predict list of a four-module MHP from various scenarios of four cranes making simultaneous lifts. The modeling results indicate the prototype MHP will undergo a list of less than 0.5 degrees as a result of four 127 metric tonne (140 ton) cranes operating anywhere on its deck. This minimal list would result in crane component loads well within normal operating limits and has been proposed as a design policy.

There is a low, yet finite, risk that a large vessel could drift accidentally into the MHP. The RANS and COSMA codes were used to predict the effect of an LHD drifting in maximum currents representative of Naval Stations in San Diego, California, and Norfolk, Virginia, and in combinations of current plus sustained wind. Effects of location of vessel impact and of water depths were also evaluated. The figure summarizes model predictions for an LHD drifting in a current of 0.7 m/sec (2.3 ft/sec) velocity. The results indicated that the mooring system reacted elastically and, in combination with fluid added mass damping effects opposing MHP motion, absorbed the energy from contact of the drifting LHD.

STARDYNE was also used to predict MHP response to compartment breaching. The MHP was found to be hydrostatically stable until six perimeter compartments and two adjacent large interior compartments at the outboard end of the outboard module were flooded; this condition will cause the superstructure to sink and rest on the mooring foundation, and the resulting load may crack the operations deck. This scope of extensive module damage could only be caused by a very extreme and rare event, such as a ramming by a large vessel that is underway, which would cause severe damage to any structure. MHP remains within operational limits for any lesser number of flooded compartments of the end module.

—Preston Springston

the MHP test bed structure only had eight watertight compartments.

Thus, the stability of the MHP test bed unit with a potentially flooded compartment as a result of damage was an important risk issue to be addressed. Because of this damage stability concern and the much shorter 30 m (100 ft) length of the test bed structure (same length as the waves likely to be encountered at sea), it was deemed prudent to close off the utility windows and the forward end of the lower service deck with seaworthy enclosures for the tow transport.

Preparation for the long towing operation included completion of a comprehensive safety checklist developed by Naval Sea Systems Command (NAVSEA). This list included attaching a secondary tow bridle (much to the satisfaction of the tow master and marine surveyor), hydrostatic testing of hatch covers, attachment of temporary navigation lights, and proof testing of tow line attachment fixtures.

The ocean tow of the MHP test bed was modeled by PCCI Inc., Alexandria, Virginia, under contract to NAVSEA, using the towing analysis programs ORCAFLEX and POSSE. These programs modeled the behavior of the test bed in random seas, and they predicted roll and pitch motions and mooring line tension. The program was used to provide the tow master with damage avoidance tactics to use in the event the tow encountered storms more severe than the anticipated design storm environment.

Towing stability was further modeled by NFESC using the dynamic analysis model, MULTISIM. The tow models indicated the MHP test bed would be seaworthy through Sea State 6 [5.5 m (18 ft) significant wave height]. This sea state value represented the limit of modeling prediction accuracy and not necessarily the limit of the MHP test bed. Both the floating pier and the tow line were instrumented to record motions and forces that were correlated with tug speed and sea state throughout the voyage.

The MHP test bed tow was instrumented using the "Smart Tow" system developed by the NAVSEA. The Smart Tow system provided the tow master with real time information regarding the roll and pitch response of the tow. Regular reports of sea conditions, towing line tension, speed, motions and position were sent to land based monitors throughout the 12-day voyage. The Smart Tow data are currently being compared with model tow predictions to validate the models and to increase confidence of towing full-scale prototype modules in the open ocean.

The MHP is designed to be deployed in typical U.S. Navy base harbors. The environmental conditions and tidal conditions of candidate harbor locations were considered in the design. The MHP facility is designed as a harbor berthing facility and has not been designed for open ocean conditions other than for open ocean tow of the modules that make up the full pier. However, the facility could be deployed in deeper protected waters by

Fig. 20. Designed and built with state-of-the-art technologies, the completed MHP test bed shown enroute to its destination, is proof of concept for a full-scale, $45 million, 400 m (1300 ft) long double-deep floating pier for the U.S. Navy.
(U.S. Navy photo. Photographer: Erick Huang.)

revising the mooring system to a chain and anchor mooring system.

CONCLUDING REMARKS

The next step for constructing a full-sized prototype is currently being evaluated by the U.S. Navy. The evaluation is being performed by an IPT of experts chartered by NAVFAC and drawn from the Navy's facilities engineering and port operations communities. The timing and location of the full-sized prototype will depend on both the budget for funding new Navy piers and on the Navy team's evaluation of the readiness of the technology for military construction.

The costs of a completely equipped full-scale MHP range from $40 to $50 million, depending on the locality and specific operational requirements. Construction costs are similar to a fixed pier that provides comparable operational support. The flexibility and ability to berth a wide range of vessel types, ability to relocate, ease and economy of reconfiguration for utilities, and lower maintenance costs create substantial life-cycle cost savings over conventional pier designs. Site testing of the MHP at its base in San Diego, California, began in January 2005 and continues to the present.

Relative to a site-built fixed pier, the modular hybrid floating pier provides a potential life-cycle savings of $15 million per structure. This savings includes a reduction of initial construction costs, avoidance of one re-construction cost (because its service life is twice that of a conventional structure), and savings in maintenance and repair costs.

The deployment of the floating pier test bed represents a project milestone of moving from a general client need for a new class of piers to a constructed physical structure based on extensive operational planning and research and development in six years. In the process of this work, materials innovations were incorporated from research and a number of universities, as well as the use of advanced materials from several construction industry suppliers.

State-of-the-art precast/prestressed concrete technology was used to maximize the amount of off-site construction, ensuring a higher level of construction quality and minimizing the amount of in-water and on-base construction activity typically required to install the facility at a naval base. The design and construction of a floating pier to a 100-year, no-repair criterion is a significant shift in thinking that has broad implications for the development of public infrastructure in general and traditional piers in particular.

This project won the prestigious Harry H. Edwards Industry Advancement Award in the 2005 PCI Design Awards Program. The jury comments were as follows:

"This is an extraordinary structure, with the new concept in marine infrastructure construction that leads us to the next generation of precast applications. This project truly meets the spirit of the Harry H. Edwards Award because it is a bona fide structure that transfers the latest technology into practice. The 100-year design life has been made possible with the newest in high performance concrete and corrosion-resistant reinforcement systems, including MMFX technology and electrically isolated tendons. This project is also a perfect example of the entire design-construction team being involved in planning and decision making. The floating precast concrete structure is a very forward-thinking concept. Many of the ideas incorporated into this project will set the standard for durable, long-life marine structures."

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MHP Test Bed Safely Towed 1100 Nautical Miles

A key operational test for the Modular Hybrid Pier (MHP) project was to demonstrate the capability to safely and economically tow the modules in the open ocean. Meeting this objective required analyses of towing costs, prediction of towing forces, fabrication of towing fixtures, and the conducting of numerous simulations of the test bed's dynamic performance in the open ocean.

Delivery Method and Preparation

Concrete Technology Corporation (CTC) manufactured modules of similar segmental precast construction for the Admiral Clarey Bridge project.[1] These modules were "dry" transported from Tacoma, Washington, to Pearl Harbor, Hawaii, on the deck of a semi-submersible barge. BERGER/ABAM Engineers and subcontractor CTC proposed transport of the MHP modules to San Diego, California, by a similar means at a cost of $536,592. Dry towing is not an effective option for the 107 m (350 ft) prototype MHP modules because they are too large.

To be economically competitive, the acquisition cost of the MHP must be comparable to or less than that of a conventional pile-supported pier of equivalent mission capability. Ocean delivery of the four modules (nominal prototype MHP) from the precasting plant to the Navy port represents a significant cost that must be minimized. The MHP is designed to be relocated once during its life cycle; thus, ocean delivery costs may be incurred a second time. To minimize delivery cost and to provide maximum flexibility for future operations, the Naval Facilities Engineering Service Center (NFESC) elected to demonstrate delivery via a "wet" ocean tow of the test bed pontoons (see Figs. A and C).

The Military Sealift Command (MSC) awarded the contract for the tow and Naval Sea Systems Command (NAVSEA) Supervisor of Salvage (SUPSALV) supervised the tow in conformance with the U.S. Navy Tow Manual.[2] The total cost of the wet tow was $514,962, which included the "wet" tow contract to Olympic Tug and Barge, preparations for tow (window boarding, wave walls, temporary ballast, and tow bridle attachment) by CTC, certification tests of the capacities of the towing pad eyes, water tightness of the hatch covers, and a hydrostatic stability test of the pontoon (to verify centers of gravity and buoyancy). The tow was insured for $5 million under the MSC contract and was inspected by a marine surveyor before and after the tow.

BERGER/ABAM Engineers specified design loads of the test bed and opening closures for the wet tow. The Navy analyzed test bed tow performance and set sea condition limits not to exceed the test bed's design loads. The Navy was responsible for towing in acceptable sea conditions and instrumented the tow to record the actual sea conditions and the tow response.

Hydrostatic Stability

Since the test bed was expected to be towed at about 3 knots, it would require a long period to reach a safe haven in the event of deteriorating sea conditions. Although seaways en route are relatively calm in the summer, offshore weather stations report waves above 3 m (10 ft), exceeding 6 m (20 ft) occasionally. Thus, the seakeeping ability of the test bed was critical. The test bed comprised two joined modules measuring only 15 × 30 m (50 × 100 ft) in plan, with draft at a level trim of 4.0 m (13.10 ft). The lower, or service, deck was located at 5.38 m (17.66 ft) above the keel. The upper, operations deck was 3.45 m (11.33 ft) above the service deck. The bottoms of the four windows in the sides were at 0.79 m (2.59 ft) above the service deck. The bow and stern were open. Free board at a level trim was only 1.39 m (4.56 ft) at the stern and bow and 2.18 m (7.15 ft) at the side windows.

At departure, the test bed was ballasted down 0.45 m (1.5 ft) at the stern to improve towing characteristics. NFESC's stability analysis[3] showed that the high center of gravity—4.37 m (14.35 ft) above the keel—and low free board would contribute to green water washing onto the service deck. Stability was poor with maximum stability occurring at the relatively slight angle of 15 degrees and diminishing at a list of 35 degrees. The analysis was repeated for the test bed with closed windows and bow. The static stability of the test bed was found to increase substantially, presenting a maximum stability at 42 degrees of list and remaining positive up to 90 degrees of list. It was decided to close the test bed windows and bow for the tow.

Fig. A. MHP test bed tow in the Santa Barbara Channel, south of Port Hueneme, California. *(U.S. Navy photo. Photographer: Preston Springston.)*

Towing Dynamics

NFESC conducted a dynamic analysis of the "closed" test bed using the time-domain code MULTISIM.[4] This code is capable of analyzing the dynamic performance of a multi-module floating platform subjected to disturbances by waves, wind, and current. The analysis procedure is based on a time-domain numerical integration of the platform's rigid-body equations of motion, taking into account the exact large amplitude motion effects. This allows the code to closely track the instant wet hull geometry and fluid forces at large inclinations; therefore, it is capable of tracing the platform performance up to capsizing.

The solution includes nonlinear effects, including forces due to fluid drag, finite amplitude wave, and ship motion, as well as a position-keeping system. The analysis simulates random seaways with Bretschneider spectra. A parametric study was conducted to confirm the performance of the code and subsequently to design a realistic numerical model that best represented the ocean tow scenario. The code was then used to evaluate test bed performance in heavy seas. The results were further compiled to determine the threshold seaways that the test bed could possibly withstand during ocean tow.

The test bed was found to be sensitive to waves of five- to nine-second periods. The dynamic stability analysis further found that the closed test bed could withstand seaways above Sea State 6 [a significant wave height of 5.5 m (18 ft)]. In Sea State 6, the test bed was predicted to roll within 15 degrees to each side, and the operation deck was predicted to remain above water at all times. Sea State 6 represented the limit of modeling prediction accuracy and not necessarily the sea-keeping limit of the test bed.

PCCI Incorporated of Alexandria, Virginia, modeled the ocean tow performance of the test bed under contract to NAVSEA SUPSALV. PCCI used the towing analysis module in the Program of Ship Salvage Engineering (POSSE) to predict tow resistance then used the ocean engineering software, ORCAFLEX, to model tow response in random seas up to Sea State 6.[5]

The MHP test bed structure hull and bulkheads were modeled and input to POSSE's Ship Project Editor module. The modeled departure condition included a displacement of 1774 LT and trim of –1.5 FT at the stern. POSSE's Tow Module duplicates the steady state tow calculations in the U.S. Navy Towing Manual.[2] POSSE predicted hydrostatic properties of the test bed and departure conditions (displacement, centers of gravity, and buoyancy and drafts) for still water. The bending moment at midship (joint between modules) was calculated for sagging and hogging that would be produced by storm conditions of a 4.5 m (15 ft) wave with crest at the bow, stern, and midship.

The motion of the test bed was obtained from frequency domain response amplitude operators (RAO) calculated using POSSE's Ship Motions Program (SMP) module and then imported to ORCAFLEX. The program ORCAFLEX is a 3D, nonlinear, time domain finite element program capable of dealing with arbitrarily large deflections of the flexible elements from the initial configuration. ORCAFLEX handles multi-line systems, floating lines, and line dynamics. Input

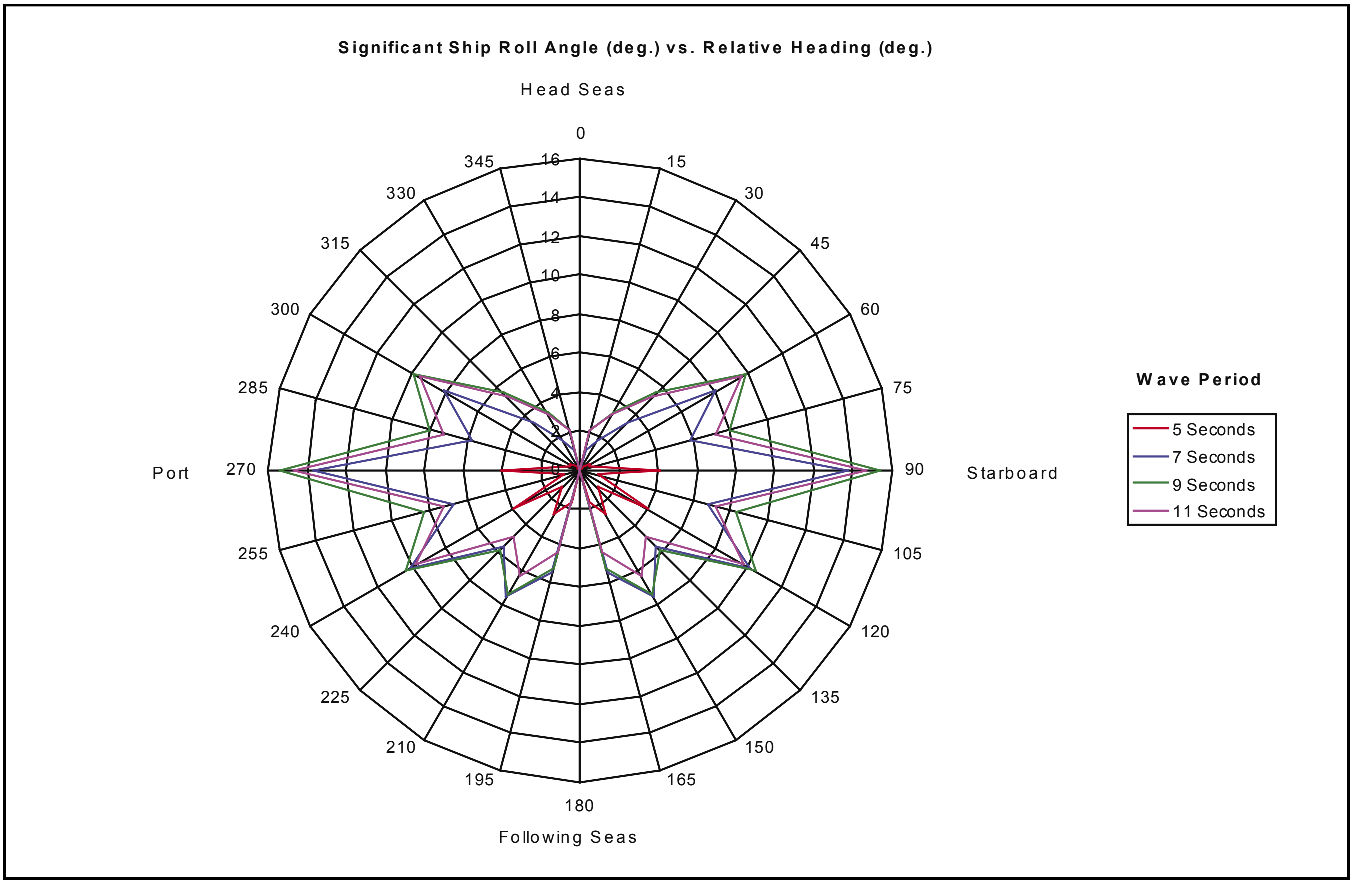

Fig. B. Significant pontoon roll angle (degrees) versus relative heading (degrees)—Tow at 3 knots in SS4.

includes ship motions (RAOs from POSSE) regular wave response, test bed speed and heading, tow hawser length and wire size, and tow bridle configuration. ORCAFLEX then simulated behavior of the test bed in random seas (Bretschneider spectra).

Hydrodynamic effects of the tow "skating" from side to side behind the tug were modeled and imposed upon the test bed trajectory. The simulation included a fictitious tug having resistance and hydrodynamic features of a 36.6 m (120 ft) tug and producing a thrust equal to the steady state tow resistance of the test bed predicted in the POSSE Tow Module. Roll, pitch, and heave motions, dynamic wave bending and shear, and towing line tension were predicted for head, beam and quartering seas. The output was graphically presented in polar charts (see Fig. B for a sample) for Sea States 4 through 6 to provide the tow master with damage avoidance tactics to use in the event the tow encountered storms more severe than the anticipated design storm environment.

The POSSE and ORCAFLEX models predicted the following results:

- Tow speed = 3 knots
- Required tug bollard horsepower = 612
- Tow resistance = 60.577 kN (13,619 lb)
- Mean hawser tension = 62.27 kN (14,000 lb)
- Predicted extreme tension = 116.0 kN (26,073 lb)

Tow Monitoring

The test bed pontoon was instrumented with the Smart Tow system developed by NAVSEA SUPSALV. The Smart Tow system consists of sensors installed on the pontoon and the tow hawser to provide real-time and time-history information on motion of the tow (roll, pitch, position relative to tug, and towline tension) and to provide early warning of compartment flooding. A laptop computer on the tug gave the tug captain real time information to assist with the safe conduct of the tow. Use of the Smart Tow system on the test bed enabled the conduct of a safe tow and provided data to validate the computer models that were used to predict the test bed tow performance (see Table A). This will enable a high level of confidence in predicting performance of prototype full-scale MHP modules during ocean tow.

This was one of the first operational tests of the Smart Tow system that will be used by SUPSALV to monitor tow of Navy vessels. The data gathered on tow performance will enable more accurate selection of the tug size (horsepower/bollard pull) and hardware that is required to tow Navy ves-

Table A. Test bed response versus design limits—Tow at 3 knots in SS6.

Parameter	Predicted	Design limit
Heave (ft)	5.8	N/A
Roll (degrees)	15	40
Moment at module connection (ft-LT)	6992	16,741
Shear at module connection (LT)	109	558

sels. This feature will result in safer and less costly towing of Navy vessels in the future.

Tow Response Analysis and Predicted Tow Response of a Prototype MHP

The tow response analysis produced by the association of the POSSE Tow Module and Ship Motion Program output with the time-domain ocean engineering modeling program ORCAFLEX is intended to provide a rational basis for selecting towing hardware for unusual and other unconventional tows not explicitly covered in the Navy Tow Manual.[2]

Dynamic towline tension may be estimated using tabular data in Appendix M of the manual, but this tabularized data does not cover unusual shapes or very high displacement tows, nor does it incorporate more than a small family of tugs. Accordingly, the tow response of the test bed provided an unusual opportunity to collect data on extreme tensions and vessel response.

The reality of the tow, insofar as the POSSE-ORCAFLEX predictions are concerned, is that very little severe sea conditions were met at sea. The observed sea was dominated by longer period waves, on the order of 9 to 10 seconds [152 m (500 ft) wave lengths] in the form of a Pacific swell. The developed sea used in predictions was characterized by worst-case 5- to 6-second waves [152 m (150 ft) wave lengths] that would excite the 30.5 × 15.2 × 9.1 m (100 × 50 × 30 ft) hydrodynamic "brick" being towed.

There was also a large difference in the tow hawser catenary used versus that employed in the predictions. Consequently, the population of extreme conditions and initial correlation is not very large. PCCI is reducing the data to correlate the observed sea conditions with the tow's speed, heading, scope, and recorded average and peak tensions in the tow hawser. Modeling predictions will then be compared with the recorded data to determine if the hydrodynamic coefficients need adjustment to accurately predict the extreme tensions that were recorded.

To date, there is close agreement at some speeds and heading (within 10 to 20 percent), whereas other records differ by as much as 40 percent. The goal is to have an 80 percent confidence limit in accuracy of the extreme tension predictions for a stipulated sea state with design conditions for tows of unusual form. Once the models are refined, they will be used to predict the performance of an ocean tow of a prototype full-scale MHP module.

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Fig. C. MHP test bed en route to its final destination, San Diego, California. *(U.S. Navy photo. Photographer: Preston Springston.)*