NAC Executive Insights

Technical Fundamentals for
Design and Construction
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Design and Construction of Marine Structures

Key Points

1. Approximately 71 percent of the earth's surface is covered in water, and the oceans hold about 96 percent of all the earth's water.
2. Construction and further development in the marine environment is essentially our primary remaining frontier on earth.
3. There exists a real opportunity and need for innovation and new technologies that have the potential to improve the quality of marine structures effectively while reducing the cost, time, and risk of construction.
4. The marine environment offers significant opportunities that do not exist with on-land construction. The most important of these is the ability to construct massive structures at an optimum location in a fully controlled environment with skilled labor and then transport an essentially complete structure great distances for installation in a severe marine environment. These structures include bridge foundations, tunnels, offshore platforms, gravity-base structures, dams, airfields, breakwaters, surge barriers, and power stations harnessing energy from wave, wind, tides, and currents. It can be a truly exciting and satisfying adventure.

Design for Construction of Marine Structures

When designing a structure for the marine environment, it is essential to first envision the means, methods, and equipment needed to build the structure. This can be considered the initial construction engineering task of marine construction. This task includes design of systems to move extreme heavy loads vertically and horizontally both in and out of water, and design of systems to control and maintain buoyancy and stability during all in-water construction phases including launch, transport, and immersion. This task also includes developing methods for stabilizing and then permanently fixing floating structures to pre-installed foundations using tremie concrete. The selected methods and equipment must not only be efficient and economical, but above all else must allow the work to be performed safely with a minimum use of diving.

Construction Operations and Resources for Working in Marine Construction

Due to the severe challenges faced in the marine environment, the safest and most efficient approach is often to perform as little work as possible at the installation site. This is typically accomplished by building as much of the structure as possible off-site, where weather, material resources, equipment, and availability of skilled labor can be fully controlled. This off-site work is typically combined with concurrent on-site pre-installation of the main foundation elements with towing of essentially complete structures long distances for at-sea mating to pre-installed foundations or anchoring systems.

The full range of tools, methods, and resources available to marine construction engineers include:

- Existing, available dry docks or graving docks for cast and launch operations
- High-capacity submersible transport barges
- Efficient, high-capacity seagoing tugs for long distance transit
- Highly sophisticated automated ballasting systems
- Specialty tremie concrete and grout for underwater placement
- Underwater remotely controlled vehicles, manned and unmanned

Because of the sensitive nature of the marine environment and the high potential of marine construction operations seriously impacting this environment, all marine construction operations and work methods should be developed with a focus on eliminating or significantly minimizing damage to the environment. A few of the potential impacts include increased water turbidity during underwater excavation, chemical spills, and impacts to marine life from high energy sonic waves transmitted through the water during pile driving operations.

Technical Fundamentals of Marine Construction

Marine structures are subjected to the full range of potential extreme loading events, including: earthquakes followed in some cases by underwater landslides or tsunamis; high cyclic wave and wind loading; collisions from floating vessels; and massive ice sheets or even icebergs. These loadings can occur during construction or in-service operations. The marine structure must resist these forces and must not be subject to progressive collapse.

The two most important fundamental principles that must be fully understood when designing marine structures are *hydrostatic pressure* and *buoyancy*. First, hydrostatic pressure. External pressure on a marine structure increases with depth and the density of the fluid. This pressure, hydrostatic pressure, acts uniformly in all directions and can be transmitted through channels within or beneath structures as well as pores or channels in the soil. Differences in pressure between two interconnected volumes cause flow to the lower pressure volume. It is important to remember that full hydrostatic pressure can be transmitted through small holes, such a ¼” diameter bolt-hole or even fine-grain, clean sand.

The second fundamental principle is *buoyancy*. Archimedes' Principle states that "a floating object displaces a weight of water equal to its own weight." This is buoyancy. Combining hydrostatic pressure and buoyancy with the laws of stability are the three most essential tools of a marine construction engineer.

The most significant parameters in controlling stability of a floating vessel are:

1. the vertical center of gravity of the vessel and cargo
2. the vertical center of buoyancy
3. the moment of inertia of the water plane where the hull breaks the water surface.

With these three pieces of information, a direct measure of stability of any floating object can be numerically determined.

Once these special analyses are completed and the loads calculated, the design of the members requires application of technical fundamentals including materials properties and structural engineering.

Narrative Project Abstracts

Tarsuit Caisson Retained Island in Canadian Arctic — The purpose of this project was to build within a three-month weather window an artificial island for year round oil exploration in the Canadian Arctic. The four concrete caissons that formed the parameter of the island were designed, built, and loaded onto a single submersible transport barge in Vancouver, B.C., for towing up the west coast of North America to the Beaufort Sea, where they were offloaded, ballasted down on to a pre-leveled gravel bed in 12 meters of water, and infilled with dredge sand to stabilize the four sides of the island. Steel gates then were used to seal each of the four corners of the island interior. The island center then was filled

with pumped dredge sand to form the interior work pad of the 8,000-m^2 island capable of resisting 12-meter storm waves and ice up to 5.6 meters thick.

The key marine construction engineering tasks in Vancouver were: design of the caisson casting operation, transport, loading and securing caissons on the transport barge, and performing stability analysis of the transport barge during loading and tow out. At site, the key design tasks for the marine construction operations included: design of the landing pad, the equipment for leveling the gravel pad, the ballast system for landing the caissons on the pad, and design of the pumping and distribution piping system for sand-in-fill of the caissons. (See photos below.)

Clockwise from upper left: Tow out from Vancouver, BC, harbor of four caissons on submersible transport barge to Beaufort Sea, Canadian Arctic; four caissons off-loaded, ballasted down onto pre-level gravel berm, and infilled with pumped sand during three-month window; fully operational exploratory drilling in mid-winter with island resisting full ice loading; completed island in operation before being locked in ice.

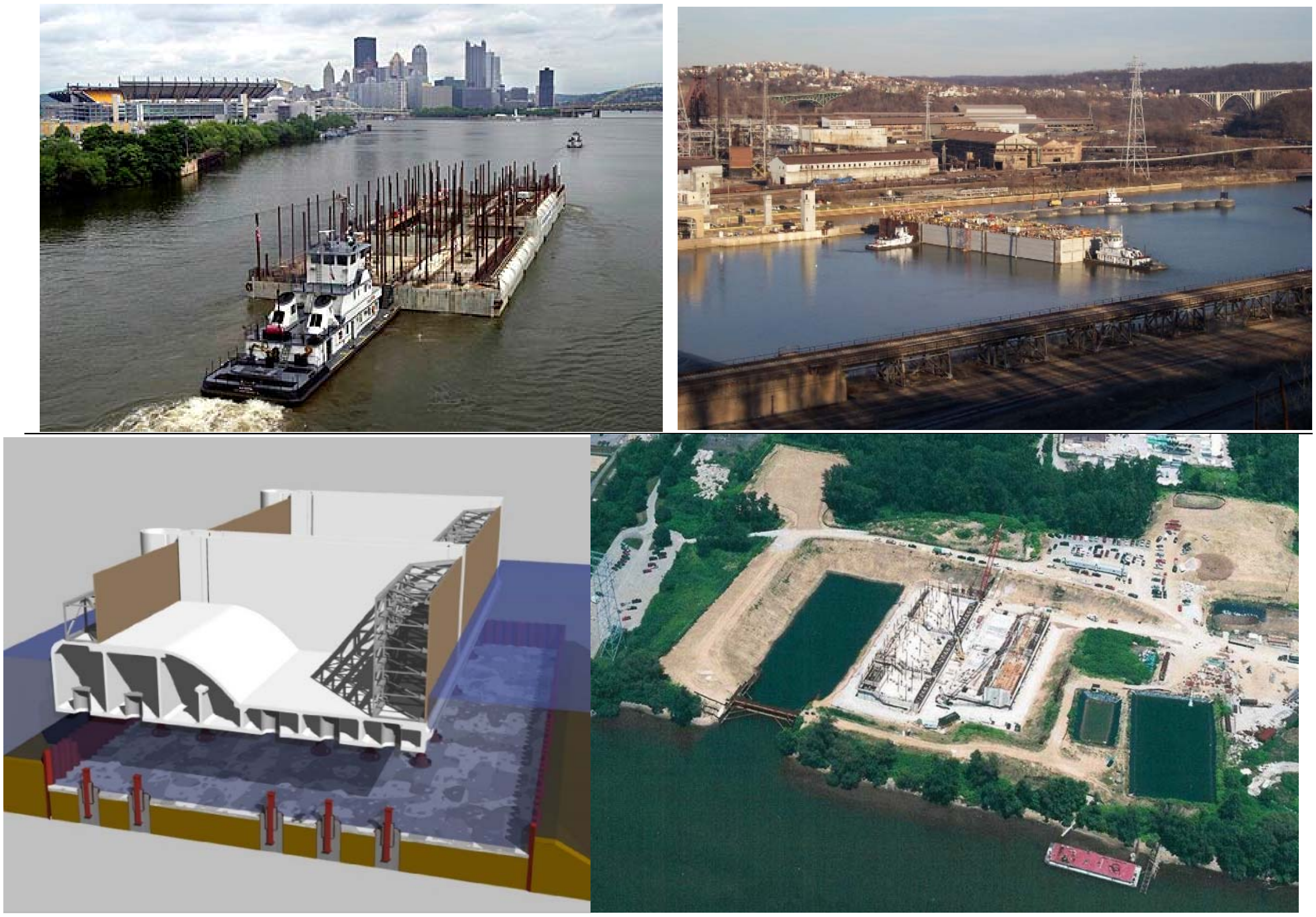
Oresund Immersed Tube Tunnel Connecting Denmark and Sweden – The purpose of this project was to cast and launch twenty 55,000-meter tunnel elements (176 meters long by 38.7 meters wide and 8.6 meters high) for a 4.05 kilometer-long immersed tube tunnel connecting Denmark and Sweden. The tunnel was designed to accommodate four highway lanes, two high-speed rail lines, and one emergency escape tunnel, all built within a single rectangular box.

The first key issue to be addressed by the marine construction engineers: how to provide continuous production to meet a two-year construction window under severe Scandinavian winter conditions. The solution developed by the marine construction engineers was to design and build a completely enclosed match-casting operation above sea level within 10 kilometers of the tunnel installation site and equip it with an indoor assembly line for prefabrication of 160 each, 22-meter long steel reinforcing cages in the shape of the tunnel and then deliver these preassembled cages to an enclosed fixed casting bed positioned over the top of six concrete skid beams. After each segment was cast and allowed to cure for 48 hours, it was pushed off the casting bed and a new reinforcing cage was pushed on to the bed to continue the casting cycle. This cycle was repeated until eight tunnel segments had been match-cast to form one 176-meter long tunnel element. Six 500-meter jacks then were used to push the 55,000-meter element a distance of 100 meters into the outfitting and float-up lock for installation of temporary post-tensioning, ballast tanks, and end bulkheads for floatation.

The second key issue addressed was how to launch each of the twenty 55,000-ton tunnel elements. This was solved by designing a two-level launch basin surrounded by a 10-meter high earthen berm with a sliding entrance gate on land and a floating exit gate at the deep end of the two-level basin. This two-level enclosed basin with an entrance and exit gate essentially created a lock system for hydraulically lowering the 55,000-ton tunnel elements to sea level. (See photos on next page.)

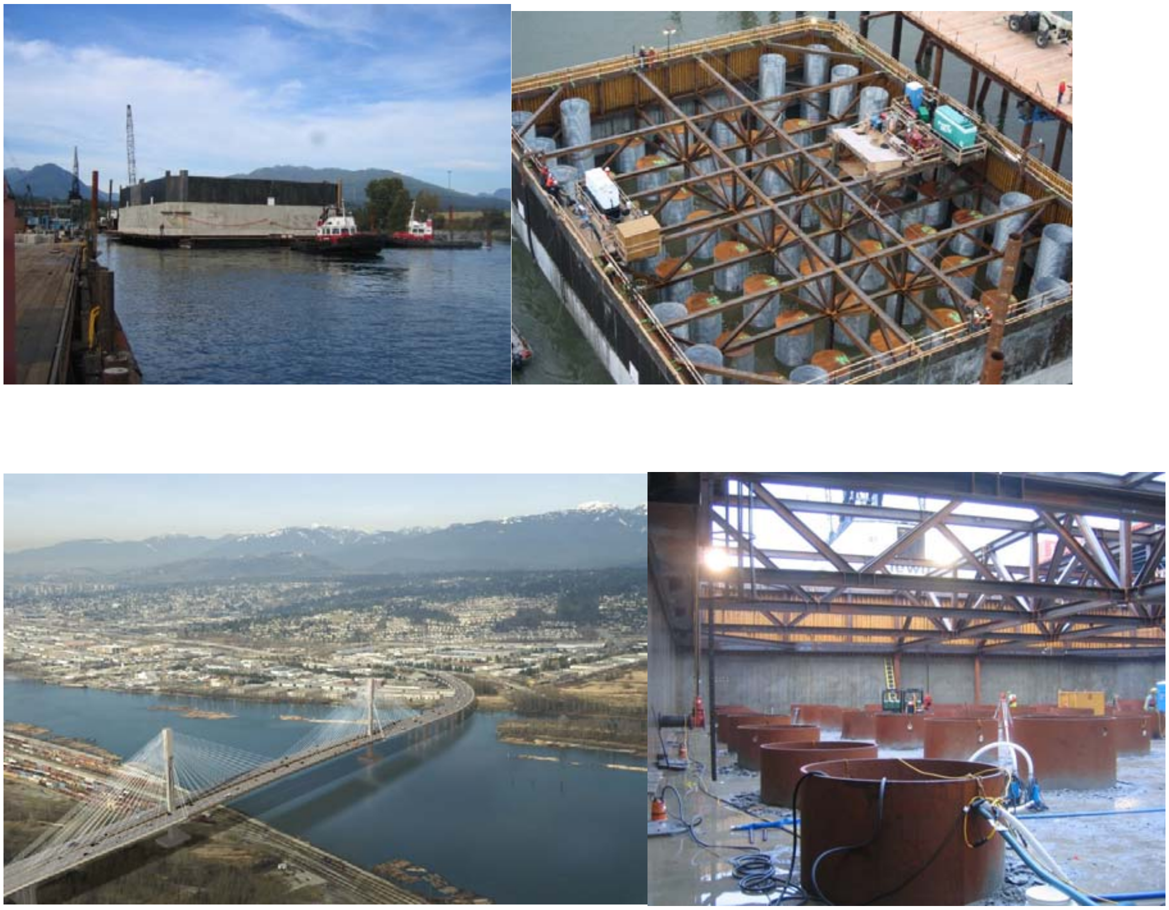
Clockwise from upper left: Match-casting of 22-m long tunnel segment in a fully enclosed tunnel production factory (mid-winter, Copenhagen, Denmark); match-casting factory and launch facility including skid beams, two-level enclosed basin with sliding entrance, gate, and floating exit gate; first completed tunnel element (eight segments) exiting cast and launch facility with immersion pontoons attached; diagram of fabrication yard and two-level launch basin.

Braddock Dam and Lock #2, Monongahela River, PA — A primary purpose of the U.S. Army Corps of Engineers for selecting the construction method used to build Braddock Dam was to develop a new “in-the-wet” method that would be faster and more economical than the conventional method of installing large circular cells to cut-off and dewater large sections of the river. This new method required several significant features including an off-site prefabrication and launch facility to pre-cast a shell of the dam, a navigable waterway connecting the fabrication site to the installation site, and a method of constructing both an adequate foundation and cut-off under the dam without dewatering the dam site. The skills required for this design and analysis included precise draft calculations and stability analysis during all phases of launch, and tow and landing of the precast dam segments. (See photos below)



Clockwise from upper left: Launch and 10-mile tow of first dam segment from casting basin to upstream outfitting and installation site at Braddock, PA; first dam segment being positioned at site prior to ballasting down onto pre-installed foundation and concrete filling; schematic of first dam segment being ballasted down for mating to pre-installed river bed foundation; cast yard and two-level launch basin.

Float-In Cofferdam for the Port Mann Bridge on the Fraser River, Vancouver, B.C. — The foundation for the main in-water tower for the new Port Mann Bridge was designed with a massive underwater concrete pile cap (42m x 33m x 7.5m deep) perched off the bottom of the river and supported by 63 1.83-meter diameter pipe piles. The solution developed by the contractor's marine engineer: precast a shell of the pile cap in a local dry dock, tow the shell to the bridge site, and ballast it down over the top of the pre-installed piles that had been cut 5m under water. The key challenges for the marine construction engineer were ensuring stability and trim of the precast shell during all stages of launch, transport, and ballasting into position on the piles. Additional challenges included developing a method for providing initial underwater support for the precast shell upon landing and providing a full, water-tight seal at the annulus between the precast shell and the piles while providing sufficient resistance to counter the full net buoyancy of the dewatered pile cap.



Clockwise from upper left: Precast pile cap cofferdam shell positioned for float-off and launch in dry dock, Vancouver; cofferedam after 15-mile tow up Fraser River pre-positioned prior to ballasting onto 63 1.83m diameter piles; completed bridge, Fraser River; main tower foundations, inside cofferdam after locking onto pipe piles, dewatering, and before placement of pile cap reinforcement and concrete.

Related Topics for Increased Depth Regarding Marine Construction Engineering

Physical aspects of the marine environment — wind, waves, currents, tides, depth, distance, corrosion, temperature, sea ice, icebergs, and sea motions of floating vessels.

Geotechnical aspects of the seafloor and marine soils — properties of marine clays, liquefaction risks of loose sands, scour of bottom founded structure, Glacial till and boulders on seafloor.

Structural materials for use in the marine environment — corrosion resistant steels, structural marine concrete, design and placement of underwater tremie concrete.

Marine and offshore equipment — dry docks, casting basins and barges of all types including: floating derricks, transport barges, semisubmersible barges, jack-up barges, launch barges, catamaran barges, pipe-laying barges, dredges, and the range of dredging techniques.

Foundation options for the marine environment — caissons, cofferdams, large-diameter drilled shafts, gravity base structures, methods for seafloor modifications and improvement, and subsea anchoring techniques.

Constructability in the marine environment — use of modular construction for off-site pre-fabrication, optimization of marine transport, minimizing the use of diving for on-site installation, and full integration of design with construction.

Glossary of Marine Construction Terminology

Ballast — weight added to a floating vessel to lower the center of gravity and increase stability.

Caisson — prefabricated steel or concrete box positioned in the water and sunk to a pre-determined depth for construction of an underwater foundation.

Cofferdam — temporary structure used to enclose a space below water for the purpose of dewatering the space to allow work in the dry.

Dredge sand — sand hydraulically pumped through a pipeline using a hydraulic dredge pump.

Graving dock — enclosed basin below sea-level with an entrance gate and dewatering capability.

Immersed tunnel — segmental prefabricated tunnel built in the dry, floated into position, and lowered into a pre-excavated trench and then backfilled.

In-the-wet construction method — any method that allows construction of an underwater structure without dewatering of the work or installation site.

Match-casting — casting a concrete segment directly against another segment to ensure precise fit.

Post-tensioned — tensioning of strands or rods within a structure to compression the structure.

Tremie concrete — concrete placed through water using a vertical fall pipe to prevent mixing of the fluid concrete with the surrounding water.

Two-level launch basin — a launch basin surrounded by an earthen berm that functions like a lock, allowing structures to be built above sea level in the dry and lowered to sea level for launch and tow out.

About the Author

Robert Bittner was elected to the National Academy of Construction in 2003. He is the co-editor of *Deep Marine Foundations*, a publication of the Deep Foundation Institute (DFI). Bittner is a member and past president of DFI. He also is a member of the Beavers and is the recipient of the Beavers Engineering Award for Outstanding Achievement in Heavy Engineering Construction. He holds bachelor’s and master’s degrees in civil engineering from Stanford University.