

Report on Floating and Float-In Concrete Structures

Reported by ACI Committee 357



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Report on Floating and Float-In Concrete Structures

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Report on Floating and Float-In Concrete Structures

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This report addresses the practical experience and engineering considerations for the design and construction of floating concrete structures. Recommendations for design loads and design criteria are presented. Design procedures and methods of analysis are discussed to better acquaint the reader with the design considerations unique to floating marine structures. Methods used to construct floating concrete structures play a major role in the success of each application. Construction methods and materials used for recent applications are presented to demonstrate the importance of the construction process during the planning and design of marine concrete structures. Important aspects of delivery, from the construction site and installation at the deployment site, are presented. The durability and serviceability of floating structures at remote sites are important considerations to project planners and developers. Construction execution, materials selection and inspection, maintenance, and repair techniques are discussed. The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI Certifications or equivalent.

Keywords: abrasion; accidents; admixtures; aggregates; concrete construction; concrete durability; detailing; dynamic loads; fatigue (materials); finite element method; floating structures; inspection; installing; lightweight concretes; limit design method; loads forces; maintenance moorings; permeability; post-tensioning; precast concrete; prestressed concrete; prestressing steels; quality control; reinforced concrete; reinforcing steels; repairs; serviceability; ships, stability; structural design surveys; towing.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

Prestressed or reinforced concrete structures are used as either permanently floating structures or temporary float-in structures to facilitate marine construction. In this report, the definition of a floating structure is a structure that is temporarily, intermittently, or continuously afloat. For those floating structures that have a bow or stern, the bow or stern may be raked or shaped as required. Certain floating structures included within this definition are designed for towing and subsequent grounding, and afterward function as fixed structures. Later, these structures may be refloated and transported to a new location. Other structures are designed to remain continuously afloat, with or without permanent mooring.

Permanently floating structures serve a variety of uses such as industrial plantships, floating bridges, floating dry docks, offshore terminals, navigation structures, and parking

and hotel structures. Applications of temporary float-in structures include the bridge pier foundations, offshore gravity-based structures, locks and dams, immersed concrete tunnels, and storm or tidal surge barriers.

In 1943, the first prestressed concrete barge was built by the U.S. Navy (U.S. Department of Transportation [USDOT] 1981). Today, the preferred construction approach for large structures is to use prestressed concrete instead of ordinary reinforced concrete. The ability of prestressed structures to control net tensile stresses and to close cracks that develop from temporary overload situations enhances water tightness and durability. Composite concrete-steel construction is also becoming popular. Concrete is used in the exterior bulkheads and base to provide durability, and steel is used for the internal framing and deck to provide weight savings (Gerwick 1975a, 1978).

The design of concrete floating structures requires knowledge of many disciplines. The designer should have a thorough understanding of concrete design principles, concrete as a material, and construction practice. Also, the designer should have an understanding of environmental loadings, marine operations, requirements for vessel certification, and the importance of structure inspection, maintenance, and repair. All of these aspects have been addressed in this report to provide the reader with a background in the subject of concrete floating structures.

1.2—Scope

This report is intended to further the development of floating concrete structures by presenting relevant design, materials, construction, installation, maintenance, and repair. Application of available technology is demonstrated for a range of floating concrete structures to show that technological risks are at a known and acceptable level.

The report starts with a historical presentation of floating structures and design concepts to establish both the versatility and technical viability of concrete floating marine structures. The durability and serviceability of floating structures at remote sites are important considerations to project planners and developers. Recommendations for design loads and design criteria are presented. Design procedures and methods of analysis are discussed to better acquaint the reader with the design considerations unique to floating marine structures.

CHAPTER 2—NOTATION, DEFINITIONS, AND ACRONYMS**2.1—Notation**

A_i	=	free surface in partially filled compartment, ft ² (m ²)
B	=	beam (width) of a floating structure, in. (m)
BM	=	distance from center of buoyancy to metacentric point, in., (m)
D	=	draft, in. (m)
$F(t)$	=	external force due to waves, lb (kN)
j	=	total number of load blocks considered
KB	=	distance from keel to center of buoyancy, in. (m)
KG	=	distance from keel to center of gravity, in. (m)
ℓ	=	length, in. (m)
M_{sw}	=	still-water bending moment, in.-lb (m-kN)
M_t	=	total bending moment, in.-lb (m-kN)

M_{wi}	=	wave-induced bending moment, in.-lb (m-kN)
m_{m1}	=	vessel mass, lb (kg)
m_{m2}	=	added mass, lb (kg)
N_i	=	number of load cycles causing failure if load block i acts alone
n_i	=	actual number of load cycles for load block i
r_i	=	distance from free surface to axis of waterplane of entire structure in direction of rotation, in. (m)
V_{sw}	=	maximum still-water hull-girder shearing force, lb (kN)
V_t	=	total hull-girder shear, lb (kN)
V_{wi}	=	maximum shearing force induced by waves, lb (kN)
x	=	displacement of the motion, in. (m)
$\dot{x}$	=	velocity of the motion, in./s (m/s)
$\ddot{x}$	=	acceleration of the motion, in./s ² (m/s ²)
β	=	linearized damping coefficient, lb-s/in. (kN-s/m)
γ	=	hydrostatic restoration coefficient, lb/ft (kN/m)
η	=	Minor's sum in accumulative fatigue damage analysis

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://terminology.concrete.org>. Definitions provided herein complement that resource.

ballast—any solid or liquid weight placed in a ship to increase the draft, to change the trim, or to regulate the stability.

ballast tank—watertight compartment to hold water ballast.

beam—width of the vessel or floating structure.

bow—the forward end of a ship.

bulkhead—vertical partition walls, which subdivide the interior of a vessel into compartments or rooms. Bulkheads that contribute to the strength of a vessel are called strength bulkheads, those which are essential to the watertight or oil-tight bulkheads, and gas-tight bulkheads serve to prevent the passage of gas or fumes.

bullard pull—pull force on a bullard.

draft—the depth of the ship below the water measured vertically to the lowest part of the hull, propellers, or other reference point.

hogging—straining of the ship that tends to make the bow and stern lower than the middle portion.

keel—the principal fore- and aft-component of a ship's framing, located along the centerline of the bottom.

metacenter or metacentric point—the intersection of a vertical line drawn through the center of buoyancy of a slightly listed vessel and the centerline plane.

sagging—straining of the ship that tends to make the middle portion lower than the bow and stern.

sea state—the overall sea condition to be used for design.

stability—the tendency of a ship to remain upright, or the ability to return to a normal upright position when heeled by the action of waves and wind.

stern—after end of ship.

trim—the difference between the draft forward and the draft aft.

2.3—Acronyms

ABS—American Bureau of Shipping

API—American Petroleum Institute

CIP—cast-in-place

DnV—Det Norske Veritas

LNG—liquid natural gas

LPG—liquid petroleum gas

LR—Lloyd's Register of Shipping

RAO—response amplitude operator

TLP—tension-leg platform

ULS—ultimate limit state

USDOT—U.S. Department of Transportation

CHAPTER 3—APPLICATIONS

3.1—Introduction

Chapter 3 presents a brief historical background on the use of concrete for floating structures, and describes examples of concrete ships, barges, plantships, storage facilities, piers, docks, and breakwaters that have been constructed or are being developed. The selection of examples is not intended to provide a comprehensive list of applications, but rather to illustrate the wide variety of marine applications for which concrete has provided safe, functional, durable, and economical solutions. These applications not only illustrate the versatility of floating concrete structures, but also highlight some creative and novel engineering solutions to complex engineering problems.

3.2—Historical background

The first use of reinforced concrete in floating vessels is attributed to Lambot who, in 1848, constructed a boat by applying sand-cement mortar over a framework of iron bars and mesh. The first self-propelled reinforced concrete ship was launched in 1917. This was the *M.S. Namsenfjord*, built by N. K. Fougner in Norway. Fougner went on to build several larger self-propelled reinforced concrete vessels (USDOT 1981).

The first self-propelled concrete ship in the U.S. was the *S.S. Faith*, which was launched in 1918. It was built in San Francisco and was, at that time, the largest concrete ship in the world, with a design deadweight of 5000 tons (4540 tonnes). It had an overall length of 320 ft (97.5 m), a beam of 44.5 ft (13.5 m), and a depth of 30 ft (9.1 m) (Fiorato 1981).

A principal impetus for continued development of concrete ships was the shortage of steel that occurred during World Wars I and II. In 1918, the U.S. Emergency Fleet Corporation instituted a program that resulted in the construction of 12 reinforced concrete vessels with deadweights up to 7500 tons (6800 tonnes) (Fiorato 1981). These vessels used lightweight concrete extensively. Expanded clay and shale aggregates were developed to obtain concretes with 28-day compressive strengths in excess of 4000 psi (28 MPa) and unit density of approximately 110 lb/ft³ (1760 kg/m³).

Although a few concrete vessels were built after World War I, it was not until World War II that another major concrete ship program was undertaken (Fiorato 1981). The U.S. Maritime Commission initiated a project in mid-1941 that eventually resulted in the construction of 104 vessels, 20 of which were self-propelled. These vessels had a minimum concrete strength requirements of 5000 psi (35 MPa) at 28 days.

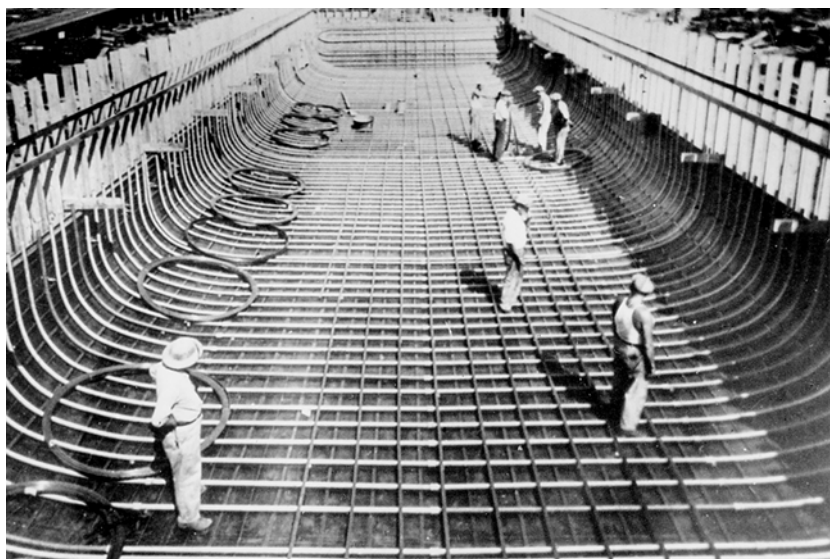


Fig. 3.1—Prestressed concrete landing craft.

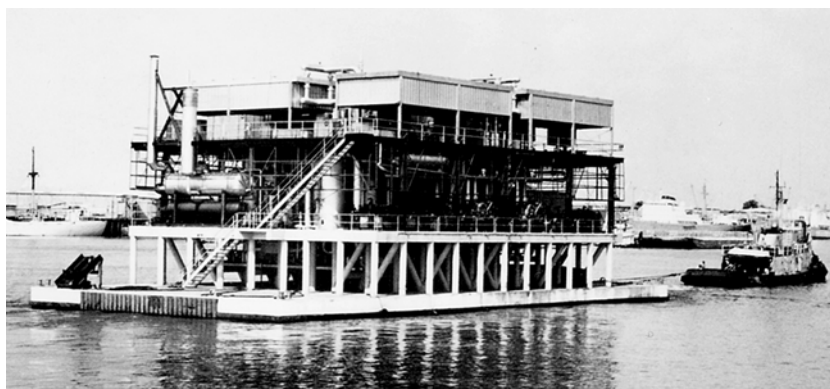


Fig. 3.2—Floating concrete bridge.

Concrete produced at the different yards had fresh unit densities ranging from 108 to 128 lb/ft³ (1730 to 2050 kg/m³) and 28-day compressive strengths ranging from 5085 to 6920 psi (35 to 48 MPa). Some of the World War I or II vessels saw extensive service, and most were eventually used for storage barges or breakwaters.

Not all of the reinforced concrete vessels constructed during World War II were ships or barges (Anderson 1975). A number of large floating concrete dry docks were also constructed, including ones in Philadelphia, PA; Norfolk, VA; and Hunter's Point, CA. One had a length in excess of 400 ft (120 m) and could dry dock a 7000 ton (6350 tonne) vessel. It is still in use for the Port of Bellingham, WA.

Two prestressed concrete vessels were also constructed during World War II. One was a landing craft and the other a barge (Anderson 1975). They were constructed of precast egg-crate cells with prestressing steel tensioned along the space between cells (Fig. 3.1). The steel was then covered with a layer of shotcrete.

Since World War II, the primary applications for floating concrete structures have been barges, oil drilling and storage

platforms, floating bridges, docks, floating breakwaters, and pontoons.

3.3—Ships and barges

Along the U.S. Gulf Coast in Louisiana and Texas, concrete barges serve as float-in-place foundations for oil production, processing, and storage facilities (The Society of Naval Architects and Marine Engineers [SNAME] 1967). The barges are used to support pump and compressor installations, processing equipment, water and wastewater treatment plants, settling basins, skimmer tanks, and living quarters (Fig. 3.2). They can also serve as floating docks. One type of barge, the Belden system, consists of an egg-crate hull made of precast reinforced concrete panels. The assembled panels are wrapped with welded wire fabric reinforcement, and shotcrete is applied to the exterior. Various topside configurations can be constructed on the hull, depending on the intended use of the barge. Once constructed, the fully outfitted facility can be towed to its destination and ballasted into position. These structures are designed to be deballasted, refloated, and relocated. More than 400 of these structures are in use (USDOT 1981).

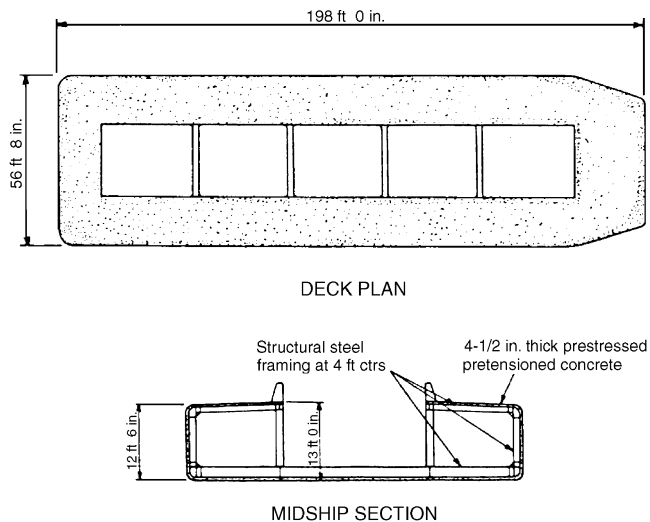


Fig. 3.3—General cargo barge.

Prestressed concrete transport barges constructed in the Philippines have been in service since 1964 (Yee et al. 1975; Sare and Yee 1977). Sixteen were built for general cargo use and three were built for bulk petroleum transport (Fig. 3.3). The typical configuration includes an inner steel framing system supporting a mild steel-reinforced and prestressed concrete hull. Deadweights range from 700 to 2000 tons (630 to 1810 tonnes). The vessels saw considerable service, including transport of ammunition, explosives, and petroleum products during the Vietnam War. The concrete in these smaller barges has resisted severe exposure from cargoes such as industrial salts and fertilizers. The interior structural steel framing, however, has been susceptible to corrosion.

To overcome the durability and maintenance limitations of the transverse structural steel framing, a concrete honeycomb framing system was developed that provides an efficient strength-weight ratio (American Concrete Institute (ACI) 1982; Anderson 1977). The total volume of internal framing occupies only a small fraction of the enclosed volume of the hull.

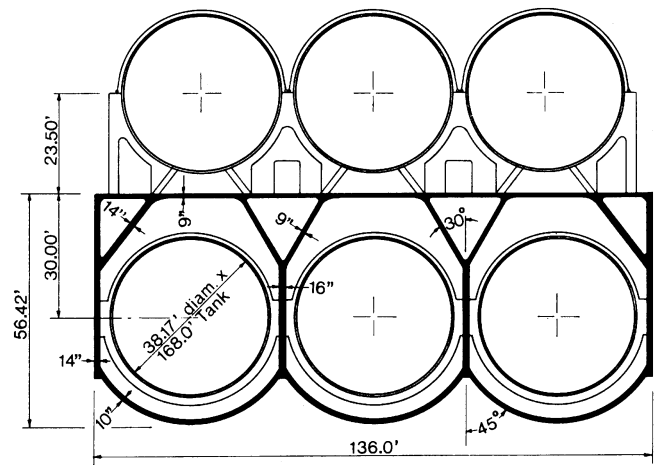
3.4—Industrial plantships

A floating terminal facility for liquefaction and storage of LPG was built for Atlantic Richfield Indonesia (Vialon and Bellbeoch 1997). The 65,000 ton (59,000 tonne) vessel, the *Ardjuna Sakti*, was designed as a post-tensioned segmental structure (Fig. 3.4(a) and (b)). Segments were individually match-cast and then post-tensioned together to form the hull. This structure was constructed in Tacoma, WA, and towed 10,000 miles (16,000 km) across the Pacific Ocean to the Ardjuna oil and gas fields in the Java Sea. It has been in service since 1976.

The N'Kossa Oil Production Unit, located 37 miles (60 km) off the coast of the Congo in 500 ft (150 m) of water, is one of the world's largest floating post-tensioned concrete structures. The main hull of the floating unit contains 35,000 yd³ (27,000 m³) of concrete, 5000 tons (4500 tonnes) of reinforcing steel, and 2350 tons (2100 tonnes) of prestressing



(a)



(b)

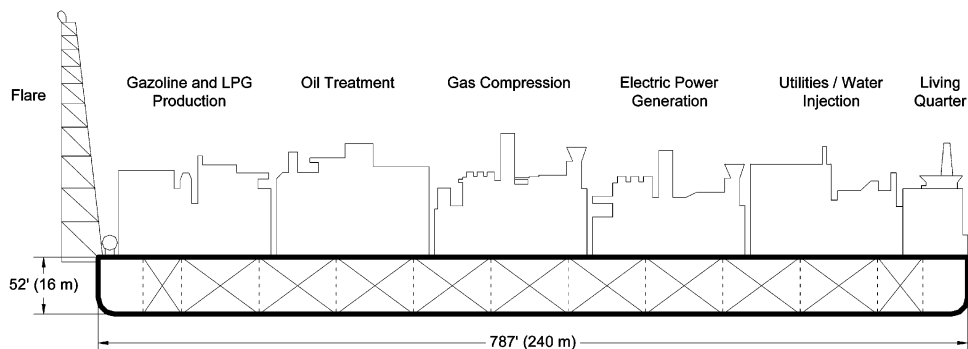
Fig. 3.4—(a) Liquid petroleum gas processing and storage facility (Ardjuna Sakti); and (b) cross section of Ardjuna Sakti.

strands (Fig. 3.5(a) and (b)). The successful construction and operation of N'Kossa have demonstrated the competitive advantages of a concrete ship over a steel ship in an offshore environment (Vialon and Bellbeoch 1997).

Offshore concrete gravity-based structures have been successfully built in the North Sea since the early 1970s (Gerwick and Hognestad 1973; Fidjestøl et al. 2004). The Hibernia offshore concrete platform, built in Newfoundland, Canada for oil production, is the first large offshore concrete platform to be built in North America and represents the largest single-use—199,000 yd³ (152,000 m³)—of high-strength concrete in North America (Hoff and Hitz 1997). The specified compressive strength of the concrete is 11,600 psi (80 MPa). The structure is designed to resist the impact of icebergs as well as the severe wave-loading of the North Atlantic Ocean. It is located in 260 ft (80 m) of water. The structure is barrel shaped, with the lower portion of the structure being 280 ft (85 m) tall and 350 ft (106 m) in diameter. The shafts extend another 85 ft (26 m) from the roof of the



(a)



(b)

Fig. 3.5—(a) N'Kossa Oil Production Unit being towed to a deep water outfitting site; and (b) a general layout of N'Kossa.

structure to support the topsides equipment (Fig. 3.6). The structure is designed to store 1.3 million barrels of oil.

The first concrete tension-leg platform (TLP), Heidrun, was constructed and installed in the Norwegian Sea at a depth of 1130 ft (345 m) in 1993-1994. The TLP is made of prestressed lightweight concrete with a gross topside weight of close to 90,000 tons (82,000 tonnes) (Birkeland et al. 1979). The concrete hull has four circular cylindrical columns 100 ft (31 m) in diameter. The columns are spaced at a center-to-center distance of 260 ft (80 m), and are interconnected by rectangular pontoons. Two rectangular modular support beams rest on brackets on the inner side of the columns. The topside modules rest on top of the beams (Fig. 3.7). Buoyancy of the hull is primarily provided by the columns and pontoons.

Four groups of tethers securely anchor the TLP hull to four individual foundations. These foundations are precast concrete boxes that were transported and installed at the site by float-in method. The vertical tether loads are taken by a combination of gravity and suction in the skirt compartment.

There are three primary types of concrete floating plant-ships (Fjeld 1988):

- Type 1—Wet-towed and moored at an installation site;
- Type 2—Wet-towed and grounded at an installation site; and
- Type 3—Dry-towed by barge that is capable of being submerged so as to offload the structure at the installation site.



Fig. 3.6—Hibernia offshore GBS under construction.

Each type may be capable of redeployment, being removed and installed at another site for production.

Design criteria selected for the different vessel types should address whether the hull is to be considered as a ship. When classed as a ship by a certification agency such as the American Bureau of Shipping (ABS), Det Norske Veritas (DnV), or Lloyd's Register of Shipping (LRS), criteria for items such as intact stability, damage stability, seaworthiness, and crew safety, are similar to those of conventional vessels. For Type 3, the hull is normally designed as a temporary floating structure. Care should be taken during design, however, to fully account for the interaction of the

concrete vessel and the supporting semisubmersible barge when afloat in the seaway.

Process applications for concrete plantships include:

- Fertilizer production;
- Manufacturing plants;
- Refineries;
- Desalination plants;
- Electric power stations;
- Chemical treatment facilities;
- Liquid natural gas (LNG) and liquid petroleum gas (LPG) terminals; and
- Tidal power generator modules.



Documents

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This list of applications illustrates the high potential for continued development.

3.5—Floating piers and docks

A floating precast prestressed concrete container dock is now in service in Valdez, AK (Precast/Prestressed Concrete Institute [PCI] 1982). The system consists of a 100 ft (30 m) wide by 700 ft (210 m) long by 30 ft (9 m) deep prestressed

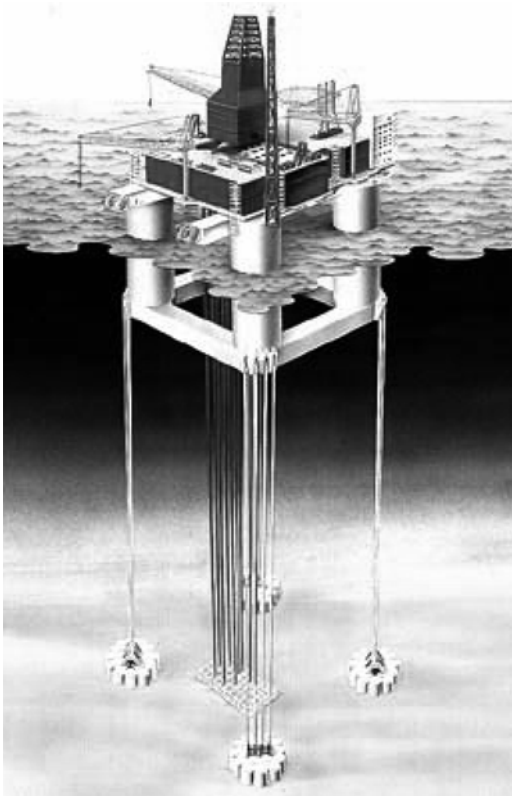


Fig. 3.7—Heidrun: the first concrete tension-leg platform.

concrete floating dock, a mooring system to hold the dock in position, and a fender system that protects both the dock and ships during berthing operations (Fig. 3.8). Construction economy and a tight schedule required the dock to be prefabricated off site and towed to the deployment location. Two dock pontoon sections were towed from Tacoma, WA, to Valdez, AK, and joined together on site. The dock provides a low-maintenance, high-capacity marine facility that rises and falls with tidal changes, providing an efficient interface with surface vessels during cargo transfer. Because it is floating, it can be redeployed.

Another example of a concrete floating dock facility is the twin ferry terminals on either side of Burrard Inlet in Vancouver, BC, Canada (ABAM 1986). Each terminal, E-shaped in plan, consists of four cellular concrete modules post-tensioned together to form a single integrated unit (Fig. 3.9). The floating system facilitates vessel berthing and eases passenger transfer. The concrete modules were assembled and prestressed in a graving dock, and floated out upon completion. While afloat, decking of the individual modules was completed. They were then joined by post-tensioning through CIP joints. Normalweight concrete with a 28-day design compressive strength of 7000 psi (48 MPa) was used throughout.

3.6—Floating bridges

Numerous floating bridges were constructed over the last century and portend significant further development and applications in the future. The Hood Canal Bridge and Ford Island Bridge are two well-known examples of floating structures that represent optimum cost-effective solutions for some difficult sites and special applications.

The Hood Canal floating bridge, which crosses Puget Sound in Washington, consists of a floating structure, fixed structure approaches to each end, and east and west road approaches (Fig. 3.10) (Nichols 1964; Abrahams and

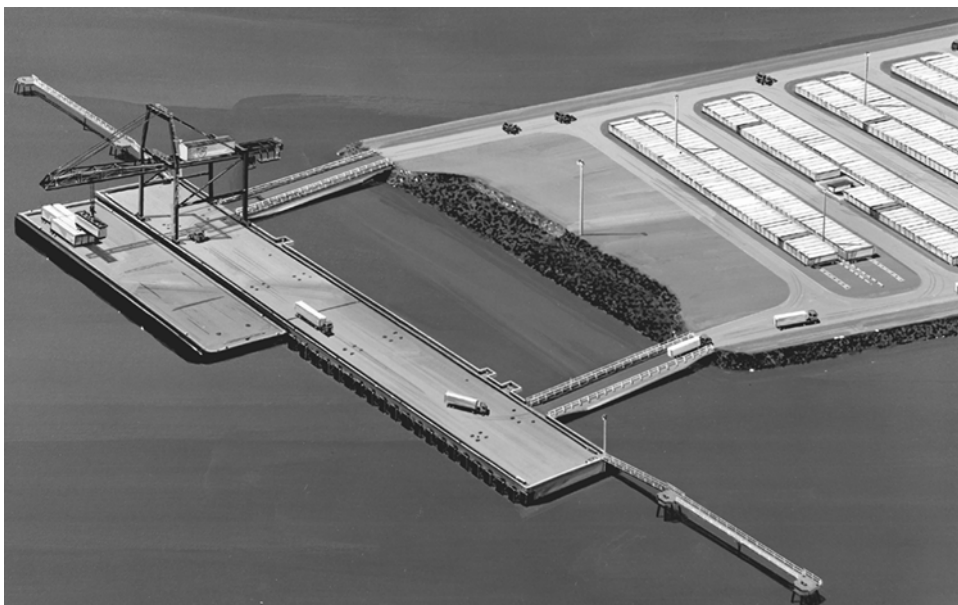


Fig. 3.8—Valdez Floating Container Pier.



Fig. 3.9—Concrete floating dock, Vancouver, BC, Canada.

Belvedere 1984; “Bridge Pontoons as Cast Singly in Tight Order” 1983). The structure was originally constructed in 1960. The bridge is 7863 ft (2347 m) long, including approach ramps, and the floating concrete portion is 6471 ft (1973 m) long. The original floating structure was designed to open to provide a 600 ft (180 m) wide channel for ship traffic. Prestressed concrete guide pontoons flanked the central floating pontoon in its open position. The pontoons were built in a graving dock in Seattle, and towed to the site in 1959. Normalweight concrete for the pontoons had a design compressive strength of 3000 psi (21 MPa) at 10 days. A schematic of the pontoon and elevated roadway structures is illustrated in Fig. 3.11.

In 1979, a severe winter storm destroyed the western portion of the bridge (Abrahams and Wilson 1998). A number of the pontoons were damaged and sank. Washington State Department of Transportation conducted an investigation into the cause of the sinking and determined that the bridge pontoons and anchor system had been loaded by a combination of waves and winds in excess of the original design criteria. A three-stage plan was developed for reconstruction of the bridge (Fig. 3.12). The plan included reconstruction of many pontoon segments (Zalocco 1984), reuse of some existing bridge segments, and a new anchoring scheme to secure the bridge. This anchoring scheme called for 26 concrete gravity anchors that are 46 ft (14 m) in diameter and 27 ft (8 m) in height (Fig. 3.13). The anchors are weighted with crushed slag and connected to the bridge segments by 1-3/4 in. (45 mm) cables. The reconstructed portion of the bridge uses larger pontoons and a wider roadway, more extensive use of prestressed concrete, and higher-strength concrete. The reconstructed bridge has been opened to traffic since October 1982. In 2003, the permanent replacement/rehabilitation of the bridge began. The scope of



Fig. 3.10—Hood Canal floating bridge.

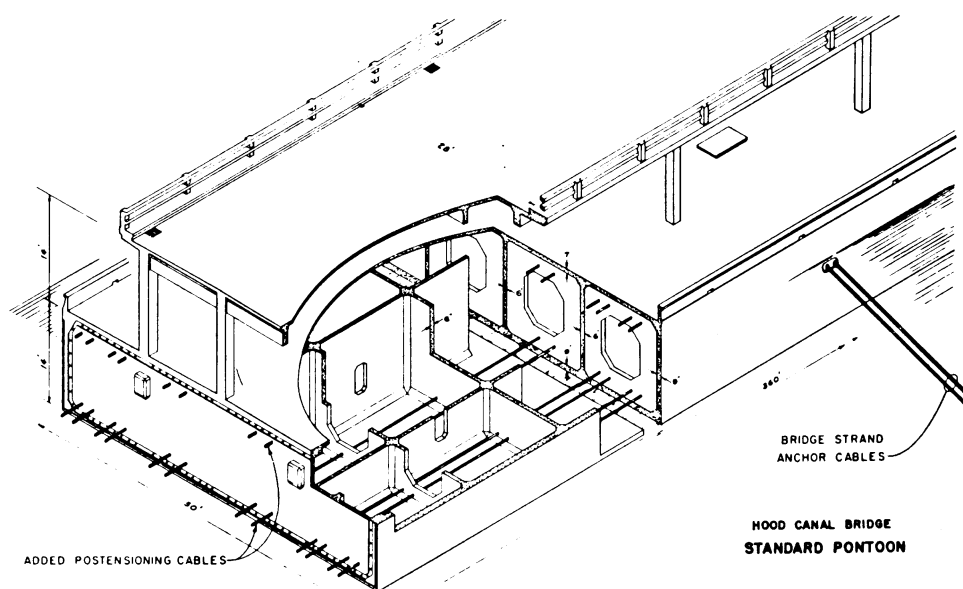


Fig. 3.11—Cutaway drawing of standard pontoon for Hood Canal Bridge.

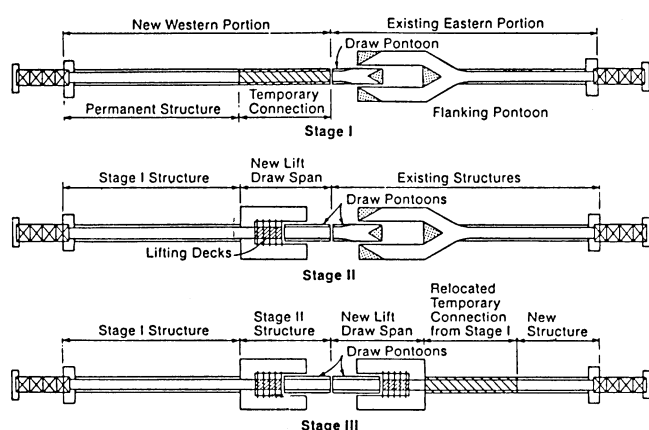


Fig. 3.12—Three-stage plan for Hood Canal Bridge construction.



Fig. 3.13—Hood Canal Bridge span replacement concrete gravity anchor during installation.

the project includes replacing the east half of the floating structure, widening the existing west half roadway deck, replacing both existing bridge approaches, replacing both transition truss spans, renovating three existing pontoons, casting and setting concrete gravity anchors, and providing a new control system for the entire bridge. The approach replacement and west side widening was completed in 2005. Concrete anchors weighing more than 1000 tons (907 tonnes) each were completed and set on the floor of Hood Canal during summer 2007. Pontoons are being cast at Concrete Technology's Tacoma, WA, graving dock and the rehabilitation of three existing pontoons is ongoing at the Port of Seattle's Terminal 91. Assembly and outfitting of the new drawspan began at Todd Shipyard in July 2007.

The Ford Island Bridge in Hawaii connects Ford Island with the island of Oahu at Pearl Harbor, includes a 1000 ft (305 m) long causeway, a 4000 ft (1219 m) long fixed trestle, and a 1035 ft (315 m) long movable section. The movable section consists of two steel transition spans and a 930 ft (284 m) floating drawspan with its two ends extending under the transition spans (Fig. 3.14). The floating section of the bridge provides a 650 ft (198 m) wide access channel through the bridge so large Navy ships can travel around Ford Island in Pearl Harbor.

The floating drawspan is made up of three 310 ft (94.5 m) long, 50 ft (15.2 m) wide, and 17.5 ft (5.3 m) deep floating concrete modules. Each module is divided into 21 watertight cells by longitudinal and transverse bulkheads, and displaces approximately 5500 tons (5000 tonnes). The pontoon modules were constructed using a mixture of precast and cast-in-place (CIP) concrete. The walls, diaphragms, and soffit of the pontoon deck are precast. The remainder of the pontoon is made of CIP concrete for the bottom slab, wall closures, and upper deck (Fig. 3.15). The entire pontoon was post-tensioned longitudinally to a level that would maintain it in constant compression under service load conditions, and



Fig. 3.14—Precast prestressed floating drawspan being retracted under fixed bridge spans.

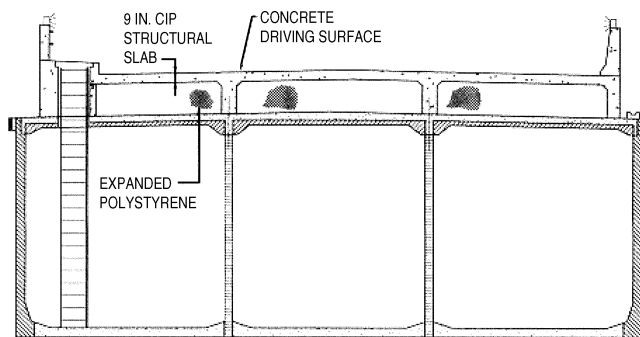


Fig. 3.15—A typical cross section of the floating drawspan of 50 ft (15.2 m) width and 17.5 ft (5.2 m) depth.

exceed the required strength calculated for the condition of one cell flooded. The three pontoons were tied together with high-strength bolts to provide the entire drawspan. The floating section was fabricated in Tacoma, WA, and towed to Hawaii for on-site assembly and installation. The bridge was completed and opened in 1998.

3.7—Immersed tunnels

Reinforced concrete segments were used to construct an underwater tunnel to connect Amsterdam with surrounding areas (Gimsing and Iversen 2001). The reinforced concrete segments were constructed in a dry dock in 70 ft (21 m) wide by 73 ft (22 m) long pieces that were assembled into 440 ft (135 m) long units before being floated to the tunnel site (Fig. 3.16). Each unit was outfitted with instrumentation to permit survey control during placement. The underwater tunnel length is 4840 ft (1475 m). Because of the unique nature of the project, special care was taken to carefully control the unit weight of the reinforced concrete segments.



Fig. 3.16—Tunnel elements being towed into position.

This permitted accurate control of launching, sinking, and final positioning.

The Oresund Crossing is a fixed traffic link between Denmark and Sweden. The link, completed in the year 2000, consists of a 13,290 ft (4050 m) long immersed concrete tunnel, a 13,250 ft (4044 m) long artificial island, and a 21,850 ft (6660 m) long bridge. It was the largest immersed tunnel at the time. The immersed tunnel consists of 20 precast concrete segments. Each segment is approximately 574 ft (175 m) long, 127 ft (39 m) wide, and 28 ft (8.6 m) in depth, and weighs 62,000 tons (56,000 tonnes). A typical cross section of the tunnel is shown in Fig. 3.17. The concrete mixture was developed to enhance durability and watertightness of the tunnel. Closure pours between the segments were made with self-consolidating concrete. Because the project design relies entirely on the concrete quality without any

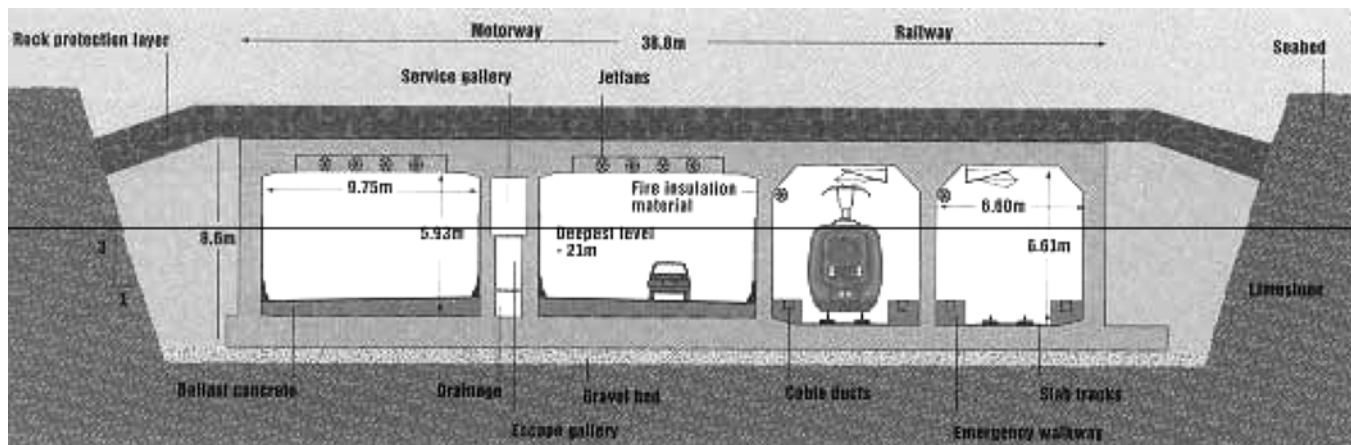


Fig. 3.17—A cross section of the Oresund Tunnel.

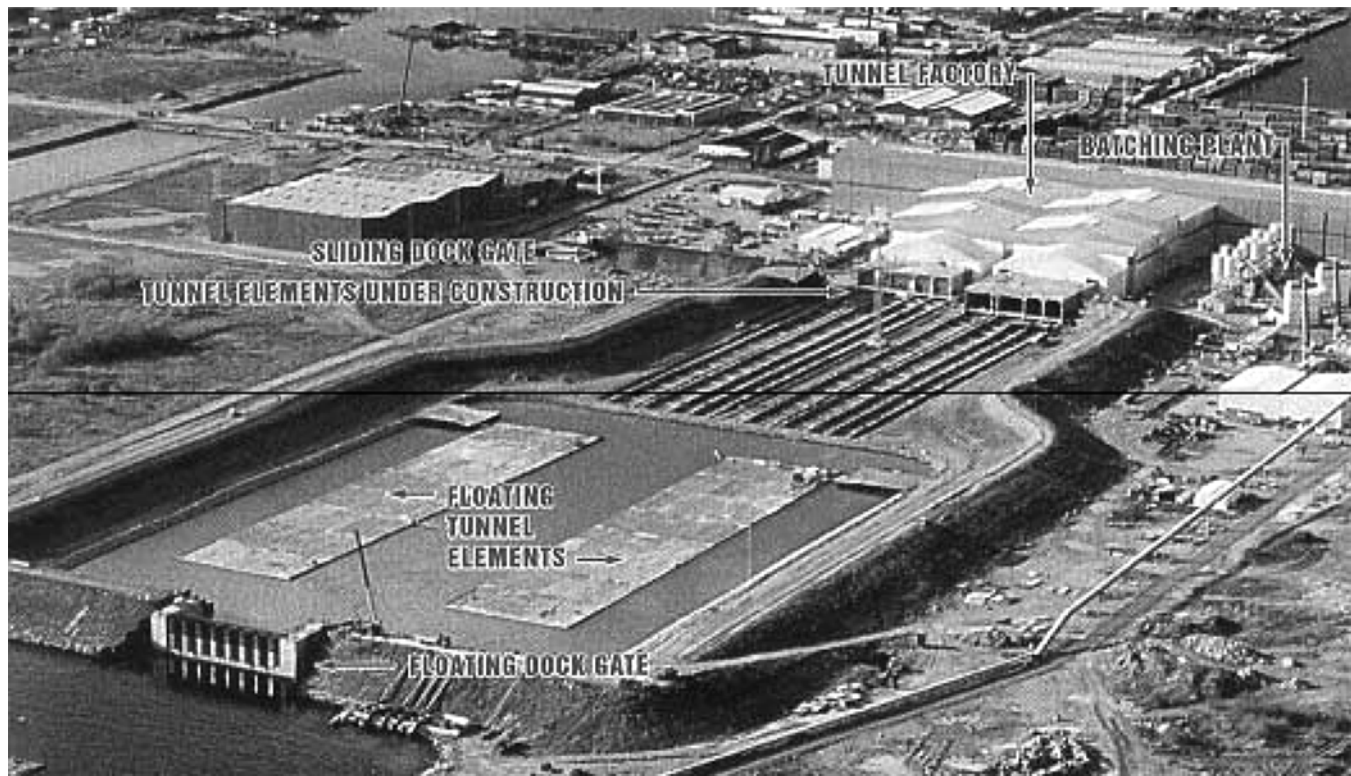


Fig. 3.18—The casting yard and launching basin (Oresund Tunnel).

external membrane, thermal cracking of the concrete was avoided by casting the whole cross section in one continuous operation, and then cooling the entire section in a uniform and controlled manner.

The tunnel segments were fabricated in a casting yard in the Copenhagen North Harbor, and towed approximately 10 miles (16 km) to the project site for immersion. The segment was cast in eight sections with a match casting method on a casting bed inside an enclosed facility protected from the weather. Launching of the immersed tunnel segments was carried in a two-level basin (Fig. 3.18). The upper level is 3.3 ft (1 m) above sea level, and the lower level is 33 ft (10 m) below sea level. Because the currents at the site are variable and often

very strong, this led to the development of a more reliable anchor system for positioning and installing the immersed tunnel segments. As a result, all of the immersed tunnel segments were placed within tolerances of 3/8 in. (10 mm) horizontal alignment and 3/16 in. (5 mm) vertical alignment.

3.8—Navigation structures

In recent years, a major development has taken place in the construction of navigation structures in the U.S. waterways—the use of an offsite prefabrication construction method, also known as “in-the-wet.” This innovative method uses precast concrete modules as the in-place form into which fresh concrete or other infill material is placed directly, without