Lwin, M.M. "Floating Bridges."
Bridge Engineering Handbook.
Ed. Wai-Fah Chen and Lian Duan
Boca Raton: CRC Press, 2000

22

Floating Bridges

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22.1 Introduction

Floating bridges are cost-effective solutions for crossing large bodies of water with unusual depth and very soft bottom where conventional piers are impractical. For a site where the water is 2 to 5 km wide, 30 to 60 m deep and there is a very soft bottom extending another 30 to 60 m, a floating bridge is estimated to cost three to five times less than a long-span fixed bridge, tube, or tunnel.

A modern floating bridge may be constructed of wood, concrete, steel, or a combination of materials, depending on the design requirements. A 124-m-long floating movable wood pontoon railroad bridge was built in 1874 across the Mississippi River in Wisconsin in the United States. It was rebuilt several times before it was abandoned. A 98-m-long wood floating bridge is still in service in Brookfield, Vermont. The present Brookfield Floating Bridge is the seventh replacement structure, and was built by the Vermont Agency of Transportation in 1978. The first 2018-m-long Lake Washington Floating Bridge in Seattle [1,2], Washington, was built of concrete and opened to traffic in 1940 (Figure 22.1). Since then, three more concrete floating bridges have been built [2,3]. These concrete floating bridges form major transportation links in the state and interstate highway systems in Washington State. The Kelowna Floating Bridge on Lake Okanagan in British Columbia, Canada [4], was built of concrete and opened to traffic in 1958. It is 640 m long and carries two lanes of traffic. The 1246-m-long Salhus Floating Bridge and the 845-m-long Bergsoysund Floating Bridge in Norway (Figure 22.2) were constructed of concrete pontoons and steel superstructures [5]. They were opened to traffic in the early 1990s.

FIGURE 22.1 First Lake Washington floating bridge.

Washington State's experience has shown that reinforced and prestressed concrete floating bridges are cost-effective, durable, and low in maintenance as permanent transportation facilities. Concrete is highly corrosion resistant in a marine environment when properly designed, detailed, and constructed. Concrete is a good dampening material for vibration and noise, and is also far less affected by fire and heat than wood, steel, or other construction materials.

22.2 Basic Concept

The concept of a floating bridge takes advantage of the natural law of buoyancy of water to support the dead and live loads. There is no need for conventional piers or foundations. However, an anchoring or structural system is needed to maintain transverse and longitudinal alignments of the bridge.

A floating bridge is basically a beam on an elastic foundation and supports. Vertical loads are resisted by buoyancy. Transverse and longitudinal loads are resisted by a system of mooring lines or structural elements.

The function of a floating bridge is to carry vehicles, trains, bicycles, and pedestrians across an obstacle — a body of water. Inasmuch as a floating bridge crosses an obstacle, it creates an obstacle for marine traffic. Navigational openings must be provided for the passage of pleasure boats, smaller water crafts, and large vessels. These openings may be provided at the ends of the bridge. However, large vessels may impose demands for excessive horizontal and vertical clearances. In such cases, movable spans will have to be provided to allow the passage of large vessels. The Hood Canal Floating Bridge in Washington State has a pair of movable spans capable of providing a total of 183 m of horizontal clearance (Figure 22.3). Opening of the movable spans for marine traffic will cause interruption to vehicular traffic. Each interruption may be as long as 20 to 30 min. If the frequency of openings is excessive, the concept of a floating bridge may not be appropriate for the site. Careful consideration should be given to the long-term competing needs of vehicular traffic and marine traffic before the concept of a highway floating bridge is adopted.

FIGURE 22.2 The Bergsoysund floating bridge.

FIGURE 22.3 Movable spans for large vessels.

FIGURE 22.4 Continuous pontoon-type structure.

22.3 Types

22.3.1 Floating Structure

Floating bridges have been built since time immemorial. Ancient floating bridges were generally built for military operations [6]. All of these bridges took the form of small vessels placed side by side with wooden planks used as a roadway. Subsequently, designers added openings for the passage of small boats, movable spans for the passage of large ships, variable flotation to adjust for change in elevations, and so on.

Modern floating bridges generally consist of concrete pontoons with or without an elevated superstructure of concrete or steel. The pontoons may be reinforced concrete or prestressed concrete post-tensioned in one or more directions. They can be classified into two types, namely, the continuous pontoon type and the separate pontoon type. Openings for the passage of small boats and movable spans for large vessels can be incorporated into each of the two types of modern floating bridges.

A continuous pontoon floating bridge consists of individual pontoons joined together to form a continuous structure (Figure 22.4). The size of each individual pontoon is based on the design requirements, the construction facilities, and the constraints imposed by the transportation route. The top of the pontoons may be used as a roadway or a superstructure may be built on top of the pontoons. All the present floating bridges in Washington State are of the continuous pontoon floating bridge type.

A separate pontoon floating bridge consists of individual pontoons placed transversely to the structure and spanned by a superstructure of steel or concrete (Figure 22.5). The superstructure must be of sufficient strength and stiffness to maintain the relative position of the separated pontoons. The two floating bridges in Norway are of the separate pontoon floating bridge type.

Both types of floating structures are technically feasible and relatively straightforward to analyze. They can be safely designed to withstand gravity loads, wind and wave forces, and extreme events,

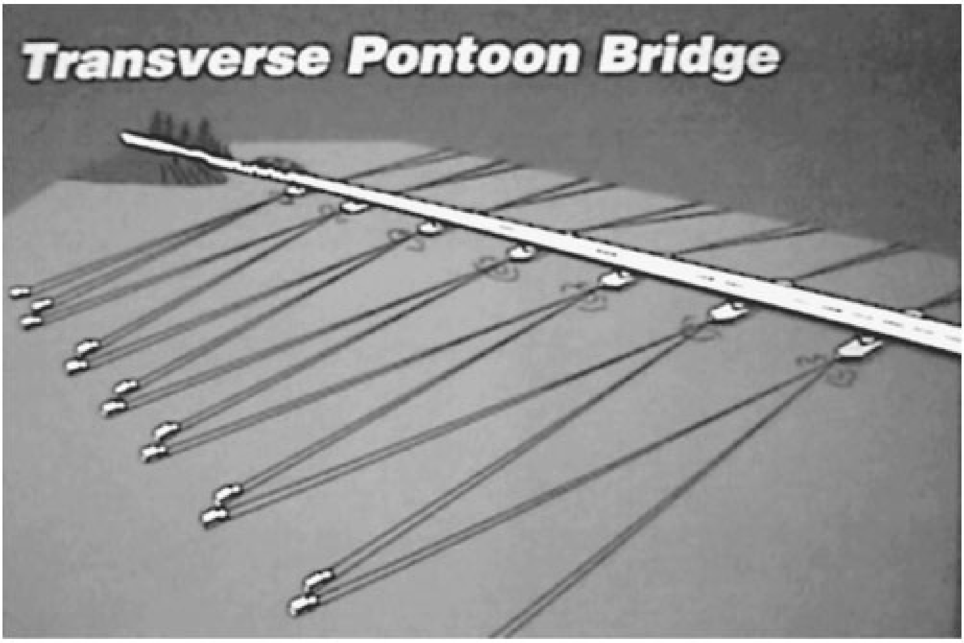

FIGURE 22.5 Separate pontoon-type structure.

such as vessel collisions and major storms. They perform well as highway structures with a high-quality roadway surface for safe driving in most weather conditions. They are uniquely attractive and have low impact on the environment. They are very cost-effective bridge types for water crossing where the water is deep (say, over 30 m) and wide (say, over 900 m), but the currents must not be very swift (say, over 6 knots), the winds not too strong (say, average wind speed over 160 km/h), and the waves not too high (say, significant wave height over 3 m).

22.3.2 Anchoring Systems

A floating structure may be held in place in many ways — by a system of piling, caissons, mooring lines and anchors, fixed guide structures, or other special designs. The most common anchoring system consists of a system of mooring lines and anchors. This system is used in all the existing floating bridges in Washington State. The mooring lines are galvanized structural strands meeting ASTM A586. Different types of anchors may be used, depending on the water depth and soil condition. Four types of anchors are used in anchoring the floating bridges on Lake Washington, Seattle.

Type A anchors (Figure 22.6) are designed for placement in deep water and very soft soil. They are constructed of reinforced concrete fitted with pipes for water jetting. The anchors weigh from 60 to 86 tons each. They are lowered to the bottom of the lake and the water jets are turned on allowing the anchors to sink into the soft lake bottom to embed the anchors fully. Anchor capacity is developed through passive soil pressure.

Type B anchors (Figure 22.7) are pile anchors designed for use in hard bottom and in water depth less than 27 m. A Type B anchor consists of two steel H-piles driven in tandem to a specified depth. The piles are tied together to increase capacity.

Type C anchors (Figure 22.8) are gravity-type anchors, constructed of reinforced concrete in the shape of a box with an open top. They are designed for placement in deep water where the soil is too hard for jetting. The boxes are lowered into position and then filled with gravel to the specified weight.

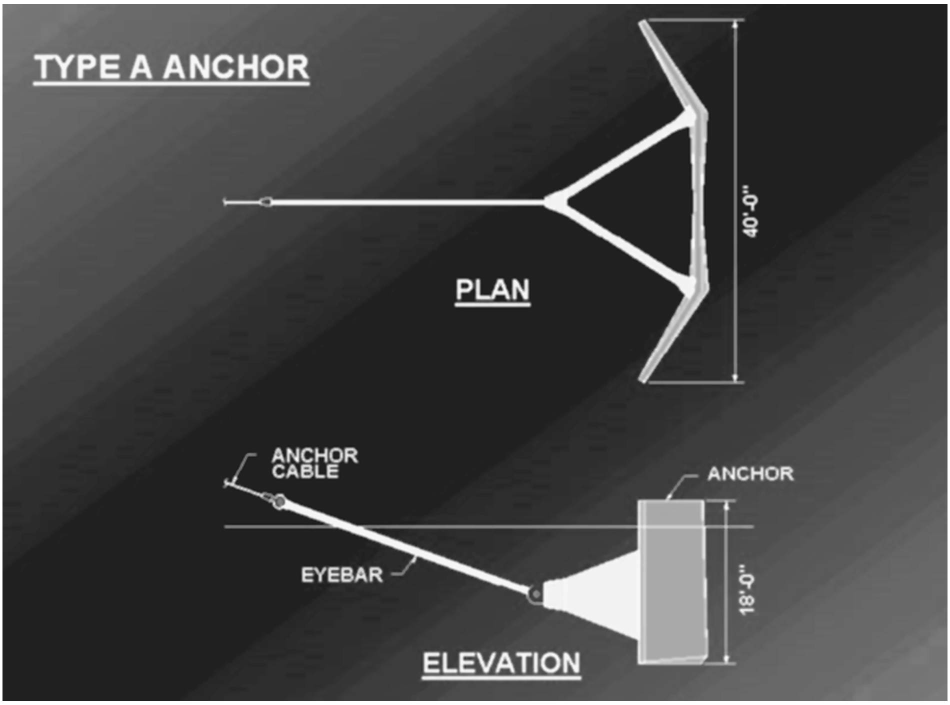

FIGURE 22.6 Type A anchor.

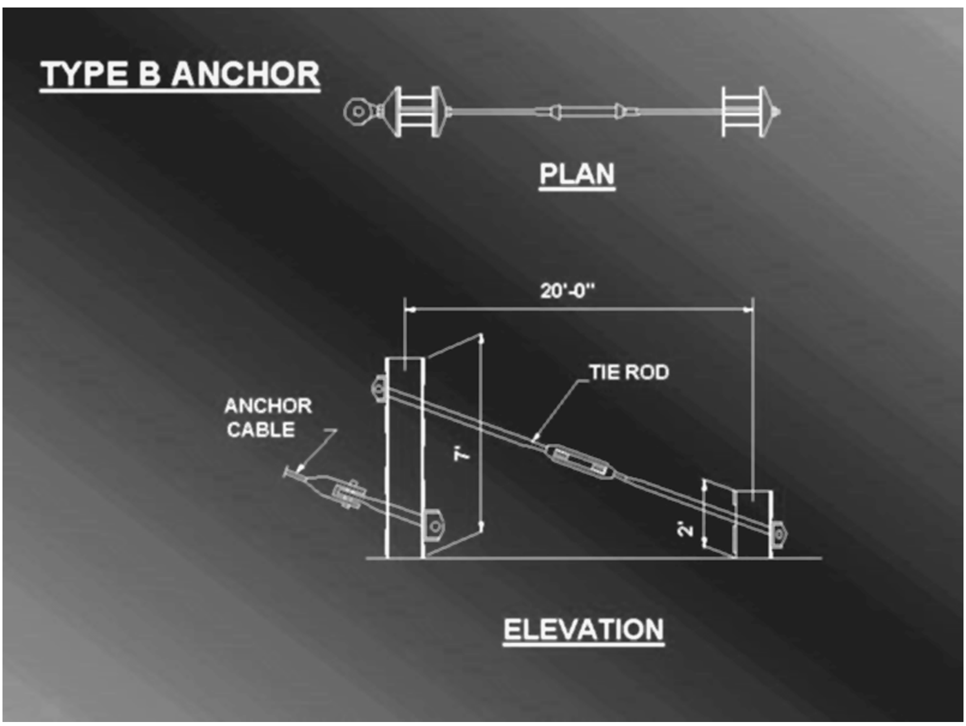

FIGURE 22.7 Type B anchor.

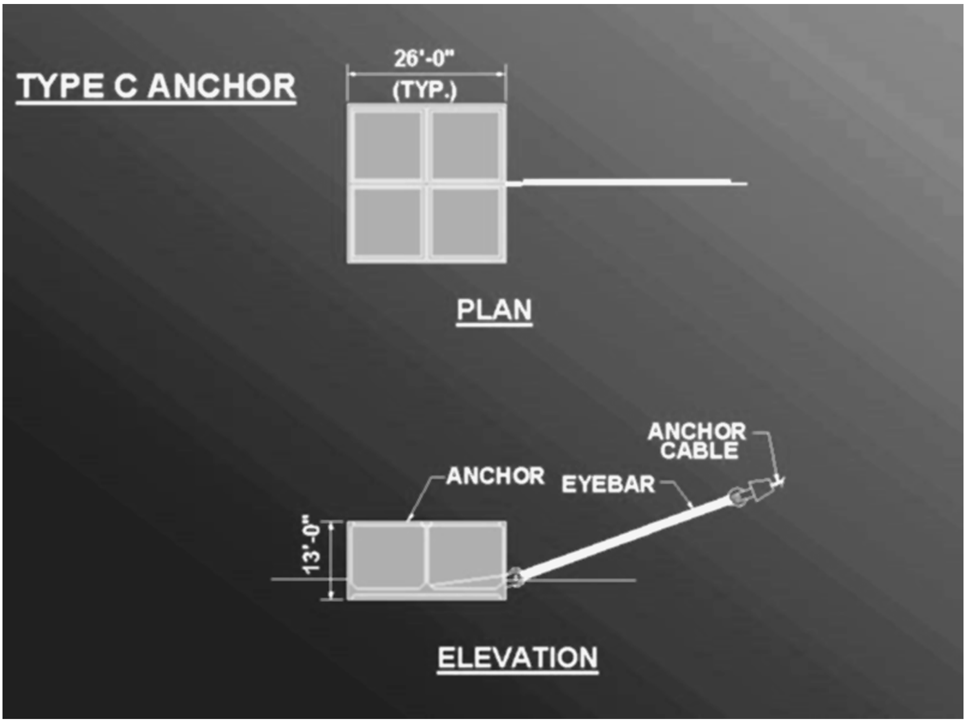

FIGURE 22.8 Type C anchor.

Type D (Figure 22.9) anchors are also gravity-type anchors like the Type C anchors. They consist of solid reinforced concrete slabs, each weighing about 270 tons. They are designed for placement in shallow and deep water where the soil is too hard for water jetting. The first slab is lowered into position and then followed by subsequent slabs. The number of slabs is determined by the anchor capacity required. Type D anchors are the choice over Type B and Type C anchors, because of the simplicity in design, ease in casting, and speed in placement.

22.4 Design Criteria

The design of a floating bridge follows the same good engineering practices as for land-based concrete or steel bridges. The design and construction provisions stipulated in the AASHTO *Standard Specifications for Highway Bridges* [7] or the *LRFD Bridge Design Specifications* [8] are applicable and should be adhered to as much as feasible. However, due to the fact that a floating bridge is floating on fresh or marine waters, the design criteria must address some special conditions inherent in floating structures. The performance of a floating bridge is highly sensitive to environmental conditions and forces, such as winds, waves, currents, and corrosive elements. The objectives of the design criteria are to assure that the floating bridge will

- Have a long service life of 75 to 100 years with low life-cycle cost;
- Meet functional, economical, and practical requirements;
- Perform reliably and be comfortable to ride on under normal service conditions;
- Sustain damage from accidental loads and extreme storms without sinking;
- Safeguard against flooding and progressive failure.

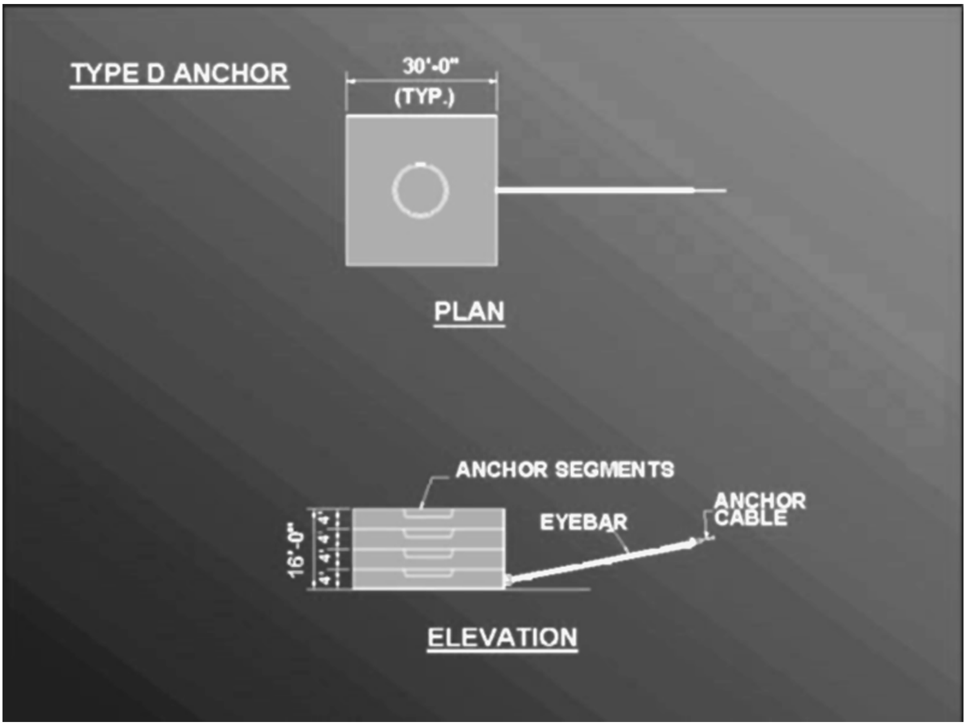

FIGURE 22.9 Type D anchor.

22.4.1 Loads and Load Combinations

The structure should be proportioned in accordance with the loads and load combinations for service load design and load factor design outlined in the AASHTO *Standard Specifications for Highway Bridges* or the AASHTO *LRFD Bridge Design Specifications,* except the floating portion of the structure shall recognize other environmental loads and forces and modify the loads and load combinations accordingly.

Winds and waves are the major environmental loads, while currents, hydrostatic pressures, and temperatures also have effects on the final design. Depending on the site conditions, other loadings, such as tidal variations, marine growth, ice, drift, etc., may need to be considered.

22.4.2 Winds and Waves

Winds and waves exert significant forces on a floating structure (Figure 22.10). Yet these environment loads are the most difficult to predict. Generally, there is a lack of long-term climatological data for a bridge site. A long record of observations of wind data is desirable for developing more accurate design wind speeds and wave characteristics. It is advisable to install instruments on potential bridge sites to collect climatological data as early as possible.

Wind blowing over water generates a sea state that induces horizontal, vertical, and torsional loads on the floating bridge. These loads are a function of wind speed, wind direction, wind duration, fetch length, channel configuration, and depth. Consideration must be given to the normal and extreme storm wind and wave conditions for the site. The normal storm conditions are defined as the storm conditions that have a mean recurrence interval of 1 year, which is the maximum storm that is likely to occur once a year. The extreme storm conditions are defined as the storm conditions that have a mean recurrence interval of 100 years, which is the maximum storm that is likely to occur once in 100 years. These wind and wave forces may be denoted by

FIGURE 22.10 Wind and wave forces.

WN = Normal Wind on Structure — 1-year Storm
NW = Normal Wave on Structure — 1-year Storm
WS = Extreme Storm Wind on Structure — 100-year Storm
SW = Extreme Storm Wave on Structure — 100-year Storm

The following modifications are recommended for the AASHTO Load Combinations where wind loads are included:

1. Substitute WS + SW for W, and WN + NW for 0.3W.
2. Use one half the temperature loads in combination with WS and SW.
3. Omit L, I, WL, and LF loads when WS and SW are used in the design.

A 20-year wind storm condition is normally used to make operational decisions for closing the bridge to traffic to ensure safety and comfort to the traveling public. This is especially important when there is excessive motion and water spray over the roadway. When there is a movable span in the floating bridge for providing navigation openings, a 20-year wind storm is also used to open the movable span to relieve the pressures on the structure.

Following is an example of a set of wind and wave design data:

Return Interval	Wind Speed (1-min average)	Significant Wave Height	Period
1-year wind storm	76 km/h	0.85 m	3.23 s
20-year wind storm	124 km/h	1.55 m	4.22 s
100-year wind storm	148 km/h	1.95 m	4.65 s

22.4.3 Potential Damage

A floating bridge must have adequate capacity to safely sustain potential damages (DM) resulting from small vessel collision, debris or log impact, flooding, and loss of a mooring cable or component. Considering only one damage condition and location at any one time, the pontoon structure must be designed for at least the following:

1. *Collision*: Apply a 45-kN horizontal collision load as a service load to the pontoon exterior walls. Apply a 130-kN horizontal collision load as a factored load to the pontoon exterior wall. The load may be assumed to be applied to an area no greater than 0.3 × 0.3 m.
2. *Flooding*:
   - Flooding of any two adjacent exterior cells along the length of the structure
   - Flooding of all cells across the width of the pontoon
   - Flooding of all the end cells of an isolated pontoon during towing
   - Flooding of the outboard end cells of a partially assembled structure
3. *Loss of a mooring cable or component*.
4. *Complete separation of the floating bridge by a transverse or diagonal fracture*. This condition should apply to the factored load combinations only.

The above potential DM loadings should be combined with the AASHTO Groups VI, VIII, and IX combinations for Service Load Design and Load Factor Design. If the AASHTO LRFD Bridge Design Specifications are used in the design, the loads from Items 2 to 4 may be considered as extreme events.

Every floating structure is unique and specific requirements must be established accordingly. Maritime damage criteria and practices, such as those for ships and passenger vessels, should be reviewed and applied where applicable in developing damage criteria for a floating structure. However, a floating bridge behaves quite differently than a vessel, in that structural restraint is much more dominant than hydrostatic restraint. The trim, list, and sinkage of the flooded structure are relatively small. With major damage, structural capacity is reached before large deformations occurred or were observed. This is an important fact to note when comparing with stability criteria for ships.

22.4.4 Control Progressive Failure

While water provides buoyancy to keep a floating bridge afloat, water leaking into the interior of a floating bridge can cause progressive failure, eventually sinking the bridge. Time is of the essence when responding to damage or flooding. Maintenance personnel must respond to damage of a floating bridge quickly, especially when water begins to leak into the structure. An electronic cell monitoring system with water sensors to detect water entry and provide early warning to the maintenance personnel should be installed to assure timely emergency response. A bilge piping system should also be installed in the bridge for pumping out water.

It is important to control progressive failure in a floating bridge caused by flooding resulting from structural damage. Damage to the floating bridge could occur from a wind storm, a collision by a boat, severing of mooring lines, or other unforeseen accidents. The interior of the pontoons should be divided into small watertight compartments or cells (Figure 22.11) to confine flooding to only a small portion of the bridge. Access openings in the exterior or interior wall or bulkheads shall be outfitted with watertight doors.

Water sensors may be installed in each watertight compartment for early detection and early warning of water entry. A bilge piping system may be installed in the compartments for pumping out water when necessary. In such cases, pumping ports and quick disconnect couplings should be provided for pumping from a boat or vehicle equipped with pumps.

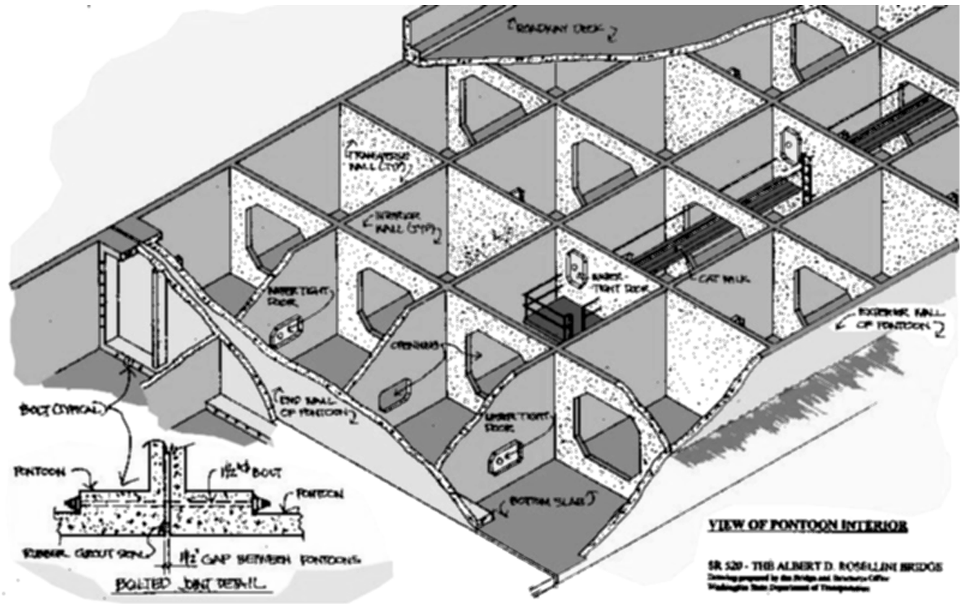

FIGURE 22.11 Small watertight compartments.

22.4.5 Design of Concrete Members

The design of reinforced concrete members should be based on behavior at service load conditions as per AASHTO Standard Specifications, or the service limit state as per AASHTO LRFD Bridge Design Specifications; except sections where reinforcement is to resist sustained hydrostatic forces the allowable stress in the reinforcing steel should not exceed 97 Mpa to limit crack width to a maximum of 0.10mm.

Prestressed members should be designed under the applicable service load and load factor provisions in the AASHTO Standard Specifications or the limit states provisions in the AASHTO LRFD Bridge Design Specifications, except the allowable concrete tensile stress under final conditions in the precompressed tensile zone should be limited to zero.

The ultimate flexural strength of the overall pontoon section should be computed for a maximum crack width of 0.25 mm and should not be less than the loads from the factored load combinations or 1.3 times the cracking moment, M_{cr}.

In a moderate climate, the following temperature differentials between the various portions of a floating bridge may be used:

1. Between the exposed portion and the submerged portion of a pontoon: ±19°C. The exposed portion may be considered as the top slab, and the remaining part of the pontoon as submerged. If the top slab is shaded by an elevated structure, the differential temperature may be reduced to ±14°C
2. Between the top slab and the elevated structure of the pontoon: ±14°C

The effects of creep and shrinkage should be considered while the pontoons are in the dry only. Creep and shrinkage may be taken as zero once the pontoons are launched. The time-dependent effects of creep and shrinkage may be estimated in accordance with the AASHTO Specifications. A final differential shrinkage coefficient of 0.0002 should be considered between the lower portion of the pontoon and the top slab of the pontoon.

High-performance concrete containing fly ash and silica fume is most suitable for floating bridges [9,10]. The concrete is very dense, impermeable to water, highly resistant to abrasion, and relatively

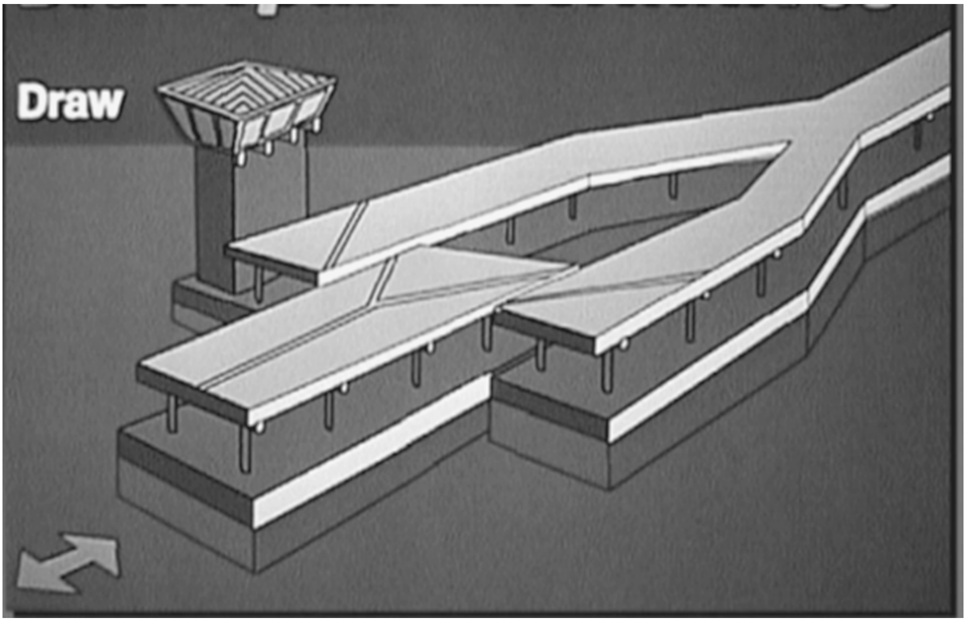

FIGURE 22.12 Draw-type movable span.

crack free. High-performance concrete also has high strength, low creep, and low shrinkage. Concrete mixes may be customized for the project.

Recommended minimum concrete cover of reinforcing steel:

	Fresh Water	Salt Water
Top of roadway slab	65 mm	65 mm
Exterior surfaces of pontoons and barrier	38 mm	50 mm
All other surfaces	25 mm	38 mm

22.4.6 Anchoring System

An anchoring system should be installed in the floating bridge to maintain transverse and horizontal alignment. The anchoring system should be designed to have adequate capacity to resist transverse and longitudinal forces from winds, waves, and current.

Adequate factors of safety or load and resistance factors consistent with the type of anchoring should be included in the design of the components of the system.

22.4.7 Movable Span

A floating bridge creates an obstruction to marine traffic. Movable spans may need to be provided for the passage of large vessels. The width of opening that must be provided depends on the size and type of vessels navigating through the opening. Movable spans of up to a total opening of 190 m have been used.

Two types of movable spans are used in Washington State — the draw-type and the lift/draw type. In the draw type movable span, the draw pontoons retract into a "lagoon" formed by flanking pontoons (Figure 22.12). Vehicles must maneuver around curves at the "bulge" where the "lagoon" is formed. In the lift/draw type of movable span, part of the roadway will be raised for the draw pontoons to retract underneath it (Figure 22.13). As far as traffic safety and flow are concerned, the lift/draw-type movable span is superior over the draw type. Traffic moves efficiently on a straight alignment with no curves to contend with.

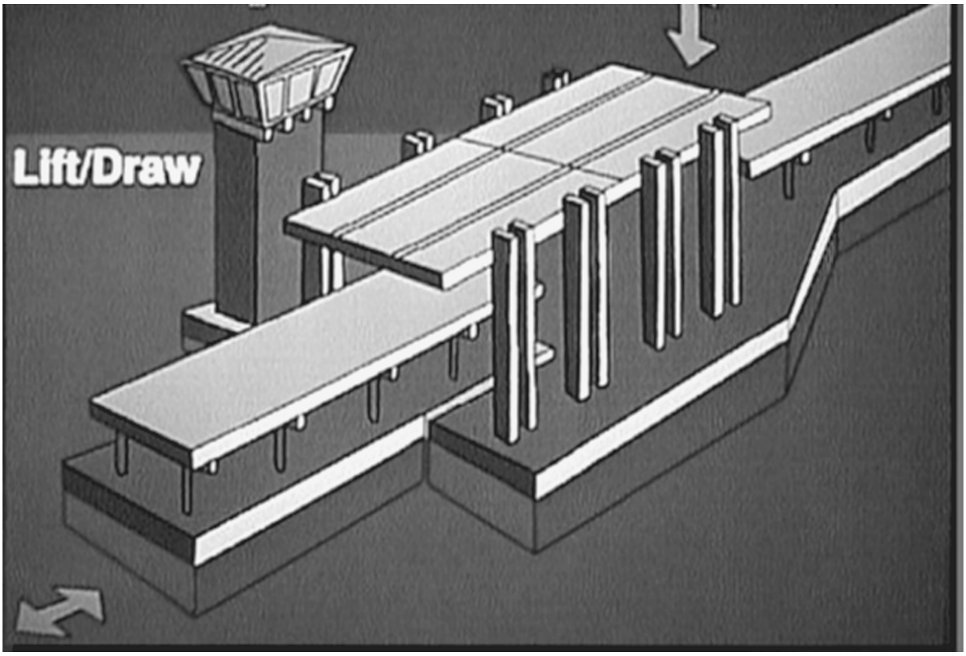

FIGURE 22.13 Lift/Draw-type movable span.

Movable spans may be operated mechanically or hydraulically. The design of the movable spans should be in accordance with the latest AASHTO *Standard Specifications for Movable Highway Bridges* [11].

22.4.8 Deflection and Motion

Floating bridges should be designed so that they are comfortable to ride on during normal storm (1-year storm) conditions and also to avoid undesirable structural effects during extreme storm (100-year storm) conditions. Deflection and motion criteria have been used to meet these objectives. The following deflection and motion limits for normal storm (1-year storm) conditions may be used as guidelines:

Loading Condition	Type of Deflection or Motion	Maximum Deflection	Maximum Motion
Vehicular load	Vertical	$L/800$	
Winds — static	Lateral (drift)	0.3 m	
	Rotation (heel)	0.5°	
Waves — dynamic	Vertical (heave)	±0.3 m	0.5 m/s^2
	Lateral (sway)	±0.3 m	0.5 m/s^2
	Rotation (roll)	±0.5°	0.05 rad/s^2

The objective of the motion limits are to assure that the people will not experience discomfort walking or driving across the bridge during a normal storm. The motion limit for rotation (roll) under the dynamic action of waves should be used with care when the roadway is elevated a significant distance above the water surface. The available literature contains many suggested motion criteria for comfort based on human perceptions [12]. A more-detailed study on motion criteria may be warranted for unusual circumstances.

22.5 Structural Design and Analysis

The design and analysis of floating bridges have gone through several stages of progressive development since the first highway floating bridge was designed and built in the late 1930s across Lake Washington, Seattle. The design has advanced from empirical methods to realistic approach, from the equivalent static approach to dynamic analysis, from computer modeling to physical model testing, and from reinforced concrete to prestressed concrete.

The most difficult part of early designs was the prediction of winds and waves, and the response due to wind–wave–structure interaction. Climatological data were very limited. The wind–wave–structure interaction was not well understood. Current state of the knowledge in atmospheric sciences, computer science, marine engineering, finite-element analysis, structural engineering, and physical model testing provides more accurate prediction of wind and wave climatology, more realistic dynamic analysis of wind–wave–structure interactions, and more reliable designs.

Designing for static loads, such as dead and live loads, is very straightforward using the classical theory on beam on elastic foundation [13]. For example, the maximum shear, moment, and deflection due to a concentrated load, P, acting away from the end of a continuous floating structure are given by

$$V_{max} = \frac{P}{2} \tag{22.1}$$

$$M_{max} = \frac{P}{4\lambda} \tag{22.2}$$

$$y_{max} = \frac{P\lambda}{2k} \tag{22.3}$$

where k = modulus of foundation

$$\lambda = 4\sqrt{\frac{k}{4EI}}$$

Designing for the response of the structure to winds and waves is more complex, because of the random nature of these environment loads. To determine the dynamic response of the bridge to wind generated waves realistically, a dynamic analysis is necessary.

22.5.1 Preliminary Design

The design starts with selecting the type, size, and location of the floating bridge (Figure 22.14). Assuming a concrete box section of cellular construction with dimensions as shown in Figure 22.15, the first step is to determine the freeboard required. The height of the freeboard is selected to avoid water spray on the roadway deck from normal storms. The draft can then be determined as necessary to provide the selected freeboard.

The freeboard and draft of the floating structure should be calculated based on the weight of concrete, weight of reinforcing steel, weight of appurtenances, weight of marine growth as appropriate, and vertical component of anchor cable force. The weight of the constructed pontoon is generally heavier than the computed weight, because of form bulging and other construction tolerances. Based on the experience in Washington State, the weight increase varies from 3 to 5% of the theoretical weight. This increase should be included in the draft calculation. Additionally, floating pontoons experience loss in freeboard in the long term. The main reason is due to weight

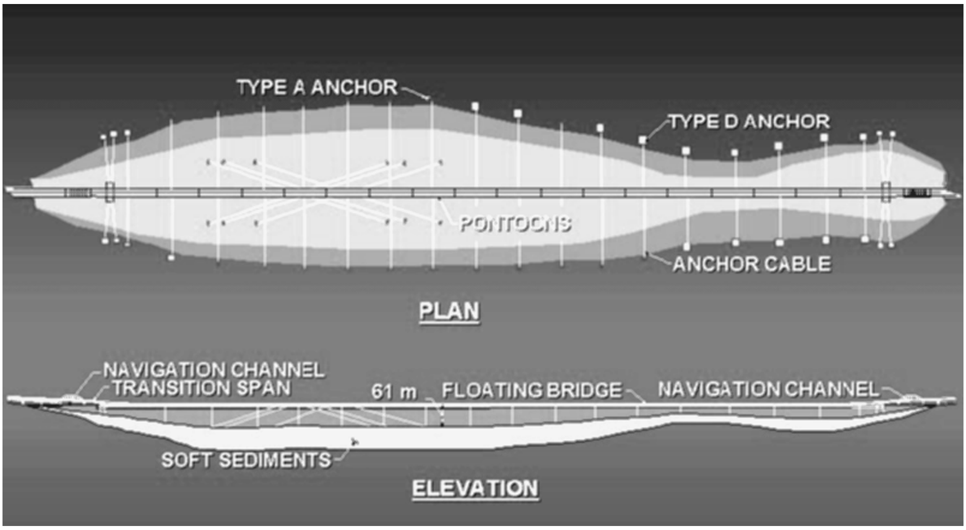

FIGURE 22.14 General layout.

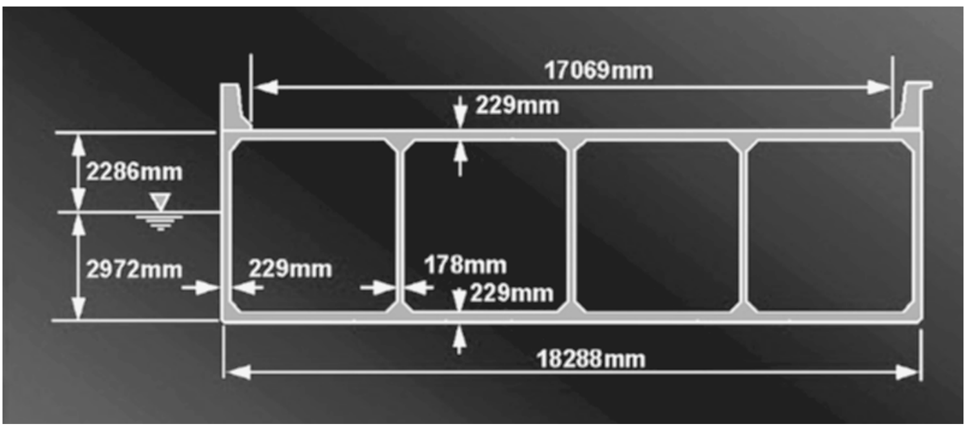

FIGURE 22.15 Typical cross section.

added as a result of modifications in the structural and mechanical elements throughout the service life of the structure. It is prudent to make allowance for this in the design. This can be done by allowing 150 to 230 mm of extra freeboard in the new bridge.

The thicknesses for the walls and slabs should be selected for local and global strength and constructibility. The wall thickness should be the minimum needed to provide adequate concrete cover to the reinforcing steel and adequate space for post-tensioning ducts when used. There must also be adequate room for depositing and consolidating concrete. The objective should be to keep the weight of the structure to a minimum, which is essential for cost-effective design of a floating bridge.

The exterior walls of the pontoons should be designed for wave plus hydrostatic pressures and the collision loads. The bottom slab should be designed for wave plus hydrostatic pressures. The interior walls should be designed for hydrostatic pressures due to flooding of a cell to full height of the wall. The roadway slab should be designed for the live load plus impact in the usual way.

The preliminary design gives the overall cross-sectional dimensions and member thicknesses required to meet local demands and construction requirements. The global responses of the floating bridge will be predicted by dynamic analysis.

22.5.2 Dynamic Analysis

The basic approach to dynamic analysis is to solve the equation of motion:

$$M\ddot{X} + C\ddot{X} + KX = F(t) \tag{22.4}$$

This equation is familiar to structural engineering in solving most structural dynamic problems of land-based structures. However, in predicting the dynamic response of a floating bridge, the effects of water–structure interaction must be accounted for in the analysis. As a floating bridge responds to the incident waves, the motions (heave, sway, and roll) of the bridge produce hydrodynamic effects generally characterized in terms of added mass and damping coefficients. These hydrodynamic coefficients are frequency dependent. The equation of motion for a floating structure takes on the general form:

$$[M + A]\ddot{X} + [C_1 + C_2]\dot{X} + [K + k]X = F(t) \tag{22.5}$$

where

$X,\ \dot{X}, \ddot{X}$ = generalized displacement, velocity and acceleration at each degree of freedom
M = mass–inertia matrix of the structure
A = added mass matrix (frequency dependent)
C_1 = structural damping coefficient
C_2 = hydrodynamic damping coefficient (frequency dependent)
K = structural stiffness matrix (elastic properties, including effects of mooring lines when used)
k = hydrostatic stiffness (hydrostatic restoring forces)
$F(t)$ = forces acting on the structure

A substantial amount of experimental data has been obtained for the hydrodynamic coefficients for ships and barges [14,15]. Based on these experimental data, numerical methods and computer programs have been developed for computing hydrodynamic coefficients of commonly used cross-sectional shapes, such as the rectangular shape. For structural configurations for which no or limited data exist, physical model testing will be necessary to determine the basic sectional added mass, damping, and wave excitation loads.

Structural damping is an important source of damping in the structure. It significantly affects the responses. A structural damping coefficient of 2 to 5% of critical damping is generally assumed for the analysis. It is recommended that a better assessment of the damping coefficient be made to better represent the materials and structural system used in the final design.

The significant wave height, period, and central heading angle may be predicted using the public domain program NARFET developed by the U.S. Army Coastal Engineering Research Center [16,17]. This program accounts for the effective fetch to a location on the floating structure by a set of radial fetch lines to the point of interest. The Joint North Sea Wave Project (JONSWAP) spectrum is commonly used to represent the frequency distribution of the wave energy predicted by the program NARFET. This spectrum is considered to represent fetch-limited site conditions very well. A spreading function is used to distribute the energy over a range of angles of departure from the major storm heading to the total energy [18]. The spreading function takes the form of an even cosine function, $\cos^{2n}\theta$, where θ is the angle of the incident wave with respect to the central heading angle. Usually $2n$ is 2 or greater. $2n = 2$ is generally used for ocean structures where the structures are relatively small with respect to the open sea. In the case of a floating bridge, the bridge length is very large in comparison to the body of water, resulting in very little energy distributed away from the central heading angle. A larger number of $2n$ will have to be used for a floating bridge. The larger the number of $2n$ the more focused the wave direction near the central heading angle. A $2n$ value of 12 to 16 have been used in analyzing the floating bridges in Washington State. The value of $2n$ should be selected with care to reflect properly the site condition and the wind and wave directions.

The equation of motion may be solved by the time-domain (deterministic) analysis or the frequency-domain (probabilistic) analysis. The time-domain approach involves solving differential equations when the coefficients are constants. The equations become very complex when the coefficients are frequency dependent. This method is tedious and time-consuming. The frequency-domain approach is very efficient in handling constant and frequency-dependent coefficients. The equations are algebraic equations. However, time-dependent coefficients are not admissible and nonlinearities will have to be linearized by approximation. For the dynamic analysis of floating bridges subjected to the random nature of environmental forces and the frequency-dependent hydrodynamic coefficients, frequency-domain analysis involves only simple and fast calculations.

22.5.3 Frequency-Domain Analysis

The frequency-domain dynamic analysis is based on the principles of naval architecture and the strip theory developed for use in predicting the response of ships to sea loads [19,20]. The essence of this approach is the assumption that the flow at one section through the structure does not affect the flow at any other section. Additional assumptions are (1) the motions are relatively small, (2) the fluid is incompressible and invisid, and (3) the flow is irrotational. By using the strip theory, the problem of wave–structure interaction can be solved by applying the equation of motion in the frequency domain [21,22]. By Fourier transform, the equation of motion may be expressed in terms of frequencies, ω, as follows:

$$\left\{-\omega^2[M+A]+i\omega\left[C_1+C_2\right]+[K+k]\right\}=\left\{F(\omega)\right\} \tag{22.6}$$

This equation may be solved as a set of algebraic equations at each frequency and the responses determined. The maximum bending moments, shears, torsion, deflections, and rotations can then be predicted using spectral analysis and probability distribution [23,24]. The basic steps involved in a frequency-domain analysis are

1. Compute the physical properties of the bridge — geometry of the bridge elements, section properties, connections between bridge elements, mass–inertia, linearized spring constants, structural damping, etc.
2. Compute hydrodynamic coefficients — frequency-dependent added mass and frequency-dependent damping.
3. Compute hydrostatic stiffnesses.
4. Calculate wind, wave, and current loads, and other loading terms.
5. Build a finite-element computer model of the bridge [25] as a collection of nodes, beam elements, and spring elements. The nodes form the joints connecting the beam elements and the spring elements, and each node has six degrees of freedom.
6. Solve the equation of motion in the frequency domain to obtain frequency responses, the magnitudes of which are referred to as response amplitude operators (RAOs).
7. Perform spectral analysis, using the RAOs and the input sea spectrum, to obtain the root mean square (RMS) of responses.
8. Perform probability analysis to obtain the maximum values of the responses with the desired probability of being exceeded.
9. Combine the maximum responses with other loadings, such as wind, current, etc., for final design.

22.6 Fabrication and Construction

Concrete pontoons are generally used for building major floating bridges. The fabrication and construction of the concrete pontoons must follow the best current practices in structural and marine engineering in concrete design, fabrication, and construction, with added emphasis on high-quality concrete and watertightness. Quality control should be the responsibility of the fabricators/contractors. Final quality assurance and acceptance should be the responsibility of the owners. In addition to these traditional divisions of responsibilities, the construction of a floating bridge necessitates a strong "partnership" arrangement to work together, contracting agencies and contractors, to provide full cooperation and joint training, share knowledge and expertise, share responsibility, and to help each other succeed in building a quality floating bridge. The contractors should have experience in marine construction and engage the services of naval architects or marine engineers to develop plans for monitoring construction activities and identifying flood risks, and prepare contingency plans for mitigating the risks.

Knowledge is power and safety. The construction personnel, including inspectors from the contracting agencies and the contractors, should be trained on the background of the contract requirements and the actions necessary to implement the requirements fully. Their understanding and commitment are necessary for complete and full compliance with contract requirements that bear on personal and bridge safety.

Construction of floating bridges is well established. Many concrete floating bridges have been built successfully using cast-in-place, precast, or a combination of cast-in-place and precast methods. Construction techniques are well developed and reported in the literature. Owners of floating bridges have construction specifications and other documents and guidelines for the design and construction of such structures.

Floating bridges may be constructed in the dry in graving docks or on slipways built specifically for the purpose. However, construction on a slipway requires more extensive preparation, design, and caution. The geometry and strength of the slipway must be consistent with the demand of the construction and launching requirements. Construction in a graving dock utilizes techniques commonly used in land-based structures. Major floating bridges around the world have been constructed in graving docks (Figure 22.16).

Because of the size of a floating bridge, the bridge is generally built in segments or pontoons compatible with the graving dock dimensions and draft restrictions. The segments or pontoons are floated and towed (Figure 22.17) to an outfitting dock where they are joined and completed in larger sections before towing to the bridge site, where the final assembly is made (Figure 22.18).

It is important to explore the availability of construction facilities and decide on a feasible facility for the project. These actions should be carried out prior to or concurrent with the design of a floating bridge to optimize the design and economy. Some key data that may be collected at this time are

- Length, width, and draft restrictions of the graving dock;
- Draft and width restrictions of the waterways leading to the bridge site;
- Wind, wave, and current conditions during tow to and installation at the job site.

The designers will use the information to design and detail the structural plans and construction specifications accordingly.

22.7 Construction Cost

The construction costs for floating bridges vary significantly from project to project. There are many variables that affect the construction costs. The following construction costs in U.S. dollars for the floating bridges in Washington State are given to provide a general idea of the costs of building

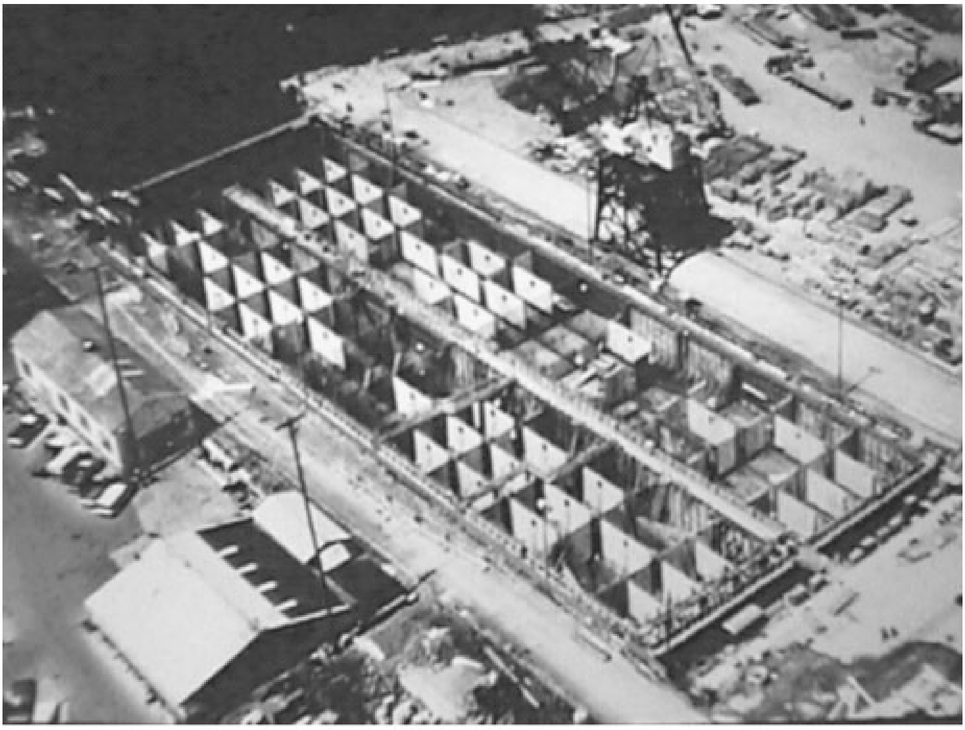

FIGURE 22.16 Construction in a graving dock.

FIGURE 22.17 Towing pontoon.

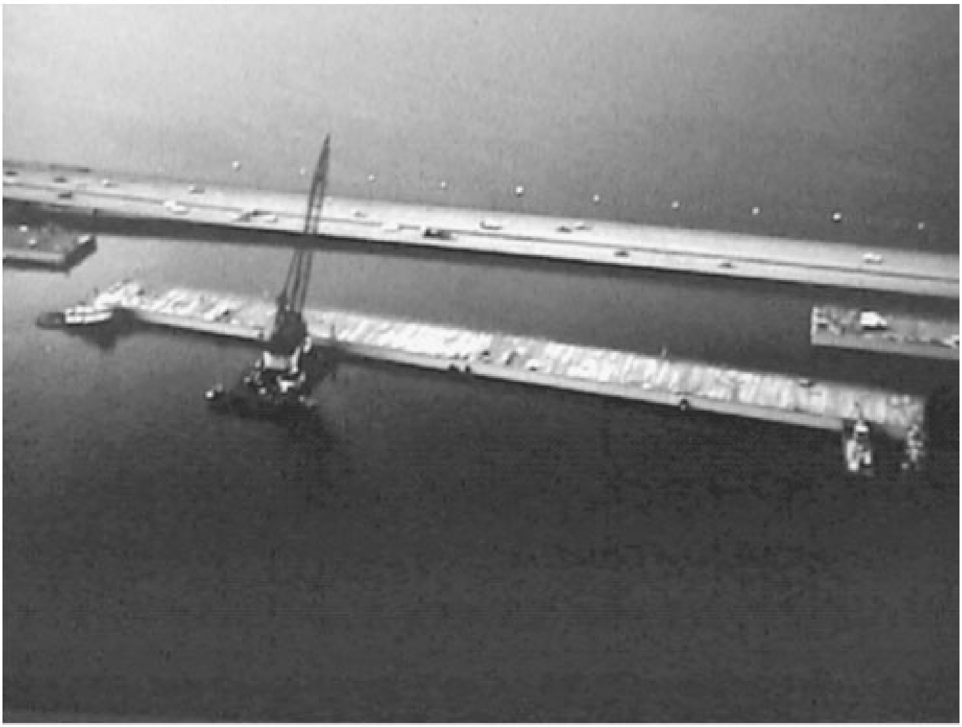

FIGURE 22.18 Final assembly.

concrete floating bridges in the past. These are original bid costs for the floating portions of the bridges. They have not been adjusted for inflation and do not include the costs for the approaches.

Name of Bridge	Length, m	Width of Pontoon, m	Lanes of Traffic	Cost, U.S. $ million
Original Lacey V. Murrow Bridge[a]	2018	17.9	4	3.25 (1938)
Evergreen Point Bridge[a]	2310	18.3	4	10.97 (1960)
Original Hood Canal Bridge[a]	1972	15.2	2	17.67 (1961)
Homer Hadley Bridge	1771	22.9	5	64.89 (1985)
New Lacey V. Murrow Bridge	2018	18.3	3	73.78 (1991)

[a] These bridges have movable spans which increased construction costs.

22.8 Inspection, Maintenance, and Operation

A floating bridge represents a major investment of resources and a commitment to efficiency and safety to the users of the structure and the waterway. To assure trouble-free and safe performance of the bridge, especially one with a movable span, an inspection, maintenance, and operation manual (Manual) should be prepared for the bridge. The main purpose of the Manual is to provide guidelines and procedures for regular inspection, maintenance, and operation of the bridge to extend the service life of the structure. Another aspect of the Manual is to define clearly the responsibilities of the personnel assigned to inspect, maintain, and operate the bridge. The Manual must address the specific needs and unique structural, mechanical, hydraulic, electrical, and safety features of the bridge.

The development of the Manual should begin at the time the design plans and construction specifications are prepared. This will assure that the necessary inputs are given to the designers to help with preparation of the Manual later. The construction specifications should require the contractors to submit documents, such as catalog cuts, schematics, electrical diagrams, etc., that will be included in the Manual. The Manual should be completed soon after the construction is completed and the bridge is placed into service. The Manual is a dynamic document. Lessons learned and modifications made during the service life of the structure should be incorporated into the Manual on a regular basis.

A training program should be developed for the supervisors and experienced co-workers to impart knowledge to new or inexperienced workers. The training program should be given regularly and aimed at nurturing a positive environment where workers help workers understand and diligently apply and update the guidelines and procedures of the Manual.

22.9 Closing Remarks

Floating bridges are cost-effective alternatives for crossing large lakes with unusual depth and soft bottom, spanning across picturesque fjords, and connecting beautiful islands. For conditions like Lake Washington in Seattle where the lake is over 1610 m wide, 61 m deep, and another 61 m of soft bottom, a floating bridge is estimated to cost three to five times less than a long-span fixed bridge, tube, or tunnel.

The bridge engineering community has sound theoretical knowledge, technical expertise, and practical skills to build floating bridges to enhance the social and economic activities of the people. However, it takes time to plan, study, design, and build floating bridges to form major transportation links in a local or national highway system. There are environmental, social, and economic issues to address. In the State of Washington, the first floating bridge was conceived in 1920, but was not built and opened to traffic until 1940. After over 30 years of planning, studies, and overcoming environmental, social, and economic issues, Norway finally has the country's first two floating bridges opened to traffic in 1992 and 1994. It is never too early to start the planning process and feasibility studies once interest and a potential site for a floating bridge is identified.

Every floating bridge is unique and has its own set of technical, environmental, social, and economic issues to address during preliminary and final engineering:

- *Winds and waves*: Predicting accurately the characteristics of winds and waves has been a difficult part of floating bridge design. Generally there is inadequate data. It is advisable to install instruments in potential bridge sites to collect climatological data as early as possible. Research in the area of wind–wave–structure interactions will assure safe and cost-effective structures.
- *Earthquake*: Floating bridges are not directly affected by ground shakings from earthquakes.
- *Tsunami and seiches*: These may be of particular significant in building floating bridges at sites susceptible to these events. The dynamic response of floating bridges to tsunami and seiches must be studied and addressed in the design where deemed necessary.
- *Corrosion*: Materials and details must be carefully selected to reduce corrosion problems to assure long service life with low maintenance.
- *Progressive failure*: Floating bridges must be designed against progressive failures by dividing the interiors of pontoons into small watertight compartments, by installing instruments for detecting water entry, and by providing means to discharge the water when necessary.
- *Riding comfort and convenience*: Floating bridges must be comfortable to ride on during minor storms. They must have adequate stiffness and stability. They must not be closed to vehicular traffic frequently for storms or marine traffic.
- *Public acceptance*: Public acceptance is a key part of modern civil and structural engineering. The public must be educated regarding the environmental, social, and economic impacts of

FIGURE 22.19 Floating Bridges on Lake Washington.

proposed projects. Reaching out to the public through community meetings, public hearings, news releases, tours, exhibits, etc. during the early phase of project development is important to gain support and assure success. Many major public projects have been delayed for years and years because of lack of interaction and understanding.

- *Design criteria*: The design criteria must be carefully developed to meet site-specific requirements and focused on design excellence and cost-effectiveness to provide long-term performance and durability. Design excellence and economy come from timely planning, proper selection of materials for durability and strength, and paying attention to design details, constructibility, and maintainability. The design team should include professionals with knowledge and experience in engineering, inspection, fabrication, construction, maintenance, and operation of floating bridges or marine structures.
- *Construction plan*: It is essential to have a good set of construction plans developed jointly by the contracting agency and the contractor to clearly address qualifications, materials control, quality control, quality assurance, acceptance criteria, post-tensioning techniques, repair techniques, launching and towing requirements, weather conditions, flood control and surveillance.

Well-engineered and maintained floating bridges are efficient, safe, durable, and comfortable to ride on. They form important links in major transportation systems in different parts of the world (Figure 22.19).

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