FLOATING BRIDGES

Henry Petroski

Bridges take many forms, from common highway girders that we drive under and over with hardly a notice, to long suspended spans that raise our cars and spirits to great heights. Whatever its type, a bridge is designed to carry something over some obstacle—a road, a valley, a river, a lake. Bridging a lake can be among the most challenging problems an engineer might face.

Walden Pond is not large enough to be called a lake, but plumbing its depths beneath the ice one winter gave Henry David Thoreau plenty of insight into the nature of things large and small. His 1846 survey drawing of the pond, which he reproduced in *Walden*, showed its surface to be no more than about 100 by 150 rods—in the units of 19th-century land surveying, with one rod equal to 16.5 feet. Thoreau also measured the depth of the pond along its major and minor axes, and found it to be deepest (about 100 feet) near where they crossed, a fact from which he generalized about the character of men.

In Thoreau's day, the state of the art of bridge building in America (and the world) would have allowed a single-span suspension bridge to be thrown across the narrowest part of the pond, where it is only 50 rods wide, but not across its widest part. Such a distance would not be bridged in a single span until the Brooklyn Bridge was completed in 1883. Even a two-span approach would have pushed the limits of mid-19th-century engineering. The sheer depth of the foundation would have exposed workers to greater pressure than men digging the foundations of the Eads and Brooklyn bridges experienced later in the century, causing the then-mysterious caisson disease now understood to be decompression sickness, or the bends.

Boat as Bridge

If a body of water as small and placid as Walden Pond could not easily have been bridged in the mid-19th century, then how did the Persian king Xerxes throw a bridge across the Hellespont—the strait between the Gallipoli Peninsula in Europe and Turkey in Asia—in order to invade Greece almost 25 centuries ago?

The solution then, as it could have been at Walden Pond, was a floating bridge. In its simplest form, such a bridge is simply a boat. In many a crowded harbor, where boats tessellate the water jammed stem to stern and port to starboard, a common way to reach an outer one is to walk across the inner ones. This was how, just a few years ago, our party of engineers boarded a riverboat at Sandouping to begin a journey up the Yangtze River and how we disembarked at several busy cities on our way to Chongking.

When a boat or ship is free of its moorings, it is metaphorically a bridge, carrying its passengers from one point of land to another. Ships are structures that float and must be designed to withstand the forces to which they will be subjected. The first test of a vessel's strength traditionally came at launch, when it slid down the ways and for the first time felt the force of buoyancy. With the stern supported in the water and the stem still on the ways, the hull was literally a bridge between water and land, and in the past many larger ships were not up to the task of carrying even their own weight. The breakup of timber ships on being launched was known to be a danger but still not understood when Galileo mentioned the phenomenon in his 1638 treatise on the then-new engineering sciences of strength of materials and dynamics.

Even when they survive launching, ships are not out of danger. Vessels on a rough sea essentially bridge the crests of waves and are as much subject to bending as is a slender plank thrown across a construction ditch. Indeed, such a situation can subject the hull of a ship to its greatest stresses since launch; if not properly designed, the hull can break up at sea.

Such extreme conditions rarely arise on inland lakes or smooth flowing rivers, where anchored boat hulls with planks spanning between them can serve as a floating bridge. And if large enough boats are connected not by planks but by substantial girders and decks, a bridge of some capacity can be assembled rather easily and quickly. Such was the kind of bridge engineer Gustav Lindenthal offered as an interim measure to cross the Hudson River at New York while his

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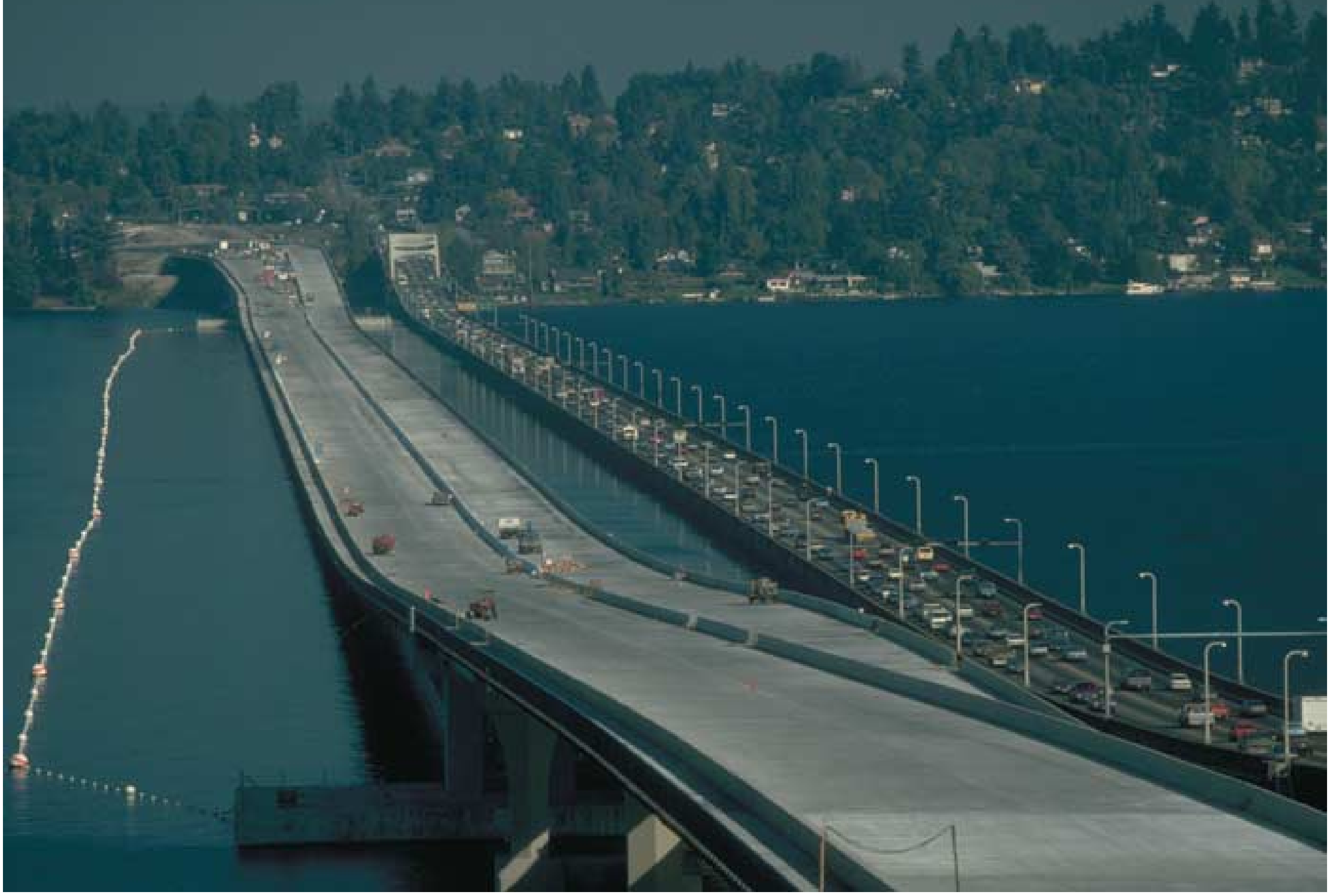

Bohemian Nomad Picturemakers/Corbis

Figure 1. Homer M. Hadley Floating Bridge *(left)*, here under construction, was commissioned in 1989 and parallels Lacey V. Murrow Floating Bridge, completed in 1940. These bridges provide the most practical solution for spanning Lake Washington, between Seattle and Mercer Island.

proposed suspension bridge of enormous proportions was under consideration.

Pontoon bridges have long been used by the military, in the tradition of Xerxes. The U.S. Army built many such multispan bridges during World War II, some exceeding 1,100 feet in total length. During the war in Bosnia in the mid-1990s, muddy conditions along a rising Sava River delayed the completion of a pontoon bridge that was to carry peacekeeping troops into Bosnia. What bridges and roads had survived the fighting would have failed under the weight of 70-ton tanks and heavy guns being moved into place, so the construction of a floating bridge was essential to the mission. When the weather permitted, 22-foot-long, 6-ton folded sections of steel and aluminum were dropped into the river by a helicopter and pushed into place by boats. When 85 pontoon sections were in place, the largest floating bridge erected since World War II was ready to carry troops and equipment across. A proof-test of sorts was conducted when an tank-recovery vehicle, one capable of towing disabled tanks, made the crossing. The bridge groaned and sank a bit under the weight, but it performed its function—until it was disassembled that night.

Challenging construction projects are not limited to wartime, of course, and often they take place under more tolerable conditions to produce structures of a more permanent kind. A large but shallow body of water can be crossed relatively easily with a solid bridge set on firm foundations. Thus the 18-mile-long Chesapeake Bay Bridge-Tunnel consists mainly of a series of modest bridge spans set on piles driven into the bottom, with the bridge traffic carried into tunnels at two strategic points to maintain unobstructed shipping lanes. A similar 24-mile-long structure, without the tunnel sections, spans Lake Pontchartrain near New Orleans, much as famous Seven Mile Bridge carries traffic to Key West, Florida.

When a wide body of water is extremely deep, however, it is not always practical to construct the number of deep foundations needed to support even a long-span bridge. In such situations, the alternative of choice is often a permanent floating bridge of such proportions that to the uninitiated driving across it seems no different from driving on a more conventional type of bridge. The mass and measure of such a floating bridge can offer substantial resistance even during storms, so economics and function drive the choice of structure.

Major permanent floating bridges are often essentially large ship hulls joined stem to stern and paved with what functions as a continuous roadway. Since such a bridge presents a solid barrier to cross-water traffic, a shipping lane has to be designed into the structure, which is usually done by leaving a gap between floating sections and spanning it with a truss or other standard bridge type, or by providing a movable span of some kind.

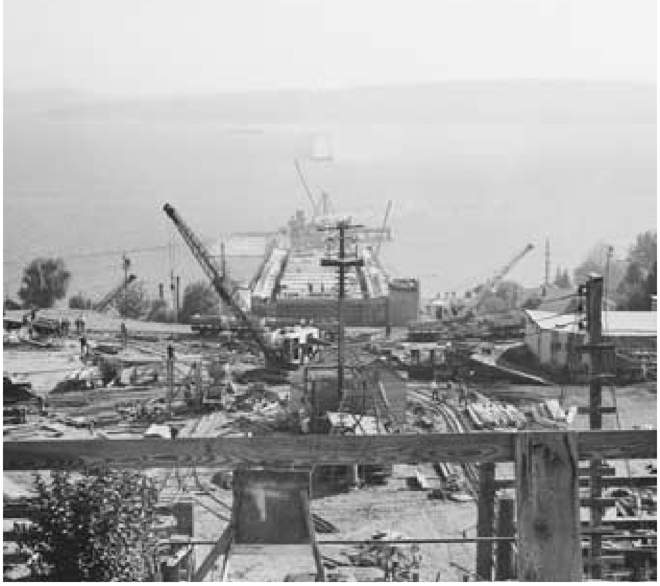

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Figure 2. Originally known as the Mercer Island Bridge, the Lacey V. Murrow Bridge was built using concrete pontoons.

Hadley's Folly

Conditions conducive for floating bridges exist in Lake Washington, which forms the eastern boundary of Seattle and separates it from the city of Bellevue. The lake, which is connected to Puget Sound by a ship canal, is almost 20 miles long and a couple of miles wide, with no significant currents or ice floes. As is suggested by the hilly topography of Seattle, the glacially carved lake is also deep. Its average depth of about 140 feet would pose considerable challenges to any engineer proposing to bridge the lake.

Homer M. Hadley was born in Cincinnati in 1885 but moved to the West Coast as a surveyor with the U.S. Coast and Geodetic Survey. When time and location permitted, he studied engineering at the University of Washington but did not receive a degree. During World War I he worked in Philadelphia building concrete ships and barges for the emergency fleet, the unorthodox material being used because there was a shortage of steel. Hadley returned to Seattle after the war, and in 1920 he suggested the use of concrete pontoons to support a floating bridge across Lake Washington. His proposal became public when he presented the idea at a meeting of the American Society of Civil Engineers, and considerable debate ensued.

The idea of a floating bridge on the scale proposed by Hadley was criticized for its lack of aesthetics by the Navy, which had a station at Sand Point, on the lake. Bankers, calling the scheme "Hadley's Folly," ridiculed his proposal to use private money to be paid back with toll revenue. Such an idea for financing large bridge projects was in the air and would make possible the near-contemporary projects of the George Washington and Golden Gate bridges. Nevertheless, in the face of the opposition, Hadley's idea went dormant. He took a new job with the Portland Cement Association, in which he was charged with promoting the use of concrete in large-scale construction projects. He went on to design an early road-paving machine and become a prominent member of the trade association, all the time keeping the floating-bridge idea in mind.

One of the people Hadley tried selling his floating bridge scheme to was Lacey V. Murrow, director of the Washington State Department of Highways. As it happened, Hadley's idea was on the table when federal highway funds became available as a result of the Great Depression, prompting Murrow to instruct his staff to study its feasibility. The floating-bridge idea was found sound, and Murrow wished to go ahead with it, but he wanted Hadley to assume a low profile regarding the project. Since the Portland Cement Association's motto was "to extend and promote the uses of concrete," Murrow feared that any

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Figure 3. Hood Canal Floating Bridge incorporates a unique "sliding" section to allow vessels to pass.

Figure 4. Osaka Harbor's Yumemai Floating Bridge is the world's first swinging floating bridge. (Images in Figures 4 and 5 courtesy of Eiichi Watanabe, Kyoto University.)

prominent involvement by Hadley would give opponents of the bridge too easy a target.

Although still considered a radical approach, the construction of what would be the world's largest floating bridge—to Mercer Island, in the southeast corner of Lake Washington—was approved in 1937, and the bridge was first crossed by traffic in 1940. The 1.4-mile-long bridge, consisting of a couple dozen 300-odd-foot-long pontoon sections, was an instant and enormous success, and opened up development of the east side of the lake. At first known as the Mercer Island Floating Bridge, in 1967, the year of Hadley's death, it was renamed the Lacey V. Murrow Floating Bridge. Murrow received such extraordinary recognition in part because he had not kept a promise to Hadley that Hadley's role in promoting the bridge would not be forgotten and that in time he would be given credit. Hadley's efforts were in the end remembered, however, when a second, parallel bridge to Mercer Island was opened and later named the Homer M. Hadley Floating Bridge.

Lake Washington is also crossed by another 1.4-mile-long buoyant structure, Evergreen Point Floating Bridge, which opened in 1963 and crosses the lake farther north. Still another floating bridge crosses the Hood Canal, which forms an obstacle to traffic headed to the Olympic Peninsula, located west of Seattle. The 1.5-mile-long Hood Canal Floating Bridge, which opened in 1961, shortened driving access to some destination on the peninsula by as much as 100 miles. An alternative highway route crosses an arm of Puget Sound via the suspension bridge spanning the Narrows at Tacoma.

Figure 5. Yumemai Floating Bridge provides Osaka Harbor with an alternative entrance in the event that the main channel becomes obstructed.

Challenges Afloat

It was the failure of the Tacoma Narrows Bridge in 1940 that at least in part prompted the choice of a floating bridge across the Hood Canal. But floating bridges pose their own problems and challenges. Among the latter are joining a series of pontoons end to end and keeping them in place by anchoring them individually to the bottom with cables that may be more than a mile long. In Seattle, joining the pontoons into a continuous longitudinal structure was chosen over the military preference for transverse pontoons, because, although it presents more resistance to waves, it results in less strain on the superstructure carrying the roadway.

Other great challenges to floating-bridge designers include accommodating tides and shipping lanes. The Hood Canal bridge, for example, must rise and fall with 16-foot tides while maintaining a smooth connection to the land. The solution is similar to the one used to connect a stationary dock to a floating one—with a movable truss. This also permits the passage of small boats. For larger vessels, a more substantial shipping channel has been provided with an unusual drawbridge arrangement. Instead of a movable span that lifts or turns to allow water traffic to pass, the Hood Canal bridge has a pontoon section that moves longitudinally from its closed position into a forked pontoon, not unlike a boat moving into a slip.

Floating bridges, put in place precisely because of the powerful demand for convenient fixed links, naturally carry heavy volumes of traffic. When the second Mercer Island floating bridge was being planned, residents of the island requested that the traffic be out of sight and the noise out of earshot. In the fashion of Boston's ongoing Big Dig, Interstate 90 was covered over on Mercer Island with what is locally referred to as "the lid." Thus, instead of an open busy freeway creating an eyesore and earaches, it carries cars in tunnels beneath land given over to quiet park space and attractive recreational facilities.

Ultimately, however, challenges on the water dominate design considerations for floating bridges. Among the most important of these, of course, is that water be kept out of the pontoon sections, and this has proved to be among the greatest problems experienced with the Seattle floating bridges. In 1990, a year after the second Mercer Island floating bridge opened, the original one, closed for reconstruction, sank in a storm. The failure was attributed to workers having left hatches open over the Thanksgiving holiday, when the storm occurred; pontoons of the unattended bridge filled with water and began to sink. Cracks in the pontoons aggravated the situation, allowing more water to enter. The failure was said to have proceeded in a falling-domino fashion. The rebuilt bridge incorporated prestressed-concrete pontoons which put them in compression and thus closed any cracks that might initiate. In addition, more watertight cells were incorporated into the new pontoons, to confine any flooding that might develop. Seattle had seen an earlier failure of a floating bridge when the western half of the Hood Canal floating bridge sank in a storm in 1979. The failed portion of the strategic bridge, which did not have a parallel companion span to which traffic could be diverted, was rebuilt within four years. The Evergreen bridge has also been battered by storms, resulting in cracks in its pontoons. But all bridge types are subject to damage and require maintenance, and Seattle's floating bridges remain the best available solution to traffic needs in the context of the area's distinctive topography.

The Seattle-area floating bridges are among the relatively few permanent pontoon structures in the world. Other notable ones include the Nordhordland Bridge, which in 1994 opened to traffic across Salhus fjord in Norway. The majority of this structure floats on transverse pontoons, and the shipping channel is spanned by a cable-stayed bridge, a type that was promoted in the mid-1950s by Homer Hadley, who called it a "tied-cantilever," and that was just then being introduced in Europe. But Hadley was again ahead of his time, for it would be another two decades before a cable-stayed bridge was built in America. Perhaps fittingly, the first such bridge in the contiguous United States was erected (in 1978) over the Columbia River, between Pasco and Kennewick, in the state of Washington, where Hadley left his mark as an engineer.

Another significant floating bridge was finished in 2002 in Osaka, Japan, and it solves the problem of maintaining a wide shipping channel in an unusual way, even for a floating structure. The floating portion of the bridge, which is almost 1,500 feet long (with a clear span of about 1,000 feet), looks not unlike a conventional steel span supported near its extremes on two massive piers. The bridge is in fact supported on two hollow steel pontoons. When a ship wants to pass, the entire bridge is rotated to the side of the channel.

Currently, the technology of floating bridges is being combined on the drawing board with that of offshore oil and gas exploration, in which it is not uncommon to tether massive drilling rigs in water depths of more than 1,000 feet. Among bridge proposals that rest on floating foundations are those designed to cross the 16-mile-wide Strait of Georgia, near Vancouver, British Columbia; the 17-mile-wide Strait of Gibraltar; and between pairs of Hawaiian islands, where water depths can exceed 2,000 feet. Such ambitious crossings are likely to be among those discussed in the coming decades, but like Homer Hadley's first Seattle floating bridge, they are not likely to be realized until there arises the right combination of circumstances—technical, economic and political.

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