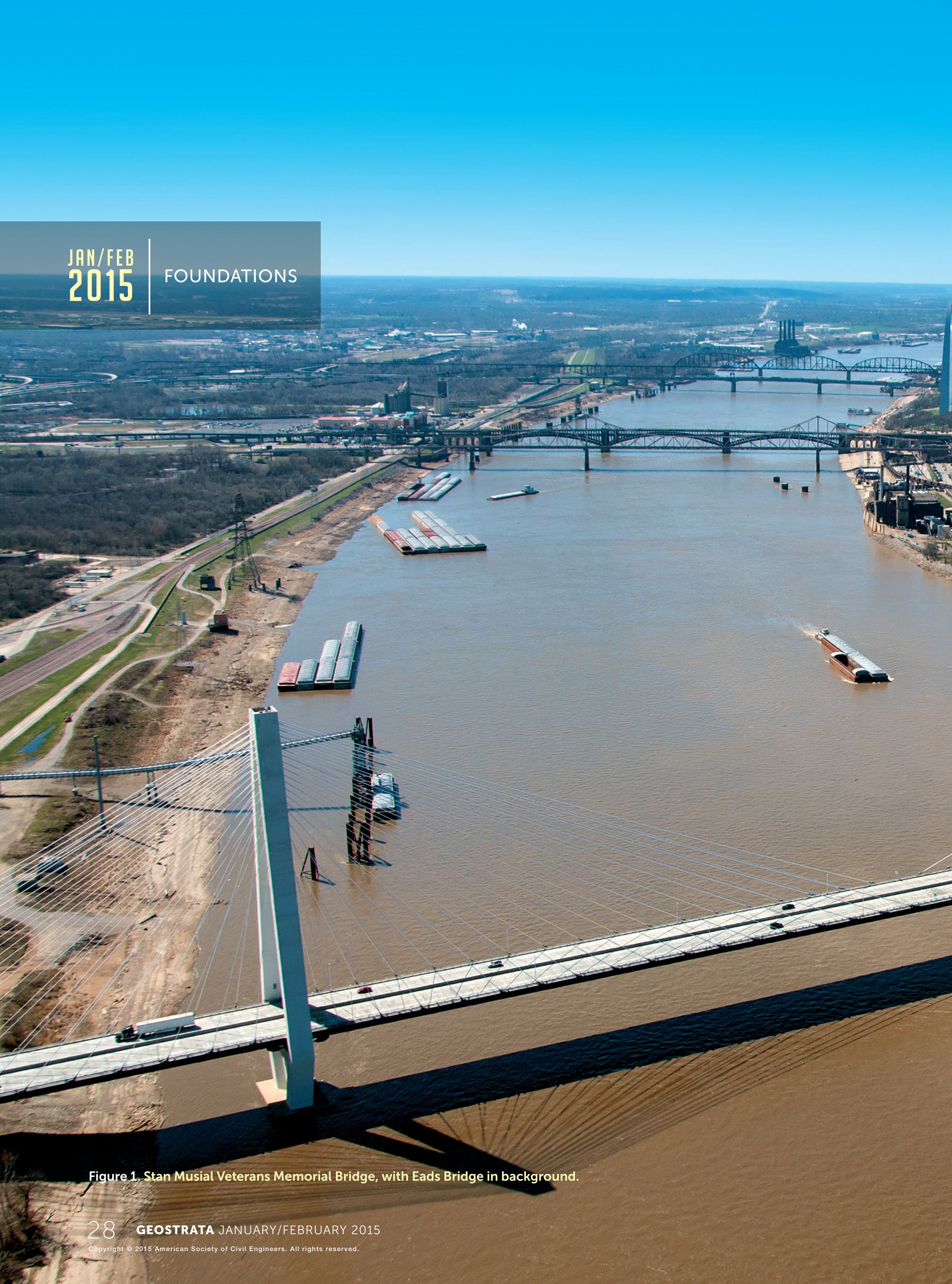
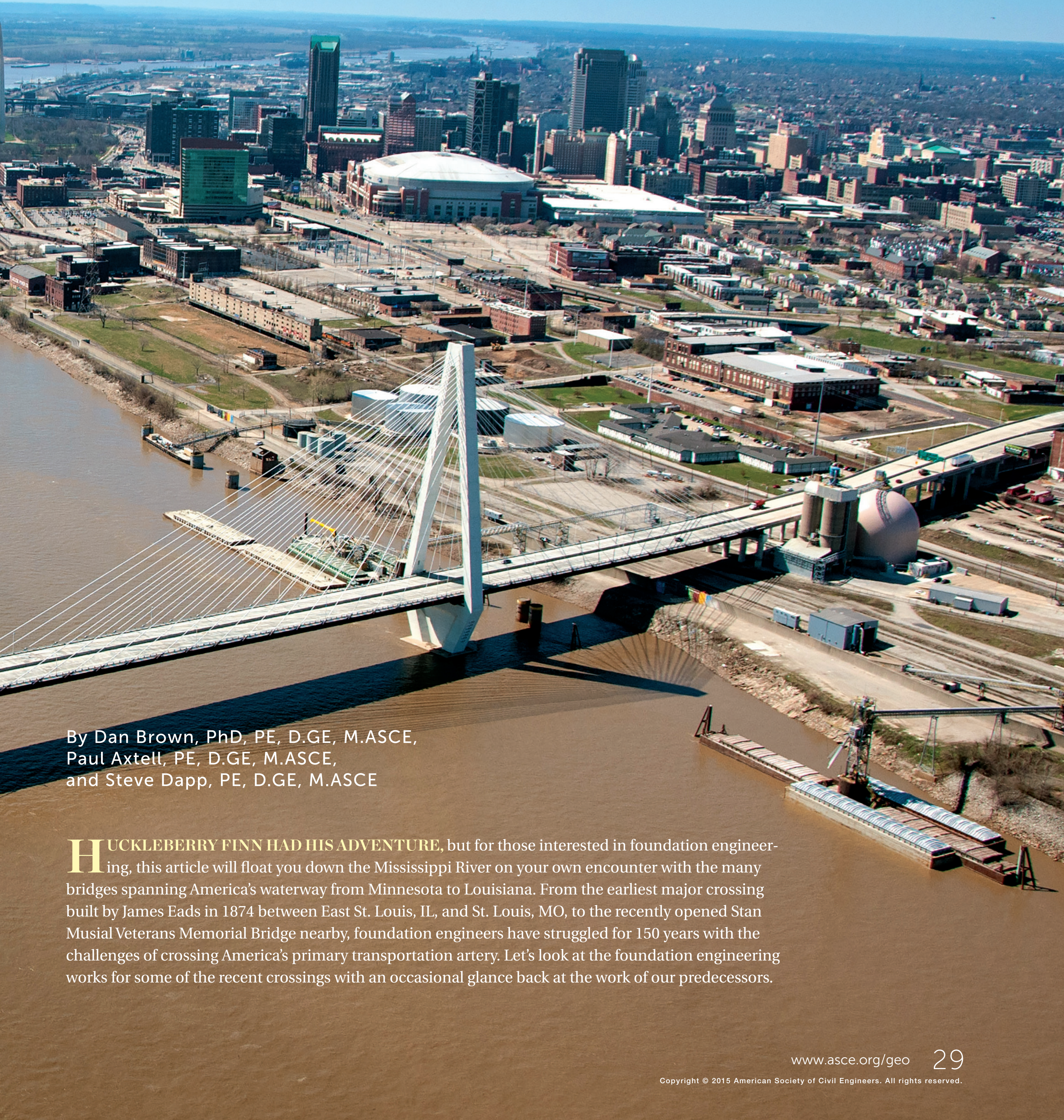


Figure 1. Stan Musial Veterans Memorial Bridge, with Eads Bridge in background.

A Foundation Engineering Trip Down the Mississippi

Foundations for Mississippi River Bridges from Minnesota to Louisiana



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HUCKLEBERRY FINN HAD HIS ADVENTURE, but for those interested in foundation engineering, this article will float you down the Mississippi River on your own encounter with the many bridges spanning America's waterway from Minnesota to Louisiana. From the earliest major crossing built by James Eads in 1874 between East St. Louis, IL, and St. Louis, MO, to the recently opened Stan Musial Veterans Memorial Bridge nearby, foundation engineers have struggled for 150 years with the challenges of crossing America's primary transportation artery. Let's look at the foundation engineering works for some of the recent crossings with an occasional glance back at the work of our predecessors.

The Upper Mississippi (Headwaters to Cairo, IL)

Near the headwaters of the Mississippi, the river is crossed by more than 100 bridges constructed by the Minnesota DOT (MnDOT). In this area, bridge foundations are designed to support typical superstructure loads plus occasional lateral forces due to ice or modest vessels. Scour is a significant consideration, resulting in unsupported pile length that demands flexural strength from individual piles. The collapse of the I-35W bridge on August 1, 2007, prompted a flurry of activity to replace a number of significant river bridge crossings in Minnesota.

Many of the older structures along the Mississippi in Minnesota were constructed on driven timber piles which were readily available, economical (remember Paul Bunyan and Babe, the Blue Ox?), and easy to install with the relatively small pile hammers of yesteryear. However, the demands of modern bridge structures, including longer and wider spans, scour, and vessel collision forces, require much higher capacity foundations.

Figure 2. Hastings Bridge piers 6 and 7 during construction.

Although the new I-35W bridge is founded on drilled shafts, MnDOT has supported most of its recent bridges on large-diameter, open-ended steel pipe piles driven to bear on bedrock. Recent new bridges in Hastings, Dresbach, and St. Paul (Lafayette and Wakota bridges) are examples of this type of foundation, all of which are supported on 42-in outside diameter pipe piles. Experience has shown that these open pipe piles penetrate quite readily without plugging through even fairly dense sands to achieve good bearing on sandstone or limestone bedrock strata, provided that the proper hammer is selected. In this condition, the axial resistance of the pile is limited primarily by the structural capacity of the cross-section and the driving stresses during installation.

Figure 2 shows the foundations under construction for Piers 6 and 7 at Hastings, with Pier 6 on the left supporting the 545-ft-long arch structure that spans the navigation channel. The 42-in diameter by 1-in-thick wall pipe piles are about 185 ft long and were quite easily installed to rock with an APE D125 single acting, diesel impact hammer. Some of these pipe piles were installed within 20 ft to the existing timber-pile supported bridge with no adverse effects from vibrations. Signal matching of dynamic load tests using PDA® indicated a mobilized axial resistance of 3,000 to 3,500 kips when driven to refusal. Rapid load tests performed using the Statnamic® device were used to obtain measured static resistance of up to 4,600 kips, with essentially elastic pile deflections of over 2 in under load.

Dynamic measurements on selected production piles were performed to ensure that piles achieved proper bearing on rock and received similar hammer energy as the preproduction test piles. It was also important to ensure that the piles were not overstressed during installation because high localized stresses at the pile toe are a concern where potential uneven bearing on rock is encountered. The maximum axial resistance that can be demonstrated by dynamic load testing using a pile hammer may be limited by the capacity of the hammer to mobilize resistance without overstressing the pile.

The Lower Mississippi (Ohio River to Gulf of Mexico)

Below the Ohio River, the Lower Mississippi River broadens, the number of bridge crossings become much fewer, the spans become longer, and the bridges and their foundations become more robust. As an example, downstream at St. Louis we encounter the newest major crossing, the Stan Musial Veterans Memorial Bridge (Figure 1). This cable-stayed bridge with a 1600-ft span carries the major east-west I-70 traffic across the Mississippi. As shown in the photo, the bridge is only about a mile upstream from the historic Eads Bridge (seen in the

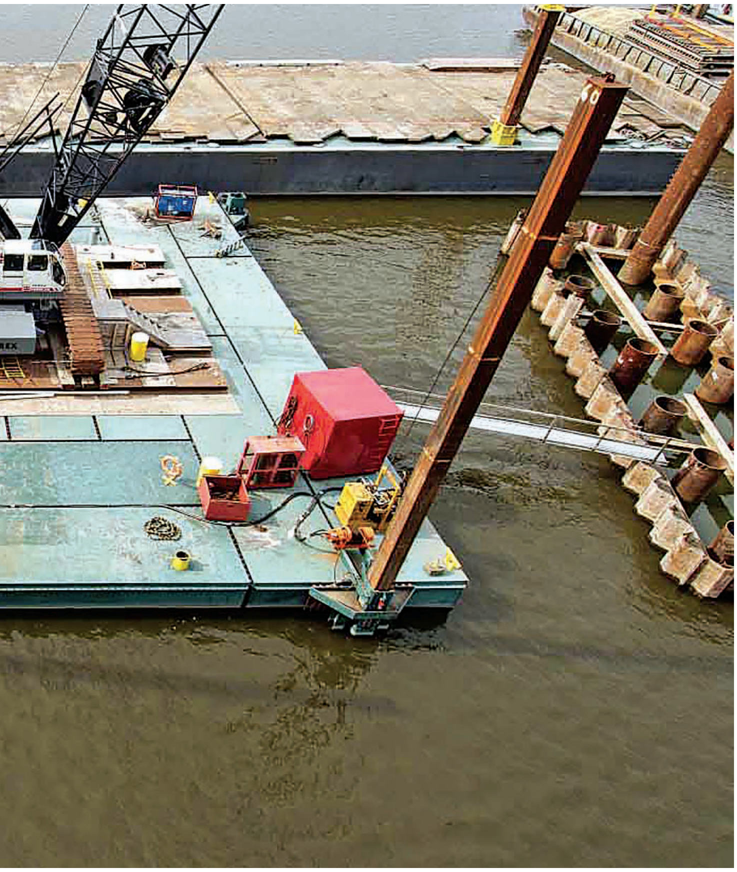

Figure 3. **Construction of drilled shaft foundations in St. Louis.**

background), the first major bridge crossing the Mississippi south of Minnesota. The two structures illustrate the changes in foundation engineering over the course of 150 years.

James Eads was a self-taught engineer who earned his fortune on the Mississippi River in the salvage diving business. His salvage excursions to the bottom of the river impressed upon him the need for a deep, scour-resistant foundation. Eads pioneered the use of pneumatic caissons in North America, a technology which became a common foundation construction technique for major bridges in the late 19th and early 20th centuries. The caissons for the Eads Bridge function as massive spread footings that were sunken below the river bottom by hand excavation beneath the caisson; the workers shoveling below worked in an environment of compressed air to keep the water from entering the work chamber. Before there was understanding that "the bends" was caused by decompression from this environment, the illness that overcame many of the workers was referred to as "caisson disease" or "digger's disease."

Although caissons were allowed as an alternate for the new bridge, drilled shaft foundations proved to be more cost-effective and faster to construct. Each tower for the Stan Musial Veterans Memorial Bridge is founded on a footing supported by six drilled shafts. Each drilled shaft includes an 11-ft diameter socket into hard limestone bedrock about 100 ft

> For 150 years, foundation engineers have struggled with the challenges of crossing the Mississippi River, America's primary transportation artery.

Figure 4. **Construction of open well caisson in Greenville, Mississippi.**

below typical river level. This foundation is designed to resist seismic forces, collision forces from large barge tows, and other wind and lateral forces in combination with soil scour above bedrock. These deep foundations were designed with sufficient flexural and axial strength to resist such loadings with modern equipment to extend the large-diameter shafts into rock (Figure 3). Test methods allow verification of the tremendous axial resistance provided by a drilled shaft into strong rock; a load test performed using the Osterberg cell method demonstrated an axial resistance of over 72,000 kips on a single shaft.

Caissons can still provide a viable foundation solution, as evidenced by our next stop as we float downriver to Greenville, MS. The old bridge had the distinction of being struck by barges on the Mississippi more than any other; therefore, it has since been replaced with a new cable-stayed structure. The deep water, alluvial soils, and scour potential made caissons the most suitable foundation type. The pneumatic method of construction with hand labor that Eads employed has been replaced with a modern, open-well type of caisson construction, as shown in Figure 4.

The caisson was designed to be fabricated off-site. It was then floated into position through a series of sealed "air domes" that were built into the caisson to provide buoyancy and allow a controlled lowering of the caisson to touch down on the riverbed. Guide piling was used to help control alignment, lean, and twist of the caisson during sinking. Once the air domes were removed, the caisson was sunk to its final depth and positioned by excavation through the dredge wells. The caisson must have sufficient weight to overcome the side resistance during sinking, and the dredging operations must be carefully controlled to maintain alignment and verticality. After concrete placement, the caisson provides what is essentially a massive gravity footing for the main span pylons.

Pneumatically sunk caissons have historically been the most common foundation type for Mississippi River crossings south of Greenville and in Louisiana, but two recent projects have employed drilled shaft foundations in a novel way. The new John James Audubon Bridge near St. Francisville is the longest span, cable-stayed bridge in America; its pylons are founded on 3 x 7 groups of 8-ft diameter drilled shafts that were base grouted to enhance the axial resistance in alluvial sand deposits. The Huey P. Long Bridge in New Orleans was originally founded on gravity caissons, but base-grouted drilled shafts have been used for a new pier constructed as part of the widening and rehabilitation project for the bridge. With no rock or hard-bearing stratum in the lower Mississippi River valley, less than 1,500 ft, base grouting has proved effective for increasing the base resistance by pressure grouting the sands at the toe of the shaft after construction.

The base grouting is accomplished using the apparatus illustrated in Figure 5. The crosshole sonic logging tubes used for integrity testing are connected across the bottom in a U-shaped configuration with a sleeve port system integrated into the bottom. First the drilled shaft is excavated; then, the reinforcement (including this apparatus) and concrete are placed. The structural integrity of the shaft is verified by crosshole sonic logging after sufficient hardening. A pressurized fluid mixture of cement and water is pumped through the tubes to the base, effectively compaction grouting beneath the foundation. The maximum grouting pressure is limited by shaft side resistance because a very high pressure can simply jack the shaft out of the

Figure 5. **(left) Base grouting assembly at the Huey P. Long Bridge, New Orleans.** Figure 6. **(right) Cofferdam construction at the John James Audubon Bridge.**

ground; however, the 180- to 200-ft-long shafts at these bridge locations provide sufficient side resistance to allow pressure grouting to 750 psi. Multiple load tests confirmed a base resistance of around 120 ksf was achieved with this technique in soils composed of dense, silty sand.

Construction of the drilled shaft supported footings in the deep water at the Audubon Bridge included a cofferdam that utilized the drilled shafts as an integral part of the construction. The cofferdam structure was constructed with a concrete bottom slab above water by supporting it on the drilled shafts and including holes in the underside of the slab at the location of each drilled shaft. Steel sheet piling is attached to the slab and the entire cofferdam lowered into position over the drilled shafts. After a seal slab is tremied into place, the cofferdam can be dewatered to finalize construction of the reinforced footing with the drilled shafts utilized to resist uplift forces on the cofferdam. Figure 6 is a photo of the work inside the dewatered cofferdam; the vertical reinforcement sticking up through the bottom mat for the footing is from the drilled shafts.

The History of Mississippi River Bridge Foundations

The design and construction of foundations for bridges along the Mississippi River has certainly evolved from the early beginnings established by James Eads, but the foundation engineering and construction for modern bridges still provide an interesting challenge for us today. In particular, the techniques of construction have evolved along with the demands of modern structures to include considerations of scour, vessel collision, and seismic loadings.

In the upper Mississippi, high-capacity, driven pipe piles are now commonly employed to meet the demands that exceed the capabilities of the earlier timber pile foundations. Pneumatic caissons are no longer used, although modern caisson techniques still have a place. High-capacity, drilled shaft foundations are now routinely employed for bridge foundations; suitable techniques include high capacity rock sockets, base grouting, and testing methods for load capacity measurement and integrity testing. Now, modern foundations engineers have a means of quality assurance never before imagined.

Crossing the mighty Mississippi in 2015 may seem to be less of an obstacle to bridge construction, but the challenges to foundation construction remain. And although it might be difficult to juxtapose the old-fashioned waterway with the extensive development of today, a modern Huckleberry Finn can still enjoy an adventure down "Old Man River" — at least if he or she is a civil engineer! GS

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