Sustainability and Reuse of Foundations for Hurricane Deck Bridge

In 2012, the Missouri Department of Transportation (MoDOT) replaced the Hurricane Deck Bridge that carries Highway 5 traffic across the Osage Arm of the Lake of the Ozarks in Camden County, Mo. The original bridge was built in the late 1920s and early 1930s, and consisted of an under-deck truss supported on four pneumatic caissons. The pneumatic caissons were excavated by hand and bear on dolostone bedrock approximately 90 ft (27 m) beneath the surface of the lake.

The replacement structure is founded on drilled shafts socketed into the bedrock. During the design phase of this bid-build project, a baseline design was developed and Alternative Technical Concepts (ATCs) were allowed from approved contractors. The ATCs were confidential and unique to the team that submitted them; either the baseline design or the ATC design could be bid by that specific contractor.

The baseline design included reuse of the four existing caisson foundations located in the lake, requiring extensive investigation and analysis of the caissons. The baseline plan was to drive temporary, large diameter, open-ended pipe piles to refusal on dolostone bedrock and construct the new superstructure on those temporary foundations. Then, traffic would be rerouted to the new structure while the original superstructure was demolished and the existing substructures modified. Finally, the new superstructure would be moved from its location on temporary piles to the existing caisson foundations, thereby ultimately maintaining the same alignment as the original structure. The benefits of providing a sustainable solution was a key consideration in the proposed approach to the baseline bridge design.

However, the successful contractor proposed, bid and was awarded an ATC that shifted the permanent alignment of the replacement bridge to the location where the temporary structure was to be located. Also, instead of four piers in the water, the span lengths were reduced, thereby increasing the number of in-water piers to seven. Each pier would be supported on drilled shafts with rock sockets.

The construction cost was about $32 million, and the difference between the awarded ATC design and the lowest bid of the baseline design was less than 1%. The general contractor was American Bridge Company, and the design consultant was Parsons Transportation Group Inc. Both Case Foundation Company and Hayes Drilling Inc. acted as subcontractors to American Bridge to
install drilled shaft foundations; Case in the water using reverse circulation drilling equipment and Hayes on the land using traditional rotary drilling equipment. Dan Brown and Associates (DBA) provided foundation engineering and design services as a subconsultant to Parsons. Terracon performed drilling and laboratory support.

Evaluation of Existing Caissons

In support of the baseline design, an extensive evaluation of the four existing caisson foundations was required. All available historical records detailing the original construction of the pneumatic caissons were obtained and reviewed. Much information was gleaned from the daily records, including reports of blasting the last foot of bedrock to help advance the caissons to their final location.

A subsurface investigation consisting of traditional rotary borings was performed to recover core samples of the 80-year-old concrete and underlying bedrock at each of the caisson locations. Generally, at least two borings per caisson were drilled, although additional holes were necessary because several of the borings could not be completed due to the presence of embedded structural steel members in the caissons or lack of sufficient plumbness of the drill string.

The majority of the borings were performed from the deck of the existing bridge. A relatively long, unsupported length of drill stem was required to reach the top of the caissons some 80 ft (24 m) beneath the bridge deck. This served to increase the difficulty of the drilling, specifically with respect to maintaining verticality. The verticality of the borings was not measured, but was known to be an issue as two of the holes exited the side of the caissons prior to reaching bedrock. In an effort to reduce the wander of the coring bit upon the initial penetration of the caisson, divers attached a steel frame to the caisson that acted as a guide for the drill stem. Wireline coring tools with diamond bits were utilized.

Borehole Evaluation and Concrete Core Testing

Subsequent to completing the multiple boreholes at each caisson, Crosshole Sonic Logging (CSL) was performed between boreholes in an attempt to further define the quality of the existing foundations and the underlying bedrock. Unfortunately, the CSL testing proved inconclusive over large zones. It is believed that the spacing between the borings in each caisson, which ranged from 15 to 21 ft (4.5 to 6.4 m), was too large. Obstructions such as embedded timber and poor quality material could have influenced the results as well. In addition, the plumbness of the borings was estimated to be within about 5% of vertical, further hindering CSL measurement and analysis. Where high quality CSL data was collected in the concrete, the wave speeds were approximately 13,000 fps (4000 mps).

Based on core recovery, laboratory test results and Acoustic Televiewer (ATV) results, the quality of the concrete in the existing caissons was excellent. Although the pneumatic caissons were effectively mass concrete, several instances of structural steel were encountered at...
FLAC3D transverse displacement results on existing caisson

maximum size chert coarse aggregate and evenly distributed, coarse grained sand consisting predominantly of chert, quartz and silica-cemented sandstone. Terracon did not observe any macrofracturing or matrix microfracturing, and no zones of coalescing voids, honeycombing or holes.

Numerical Modeling and Analysis
Following the subsurface investigation, numerical modeling and limit equilibrium calculations were performed to evaluate the existing caissons under the load of the new structure and according to current design code specifications. The top of the caisson was about 15 ft (4.5 m) beneath the lake level. In plan dimension, the caissons were 18 ft (5.5 ft) wide by 36 ft (11 ft) long. Although height varied at each of the four locations, according to the top of bedrock elevation, the caissons were 65 to 70 ft (19.8 to 21.3 m) tall. The computer software FLAC3D was used to evaluate the caissons in addition to limit equilibrium hand calculations to evaluate overturning and bearing.

Following the extensive subsurface investigation and subsequent analytical evaluation, it was concluded that the four existing pneumatic caissons were adequate to serve as the foundations for the new structure. This conclusion was valid even considering the substantially more stringent design codes in effect today relative to those that may have existed in the 1920s when the original bridge was designed.

The baseline design was advanced accordingly. Large diameter, open-ended pipe piles were designed to temporarily support the replacement superstructure during construction and prior to sliding onto the existing caissons. Although very large axial nominal resistance values were necessary, the pipe pile design was relatively ordinary in the sense that steel piles would be driven to refusal on bedrock. The most difficult aspect was the relatively large unsupported length of the piles at some locations. Wave-equation analysis and LPILE were utilized to design the large diameter, open-ended pipe piles.

Upon advertisement of the baseline contract documents, several prequalified contractors submitted confidential ATCs, some of which completely changed the design. Ultimately, the project was awarded to American Bridge and its ATC was approved and constructed. The ATC design did not rely at all on the four existing caissons and removed the need for temporary pipe piles.

ATC Foundation Design

The successful ATC required a completely new foundation design including additional subsurface investigation. A new permanent bridge alignment was proposed as part of the ATC, and the span lengths were reduced thereby increasing the number of piers. The 11 two-column bents were supported on drilled shafts with rock sockets. The two shafts at each bent were tied together with a waterline strut oriented in the transverse direction of the bridge.
The axial geotechnical design of the drilled shafts was conducted in general accordance with the MoDOT Engineering Policy Guide (EPG). This recently revised EPG incorporates the LRFD design framework and the entire approach, including resistance factors, has been regionally calibrated to large-scale load test results.

The diameter was controlled by lateral considerations and the relatively large unsupported length between the mudline and the waterline strut. The submerged overburden soil was soft and provided little lateral resistance. In some locations, the water was 80 ft (24 m) deep with only about 10 ft (3 m) of soil above bedrock. Due to the relatively large unsupported shaft length, the structural engineer concluded and specified that the maximum allowable plumbness tolerance was 1%.

The socket length was controlled by a combination of lateral and axial considerations, and less favorable bedrock conditions were encountered at some shaft locations. The core recovery and RQD at some locations indicated soil-filled solution cavities and poor quality bedrock at a few of the shafts.

**Foundation Construction**

The drilled shafts at Bents 4 through 10 were constructed by Case Foundation. These locations represented the over-water bents and included a total of 14 shafts. After installing the permanent casing into bedrock and removing the soil overburden inside the casing, Case Foundation drilled the rock sockets with a reverse circulation drill rig. The rig was mounted to the top of the permanent casing and the excavation was advanced using a full-face cutter assembly. The configuration of drill rig and cutting tool combined to make what was essentially a large plumb bob. This proved beneficial in achieving the maximum 1% vertical tolerance specified in the construction documents.

Another benefit of the reverse circulation drilling method was that an airlift was constantly working to remove cuttings. This process resulted in a very clean excavation, which greatly reduced the risks of post-construction integrity test anomalies as well as provided more reliable base resistance.

Following the excavation of the drilled shafts, standard MoDOT drilled shaft construction specifications required each rock socket be visually inspected with a television camera. The socket walls and base were viewed with the camera and indicated a very clean excavation and rock socket conditions commensurate with the design.

At one shaft location, a clay-filled solution cavity was encountered that required mitigation. The cavity was approximately 2 to 3 ft (0.6 to 0.9 m) in vertical dimension, and the top of the cavity was approximately 5 ft (1.5 m) beneath the top of bedrock. Upon encountering this feature, the drill stem advanced rapidly and was immediately retrieved to prevent potential loss of the tool.

**Conclusion**

In today's economic climate, an emphasis on sustainability is prevalent. However, economy still appears to rule. The baseline design sought a sustainable solution that was still economical. The ATC that was ultimately awarded and constructed obviously provided better economy, at least at bid time. The ATC included reducing the span lengths and increasing the number of new substructures, thereby removing the need to reuse the existing foundations. It is of interest to compare the bid of the successful ATC to the next lowest unsuccessful bid of the baseline design. The difference in cost was about 1%. Although subject to the procurement rules set forth in the solicitation, it can perhaps be concluded that sustainability wasn't worth 1%.

A previously agreed upon contingency plan was instituted immediately to mitigate the issue. This contingency plan was included in the drilled shaft installation plan and proved very valuable. Because the risk of encountering such features was made known early in the project, the owner, engineer and contractor were able to rapidly respond to the issue and successfully and efficiently resolve the problem under fair financial terms. A well thought-out installation plan provided by the contractor, in combination with a thorough identification and description of construction risks by the engineer, helped the owner feel comfortable agreeing to the financial terms of the possible mitigation effort prior to the commencement of construction.

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