SUSTAINABILITY AND CONSIDERATION OF THE RE-USE OF FOUNDATIONS FOR THE HURRICANE DECK BRIDGE


The Missouri Department of Transportation (MoDOT) recently replaced the Hurricane Deck Bridge that carries Highway 5 traffic across the Osage Arm of the Lake of the Ozarks in Camden County, Missouri. The former bridge was constructed in the 1920’s and was supported on pneumatic caissons bearing on dolostone bedrock. 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 (ATC’s) were allowed from approved contractors. Those ATC’s were confidential and not shared between teams. Either the baseline design or the approved ATC design could be bid by the respective contractors. The baseline design included re-use of the 90-year old caisson foundations. Accordingly, an extensive evaluation of the caissons and underlying bedrock were conducted by coring, laboratory testing, acoustic tele-viewer (ATV), and cross-hole sonic logging (CSL) methods. The results of the investigation indicated the caissons were in excellent condition and suitable for re-use. However, a more cost-effective ATC was submitted, awarded, and constructed that did not re-use the existing caisson foundations but rather reduced the span lengths, increased the number of piers in the water, and supported those piers on drilled shafts. Interestingly, the difference in low bid price between the awarded ATC and the baseline design was less than one percent of the construction cost. This paper describes the multiple foundation designs that were necessary for this interesting project. The various foundation evaluations include the existing pneumatic caissons, large-diameter open-ended pipe piles to support the baseline design, and the design of rock-socketed drilled shafts that were successfully constructed in 2012.

Introduction

The Hurricane Deck Bridge carrying Highway 5 traffic across the Osage Arm of the Lake of the Ozarks in Camden County, Missouri has recently been replaced. The location of the project in Central Missouri is provided in Figure 1 and a photograph of the original bridge is provided in Figure 2. The original structure was built in the late 1920’s and early 1930’s 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 90ft beneath the surface of the lake.

The bid-build procurement process was used by MoDOT although bid-phase ATC’s were also allowed. Those ATC’s were confidential and unique to the team that submitted them and either the baseline design or the ATC design could be bid by that specific Contractor.
The baseline design included re-use of the four existing caisson foundations located in the lake and therefore required 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 is supported on drilled shafts with rock sockets.

The construction cost was about than $32 million and the difference between the awarded ATC design and the lowest bid of the baseline design was less than one percent.

The owner is MoDOT, the general contractor is American Bridge, and the design consultant is Parsons. Both Case Foundation and Hayes Drilling acted as sub-contractor 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 sub-consultant to Parsons. Terracon provided 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. A good deal of insight 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 as 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 as shown in Figure 3. Necessarily, a relatively long, unsupported length of drill stem was required to even reach the top of the caissons some 80 ft 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.

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 boreholes in each caisson, which was on the order of 15 ft to 21 ft, was too large.
Obstructions such as embedded timber and or poor quality material could have influenced the results as well. In addition, the plumbness of the borings was estimated to be within about five percent of vertical, further hindering CSL measurement and analysis. Where high quality CSL data was collected in the concrete, the wave speeds were on the order of 13,000 fps.

Figure 3: Investigation Drilling from Bridge Deck.

On the basis of core recovery, laboratory test results, and acoustic tele-viewer (ATV) results, the quality of the concrete in the existing caissons was excellent despite extremely difficult drilling. Although the pneumatic caissons are effectively mass concrete, several instances of structural steel were encountered at various locations throughout the drilling. Needless to say, the presence of the structural steel caused considerable delay and damage to the coring operations. A photograph of the recovered concrete core is shown in Figure 4 that was representative of all foundations. Figure 5 shows a photograph of a piece of structural steel encased in the concrete core.

Figure 4: Existing Caisson Concrete Core.

The average unconfined compressive strength ($q_u$) of the concrete cores as measured in the laboratory was 7,410 psi. The measured $q_u$ values on the 83 samples tested ranged from 3,730 psi to 13,470 psi with a standard deviation of 1,760 psi. The average unit weight of the core samples prior to testing in the laboratory was 142 pcf.

The completed boreholes were also logged with an Acoustic Tele-Viewer (ATV) in an effort to further evaluate the quality of the bedrock and the interface between the bedrock and the caissons. This technology has been successfully utilized on other bridge projects in Missouri and was instrumental in evaluating the interface between the existing caissons and the bedrock. This region is known to contain karstic features in the bedrock and the ATV logs have provided a reliable means to inspect borehole walls for such features. An example of the ATV results at the caisson/bedrock interface is provided in Figure 6 and can be compared to the respective core recovery at the same location shown in the photograph in Figure 7. More information regarding the ATV measurement and interpretation can be found in Keller, 2010.

The dolostone bedrock beneath the caissons was determined to be adequate on the basis of the core results. The average unconfined compressive strength ($q_u$) of the bedrock cores as measured in the laboratory was 5,680 psi. As is typical with sedimentary bedrock in the Midwestern United States the $q_u$ of the bedrock cores contained a fair amount of variability and therefore many tests were performed in an effort to quantify the variability. The measured $q_u$ values on the 225 samples tested ranged from 650 psi to 18,420 psi with a standard deviation of 3,090 psi. The average unit weight of the bedrock core samples prior to testing in the laboratory was 159 pcf. Although 225 samples of bedrock core were tested, only about one third of those were originally tested for the baseline design. The remaining tests were
performed in support of the subsequent drilled shaft ATC.

Petrographic analyses were performed by Terracon on four recovered concrete core samples. On the basis of the results presented by Terracon, on average, the total aggregate was measured to be 70.7 percent and ranged from 67.4 to 76.6 percent. The total cementitious materials averaged 28.8 percent and ranged from 22.8 to 32.5 percent. The total air content averaged 0.6 percent and ranged from 0.1 to 1.0 percent. The general findings of the petrographic analyses indicated well-consolidated and well-mixed concrete that varied from well-proportioned to slightly aggregate heavy. The aggregate was in good condition and consisted of 1.5 inch maximum size chert coarse aggregate and evenly distributed, coarse grained sand consisting predominantly of chert, quartz, and silica-cemented sandstone. A photograph of one of the core samples that has been sawn and had phenolphthalein applied is provided in Figure 8. From the conclusions of the Terracon report, no macrofracturing or matrix microfracturing was observed and no zones of coalescing voids, honeycombing, or holes were observed.

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. A typical drawing of one of the four original pneumatic caissons is included in Figure 9. The top of the caisson, i.e., beneath the two columns, was about 15 ft beneath the lake level. In plan dimension, the caissons were

Figure 6: ATV Results at Interface between Existing Caisson Concrete and Dolostone Bedrock.

Figure 7: Core Recovery at Interface between Existing Caisson Concrete and Dolostone Bedrock.

Figure 8: Section of Concrete Core.

Generally, core recovery was high, mostly above 90 percent although the Rock Quality Designation (RQD) ranged from 0 to 100 percent with an average value on the order of about 60 percent.
18 ft wide by 36 ft long. Although it varied at each of the four locations according to the top of bedrock elevation, the caissons were about 65 ft to 70 ft tall.

The computer software FLAC3D was used to evaluate the caissons in addition to limit equilibrium hand calculations to evaluate overturning and bearing. An example of the FLAC3D results indicating the computed displacements in the transverse direction of the bridge in one of the caissons is shown in Figure 10.

![FLAC3D Transverse Displacement Results on Existing Caisson.](image)

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 1920’s when the original bridge was designed.

The baseline design was advanced accordingly. Concurrently, 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 primarily utilized to design the large diameter open-ended pipe piles.

![Figure 9: Existing Caisson Elevation and Section.](image)

Upon advertisement of the baseline contract documents, several pre-qualified Contractors submitted confidential ATC’s, some of which completely changed the design. Ultimately, the project was awarded to American Bridge and their 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 included 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 eleven 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. Each column was supported by an 8.5 ft diameter drilled shaft permanently cased to rock and with an 8 ft diameter socket extending about 20 ft into dolostone bedrock.
The axial geotechnical design of the drilled shafts was conducted in general accordance with the Missouri Department Transportation (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 relative large unsupported length between the mudline and the waterline strut. The submerged overburden soil was soft and provided little lateral resistance. A schematic of the subsurface profile longitudinal with the bridge is provided in Figure 11 with the bent locations superimposed. At some locations, the water is 80 ft deep with only about 10 ft 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 one percent.

The socket length was controlled by 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.

Contributions from both side and base resistance were included in the computations for geotechnical nominal axial resistance.

Foundation Construction

The drilled shafts at Bents 4 through 10 were constructed by Case Foundation under subcontract to American Bridge. These locations represent the over-water bents and included a total of 14 shafts. The drilled shafts necessary to support the bents on land were constructed by Hayes Drilling under subcontract to American Bridge.

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 as shown in Figure 12 and the excavation was advance using a full-face cutter assembly as shown in Figure 13.

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 one percent vertical tolerance specified in the construction documents.

The socket walls and base were viewed with television cameras to inspect visually for cracks or departures from smoothness.

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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 two to three feet in vertical dimension and the top of the cavity was approximately 5 ft beneath the top of bedrock. Upon encountering this feature, the drill stem advanced rapidly as would be expected when transitioning from bedrock to clay. The drill assembly was immediately retrieved to prevent potential loss of the tool.

Figure 13: Full-Face Cutter Assembly.

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 were made known early in the project, the Owner, Engineer, and Contractor were able to rapidly respond to the issue and successfully and efficiently mitigate the problem under fair financial terms. A well thought 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. A photograph of the completed Hurricane Deck replacement bridge is provided below in Figure 14.

Figure 14: Photograph of New Hurricane Deck Bridge (courtesy of OxBlue Construction Camera Service).

Summary

Several aspects of foundation engineering were necessary during the design phase of this interesting bridge replacement project. The final selected foundation elements included drilled shafts with rock sockets and one instance of a spread footing bearing on shallow bedrock. The baseline design included temporary, large-diameter open-ended pipe piles and re-use of four existing pneumatic caissons constructed in the late 1920’s as permanent foundations.

Upon intensive investigation and numerical modeling of the existing caissons, it was ultimately concluded that they were in good condition and suitable for re-use. This conclusion was made in light of the more stringent design requirements currently in practice.

During the investigation of the existing caissons, ATV testing proved very beneficial, particularly in zones with low core recovery or RQD. The ATV was also helpful in evaluating the condition of the interface between the caissons and the bedrock.

Little benefit was gleaned from the CSL testing of the caissons. This is likely a result of the large spacing between boreholes although the
amount of timber and steel found in the core holes may have contributed as could have the relative lack of borehole verticality. In future investigations, seismic cross-hole methods may be more beneficial where the source is capable of generating more energy.

The requirement for a detailed drilled shaft installation plan to be submitted and approved should not be considered mundane. A comprehensive plan agreed upon by all parties in advance of the construction can and did yield benefit. A good plan should include a consideration of the anticipated risks and an agreement on how to proceed if difficulties associated with those risks are encountered. A good faith effort is necessary by the Contractor and a willingness to share risk is necessary by the Owner.

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. An ATC that was ultimately awarded and constructed obviously provided better economy, at least at bid time. That ATC included reducing the span lengths and increasing the number of new substructures thereby removing the need to re-use 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 one percent. Although subject to the procurement rules set forth in the solicitation, perhaps it can be concluded that sustainability wasn’t worth one percent.

References
