Paper No. 22

Structural Elements

Foundation Strengthening Of Bascule Piers At The Bridge Of Lions

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INTRODUCTION

Rehabilitation and strengthening of existing bridge foundations are required for a variety of circumstances including scour, deteriorated foundation structures, new design requirements such as vessel impact and seismic design, and added dead and live loads. Compared to bridge superstructures, bridge substructures are usually more challenging to strengthen since they support existing superstructures, many foundations are in water, and both roadway and waterborne traffic must be considered. These make load transfer and construction of the strengthening components more difficult. A case study is presented in this paper to discuss the design development and alternates for strengthening of the existing bascule pier foundations for the Bridge of Lions. The Bridge of Lions, constructed in 1927, carries SR A1A over the Matanzas River in St. Johns County, Florida, connecting the City of St. Augustine with Anastasia Island. The bridge is on the National Register of Historic Places and is being rehabilitated due to structural deficiencies and functional obsolescence.

Considering the structural conditions and historic features of the bridge, the bascule piers of the bridge are to remain and be strengthened to resist vessel impact and scour. The bascule piers consist of waterline footings supported by six 8' diameter caissons, each with independent mudline footers supported by timber piles. A general view of the bascule span is shown in Figure 1. Micropiles and drilled shafts were considered to strengthen the piers at the waterline footing, or at the mudline footers. Final design has been carried out for a new waterline footing supported by new drilled shafts to strengthen the existing bascule pier foundations.

Fig. 1 General View of the Bridge of Lions

DESIGN REQUIREMENTS FOR BASCULE PIERS

The existing bascule piers have been in place for approximately 75 years with no structural problems. The bascule piers are to be strengthened based on the following design requirements:

VESSEL COLLISION: Based on the vessel impact analysis that considered the approach piers and bascule piers together, the lateral vessel collision force that must be resisted by each bascule pier is 2000 kips.

SCOUR: The elevation of the bottom of the channel is approximately -23.0 feet at the west bascule pier and -27.0 at the east bascule pier. The tip elevation of the existing timber piles is approximately -57 feet. Per the scour analysis and scale model test conducted for the project, the total scour for the 100-year storm at the bascule piers would be approximately 23.5 feet, which translates to an elevation of approximately -46.5 feet at the west bascule pier and -50.5 feet at the east bascule pier, respectively[1].

ADDED WEIGHTS: The new approach spans are 6'-5" wider than the existing spans. The new bascule leaves have the same width as the existing but have a solid roadway deck instead of the open grid deck. In addition, modifications on the bascule piers include closing of the openings in the existing waterline footing, new machinery platforms and new concrete floors at the machinery level.

OPTIONS FOR FOUNDATION STRENGTHENING

OPTION 1: MICROPILES DESIGNED FOR VESSEL IMPACT ONLY

Based on the original scope of work for the project, the bascule piers did not require strengthening for vertical load carrying capacities. Because of this, micropiles were considered as a possible strengthening element for the piers to resist vessel impact forces, since they can be easily installed with a batter, in access-restricted environments and have a tension capacity almost equal to that of compression.

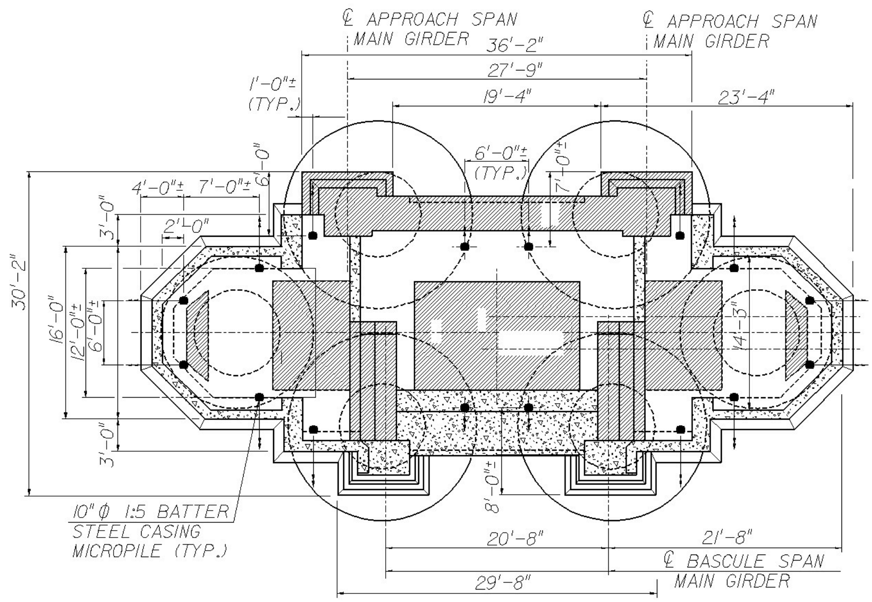

Fig. 2 Micropile Layout for Foundation Strengthening

Analysis of this option using the STAAD/Pro[2] and FB-Pier[3] programs indicated that installation of 16-10" diameter, 1:5 battered micropiles per bascule pier, acting together with the existing foundation would be adequate to resist the 2000 kip design vessel impact force. The 10" diameter micropile was assumed to have a tension/compression capacity of 200 kips[4]. See Figure 2 for the proposed micropile layout.

The estimated construction cost was $1,500,000 with 15% contingency. This option was eliminated after a new scour analysis for the project had been completed and the decision was made to strengthen the existing bascule piers for both vertical and horizontal capacities.

OPTION 2: MUDLINE FOOTERS STRENGTHENED WITH DRILLED SHAFTS

The use of drilled shafts to provide the strength needed to resist vessel impact and the ultimate scour conditions of the 100 and 500 year storms was investigated with FB-Pier.

The option consisted of installing five 8'-0" diameter drilled shafts at the level of the mudline footers. Four of the new drilled shafts were located at the four corners of the foundation, outside of the limits of the existing circular footers. A fifth drilled shaft was located at the center of the foundation. Loads were transferred from the mudline footers to the new drilled shafts by the addition of a new mudline foundation which encompassed the existing individual foundations and the tops of the new drilled shafts. See Figure 3 for the drilled shaft layout. Figure 4 shows a 3-D visualization of this option. The darker solid shapes show the new structure. Dowels would be used to transfer loads from the existing foundations to the new drilled shafts. The new mudline foundation would be constructed using a cofferdam. Because the new drilled shafts and foundation are at the mudline, the new drilled shafts could be located symmetrically about the centerlines of the bascule piers, and the new shafts could be installed outside the limits of the existing foundations without interfering with the navigation channel. The new drilled shafts would be designed to carry all of the loads of the bascule pier, including vessel impact, and withstand the 100 year and 500 year scour events, thus, the existing timber pile foundations could eventually fail without adversely affecting the strength of the piers.

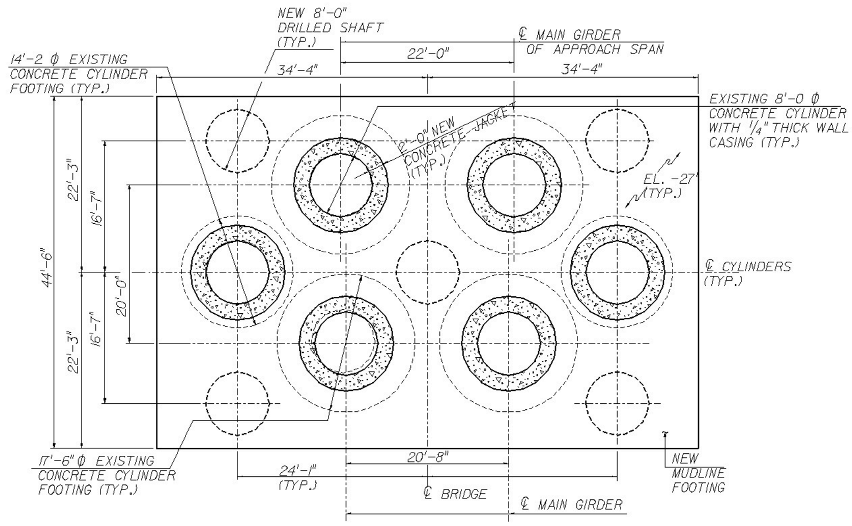

Fig. 3 Plan View of Drilled Shafts at Mudline Footers

The existing steel encased concrete caissons, which transfer the bascule pier loads from the upper waterline footing to the lower mudline footers, would require strengthening to resist the required vessel impact loads. Under this option, this would be accomplished by encasing the caissons in a ring of reinforced concrete. Because of the unknown condition of the steel caisson shells and the concrete inside the caissons, the new reinforced concrete rings would be designed to carry all of the loads of the bascule pier, including ship impact.

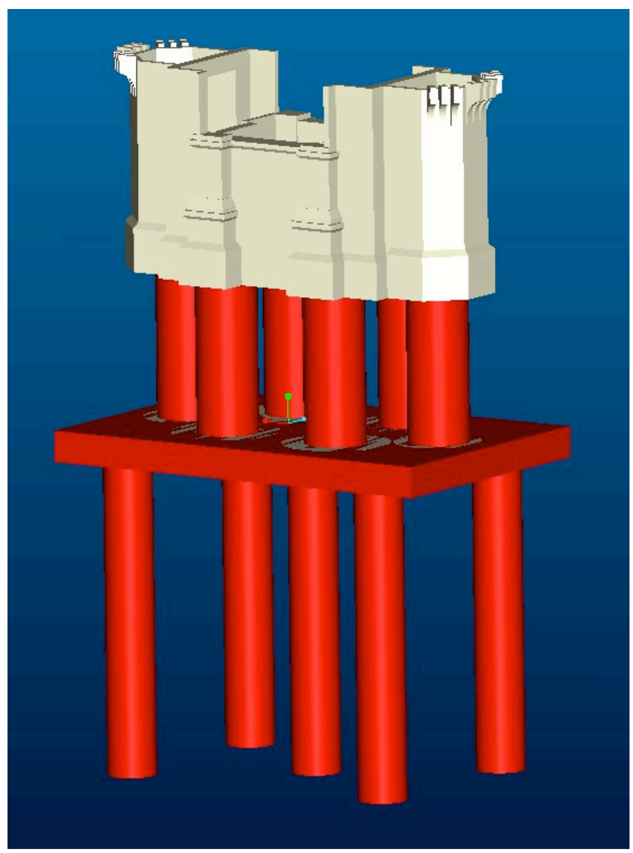

Fig. 4 3-D Visualization of Drilled Shafts at Mudline Footers

The construction cost for this option was estimated to be $5,053,710 with 15% contingency.

OPTION 3: NEW WATERLINE FOOTING SUPPORTED BY DRILLED SHAFTS

The third option for strengthening the existing bascule pier foundations consisted of five new drilled shafts with a new waterline footing. In order to transfer the loads from the existing waterline footing to the new drilled shafts, the drilled shafts would be capped with the new concrete footing extending under the existing waterline footing. See Figures 5 and 6 for the elevation and plan view of this option. The

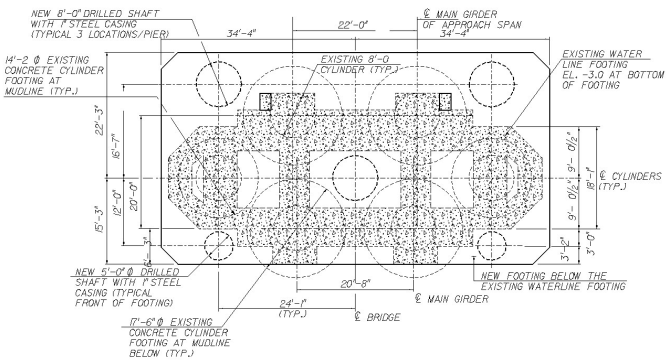

Fig. 5 Elevation of Drilled Shafts with New Waterline Footing

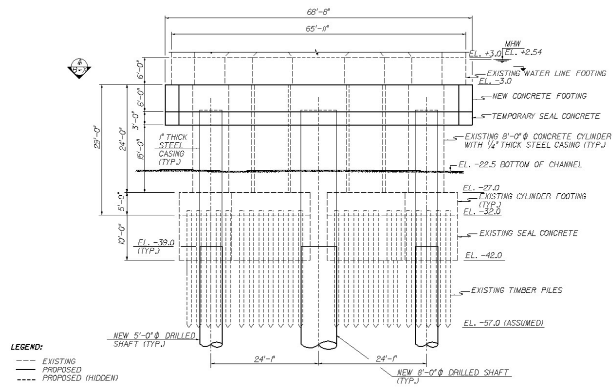

Fig. 6 Plan View of Drilled Shafts with New Waterline Footing

analysis was performed with FB-Pier. Because the new drilled shafts extend above the mudline, the locations on the channel side of the piers were restricted to the footprint of the existing waterline footing so that they do not interfere with navigation. The new shafts at the rear of the existing piers could be placed as needed without restriction. The restriction on placement of the front drilled shafts also limited the size of these shafts to 5'-0". The rear drilled shafts and the shaft placed at the center of the pier were 8'-0" diameter. 3-D visualizations of this option refined in the final design from different angles are shown in Figures 7 through 11. The darker solid shapes show the new structure.

The new waterline footing could be built using a partial depth "tub" rather than a full depth cofferdam. The new drilled shafts and footing would be designed to carry all the bascule pier loads, including vessel impact and scour. Therefore the condition of the existing steel encased caissons, mudline footers, and timber piles could not control the capacity of the rehabilitated structure.

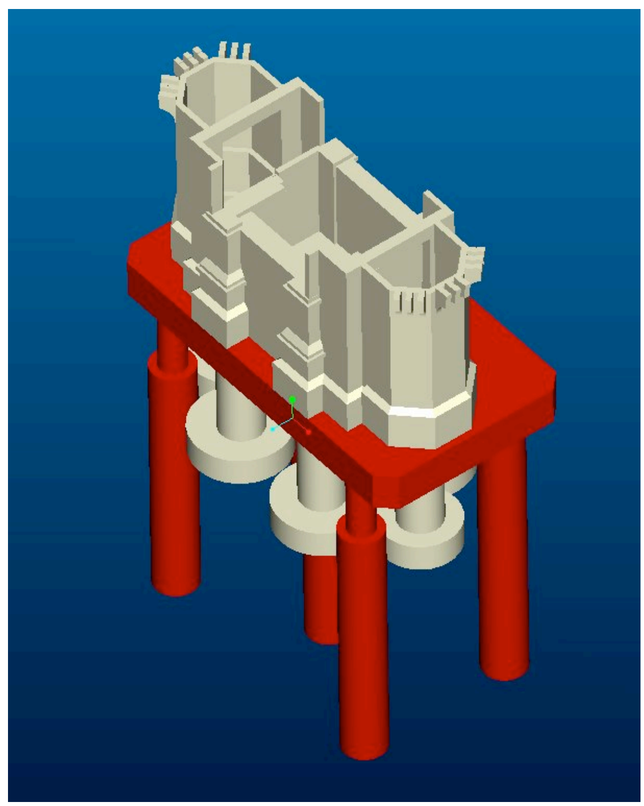

Fig. 7 3-D Visualization of Drilled Shafts with New Waterline Footing

The estimated construction cost for this option was $3,584,446 with 15% contingency.

FINAL DESIGN OF BASCULE PIER FOUNDATION STRENGTHENING

Based on the structural mechanism of the strengthening and the estimated construction costs, it is not difficult to determine that Option 3: addition of new drilled shafts with new waterline footing under the existing footing was selected as the most appropriate strengthening option.

Due to insufficient vertical bearing capacities, the 5' drilled shafts in Option 3 were replaced with 8' diameter drilled shafts below mudline, on which 5' columns were monolithically constructed. The new drilled shaft/footing consists of 5 - 8 foot diameter drilled shafts with 1" thick steel casing and 7 feet thick footing/shaft cap immediately below the existing waterline footing, as shown in Figures 5 through 11.

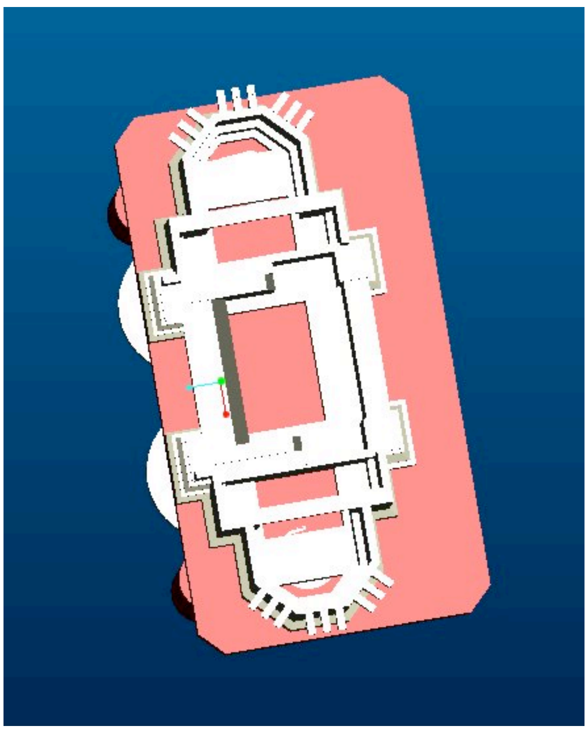

Fig. 8 Top View of Pier with New Footing

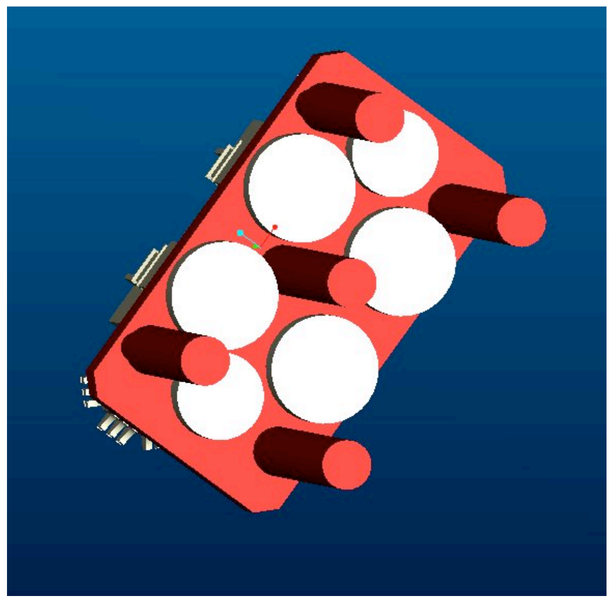

Fig. 9 Bottom View of Pier with New Drilled Shafts and Footing

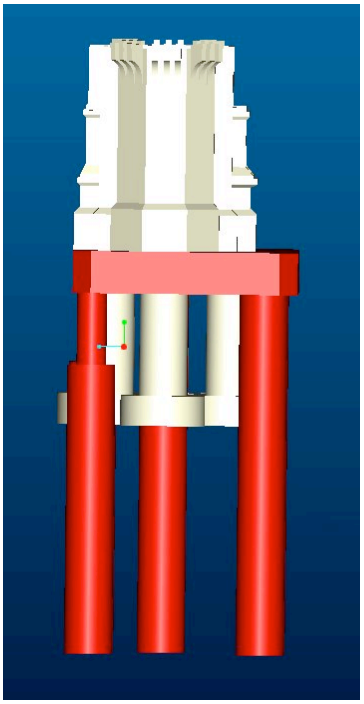

Fig. 10 Side View of Pier with New Drilled Shafts and Footing

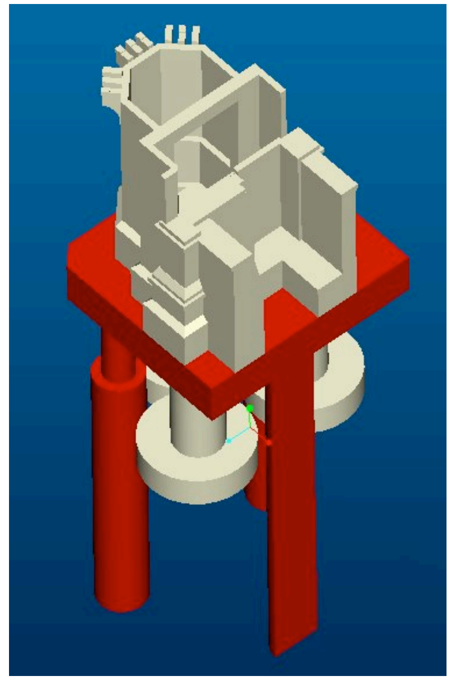

Fig. 11 Half Pier View of Pier with New Drilled Shafts and Footing

LATERAL CAPACITY OF THE DRILLED SHAFT/FOOTING FOUNDATION

A three-dimensional analysis of the drilled shaft/footing foundation was performed using the FB-Pier, Version 2.14 by the Florida Department of Transportation and the Federal Highway Administration. The analysis with FB-Pier considers the nonlinear behaviors of the structure and the interaction between the structure and the soils. The resistance factor for the lateral capacity of the drilled shaft/footing foundation is 1.0 per Florida DOT Structures Design Guidelines for Load Factor Design, Version 2000[5]. The lateral capacity resists any horizontal loadings, such as wind loads, braking loads, stream pressure loads, and most significant in this case, the vessel impact forces.

The AASHTO extreme event load combinations including vessel impact control the design for the lateral capacity of the new drilled shaft foundation. Per FDOT Structures Design Guidelines, the analysis assumes half of the 100-year scour depth. The 3-D analytical model with FB-Pier is shown in Figures 12 and 13.

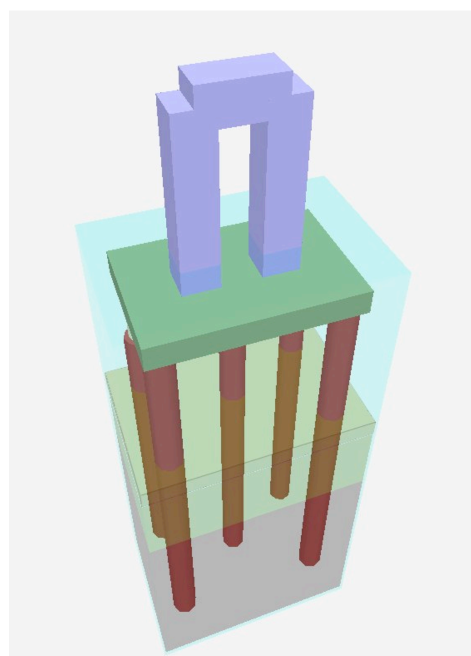

Fig. 12 3-D Visualization in FB Pier

VERTICAL CAPACITY OF THE DRILLED SHAFT/FOOTING FOUNDATION

The vertical loads at the heads of the drilled shafts were obtained from the 3-D FB-Pier analysis. Actually, the vertical capacities of the drilled shafts were checked against the loads on the foundation in the FB-Pier analysis, assuming a resistance factor of 1.0. The ultimate vertical resistances of the drilled shafts were obtained with Vertically Loaded Drilled Shaft Analysis Program, Version 5.0 by ENSOFT, Inc. A resistance factor of 0.55 was selected by the Geotechnical Engineer, based on FDOT Structures Design Guidelines (LRFD), 2003 Version, since FDOT Structures Design Guidelines for Load Factor Design (2000) does not have similar provisions for the resistance factor. Comparing the factored loads by LFD to the resistance by LRFD is conservative for the design.

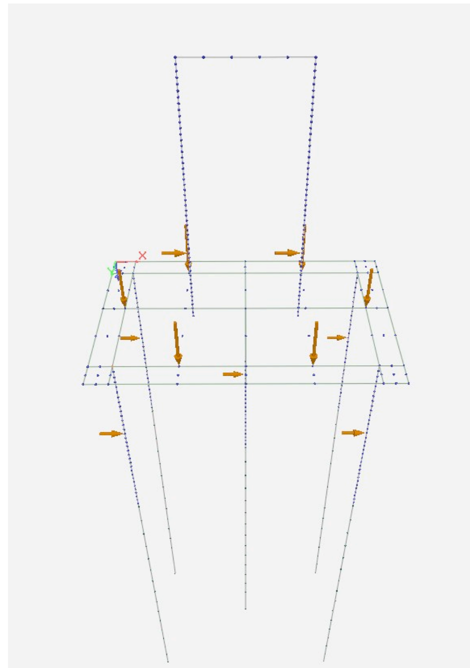

Fig. 13 3-D FEM Model in FB Pier

For vertical capacity of the drilled shafts, the AASHTO strength load combinations control the design. The maximum factored vertical load at the heads of drilled shafts is 1170 tons per shaft. The calculated ultimate vertical resistance of the drilled shafts is 1740 tons. Comparing the load and the resistance results in a resistance factor of 0.67, which is greater than 0.55. Due to the limited available space and exploration depth of the existing borings, increases in size, embedment depth or number of drilled shafts were not feasible.

The calculated factored vertical loads on the drilled shaft heads were calculated under all the loads, including the weights of the existing 8’ diameter concrete caissons, their mudline footers and seal concrete. Consider the fact that even after the predicted 100-year scour, the existing timber piles still have an embedment of 11.5 feet at the west bascule pier and 6.5 feet at the east bascule pier. If the weights of the 8’ diameter concrete caissons, their mudline footers and seal concrete are taken by the existing timber piles, the maximum factored vertical load on the drilled shaft heads would be reduced to 910 tons per shaft. That translates to a resistance factor of 0.52, less than the required 0.55. If the existing timber piles were unable to support those weights, the seal concrete would be separated from the mudline footers due to lack of bond between them. Removing the seal concrete from the system results in a resistance factor of 0.61, which is slightly higher than 0.55. If the predicted 100-year scour does occur and the existing timber piles do not provide any support, the 8’ diameter concrete caissons and their mudline footers could be cut off.

STRUCTURAL DESIGN OF THE DRILLED SHAFTS AND FOOTING

All information on drilled shafts including reinforcing steel and steel casings were required for the nonlinear analysis performed with the FB-Pier program. The drilled shafts were designed during their iterative analyses with FB-Pier by adjusting the drilled shafts.
Footing

The moments and shears in the footing were obtained from the FB-Pier analysis. The reinforcing steel in the footing was designed as a two-way slab with the maximum moment and shear in the top and bottom of the footing. Additional reinforcing steel is provided in the load paths and to enclose the holes formed by the existing concrete caissons.

CONSTRUCTIBILITY OF THE NEW PIER FOUNDATION

Placement of the new drilled shaft foundation is difficult but constructible.

1) Drilled Shafts

The construction of the 8' diameter drilled shafts is relatively straightforward except for the limited overhead and side spaces. The 8' diameter drilled shafts with 5' diameter column on the top requires more attention to their construction. Following is a suggested installation procedure for the 5' diameter columns on 8' diameter drilled shafts:

a) Drill the 8' diameter drilled shafts with the permanent casing extending above the waterline. Limited headroom above the locations of the front (channel side) drilled shafts requires splicing of the casings for the 8' diameter drilled shafts to obtain the total length required.

b) As the concrete pour for the 8' shaft advances and approaches the top of the 8' shaft, install the casing for the 5' column. The casing may require a centering ring around the outside to keep the concrete from overflowing between the 8' casing and the 5' casing above the required elevation of the 8' drilled shaft. The 5' casing also requires stops attached near the top to help center the casing and to keep it from dropping into the 8' drilled shaft.

c) The 5' column will be cast monolithically with the 8' drilled shaft. After completing the shaft, cut the 8' diameter steel casing at the top of the 8' shaft, which is below the mudline.

2) Footing

The new footing is to be constructed under the existing waterline footing. In addition, the existing 8' diameter concrete caissons go through the new footing. The space is tight for the placement of the reinforcing steel and concrete for the new footing. It is expected to use high slump concrete for the footing. Since the new footing is below water level, a full depth cofferdam or half depth "tub" is required in order to have a dry environment for the construction of the new footing.

SUMMARY

From the design development of strengthening of the bascule pier foundations, the following are summarized:

1) Drilled shafts and micropiles, which could be viewed as small drilled shafts, are very effective in strengthening foundations with minimal impact on existing foundations.

2) Two big advantages for the micropiles are the load transfer between the micropiles and the existing foundations and the almost equal capacities in tension and compression. Micropiles can be installed in a restricted space and from the top through the existing structure or a water body without cofferdam. The micropiles can be battered easily without incurring an additional cost.

3) With the nature of drilled shafts, they are effective in supporting large loadings with long unsupported lengths. The load transfer from the existing structure to the new added drilled shafts is always challenging.

4) Constructability of pier foundation strengthening elements is always an issue in the design due to limited access and limited selection of the means for load transfer from existing to the new supporting structure.

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REFERENCES

1) Law Engineering and Environmental Service, Inc., “Report of Geotechnical Exploration for Bridge of Lions Rehabilitation,” 2003.

2) Research Engineers International, “STAAD.Pro 2002”, 2002.

3) FDOT and FHWA, “FB-Pier V. 2.13”, 2002.

4) DBM Contractors, Inc., “Micropile Design and Construction Guidelines. Implementation Manual. U.S. Department of Commerce, NTIS, 2000.

5) FDOT Structures Design Office, “Structures Design Guidelines for Load Factor Design, 2000”.