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Forensic Engineering Analysis of an Emergency Bridge Replacement Project

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Abstract

A bridge that provided grade separation and vehicle access over a commercial rail line in a small town in the Southeast had sustained soil erosion and settlement as a result of a severe storm. Replacement of the bridge was undertaken by the State Department of Transportation as an emergency project in cooperation with the Federal Highway Administration using the design-build procurement method. Subsequent to the bidding, the design-build team made several changes to the bridge foundations and superstructure that significantly increased the cost of construction. The contractor claimed damages against the other members of the design-build team resulting from design errors and an alleged breach of the customary standards associated with the design-build concept.

Keywords

Design-build, bridge foundation, PDA, pile capacity

Project Background

The bridge structure was supported on a system of shallow foundations at each abutment and three internal bents (internal column and pile support), which were spaced about 25 feet on centers and spanned the railroad tracks (**Figure 1**). They supported concrete columns that, in turn, supported the bridge deck. Settlement at one of the bridge abutments caused closure of the roadway (**Figure 2**).

State Department of Transportation (SDOT) engaged a firm to prepare a request for proposal (RFP) for the bridge replacement and asked that a local geotechnical engineer conduct the investigation associated with the RFP. SDOT issued the RFP for the project in April 2012. Included in the RFP was a geotechnical data summary report prepared by that engineer.

A construction company (contractor), well known to SDOT and local to the area, was one of several companies that responded to the SDOT RFP. As part of its response, the contractor selected a local design engineer for the design-build team. The design engineer contracted with the same geotechnical engineer that participated in the development of the RFP for geotechnical design on the project. This design-build team was chosen as the successful bidder for the replacement bridge project.

Basis of Bid

Rather than replace the bridge in kind, the design team selected a pre-stressed concrete single span arch as the primary component of the bridge replacement

Figure 1
Vehicle bridge over Norfolk Southern Railroad.

Figure 2
Settlement resulting from soil erosion at the bridge abutment.

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section (**Figure 3**). The design engineer had an expectation of using either H-piles or pipe piles for the foundation support based on the geotechnical engineer's recommendation.

For the bid quantities, the length of the abutment wall — and therefore the length of the bridge foundation — was assumed to be 45 feet. The SDOT design minimum was 44 feet; however, there was a note in the RFP that because the alignment of the bridge was skewed to the alignment of the railroad (**Figure 4**), additional foundation width would be required, should the precast reinforced concrete floorless culvert option be chosen. The wing walls on either side of the abutments were assumed to be supported on shallow foundations. The number of piles supporting the bridge structure was assumed to be two rows of piles spaced 5 feet on centers for the length of the foundation for a total of 16 piles for each abutment. A pile length of 40 feet was used in the calculation to determine a total of 1,280 linear feet of piles for the project.

As part of the design-build process, the design team, once selected, was required to prepare and submit for review design drawings responsive to SDOT standards at three stages: 50% design, 90% design, and final design. A detailed geotechnical report supporting the design was to accompany each design submission.

Design Submission 50%

The geotechnical recommendations for pile support of the bridge abutments were based entirely on the results obtained from the two borings drilled for the SDOT RFP, even though it was "encouraged" in the RFP that the proposers obtain additional subsurface explorations prior to bid submission. The borings drilled for the RFP were located approximately 50 feet from the proposed pile locations. The only additional information included with the 50% design was the laboratory classification testing of selected soil samples obtained during the RFP drilling effort.

Based on the geotechnical engineer's experience, HP 14x73 steel piles were recommended for support of the abutments (**Figure 5**). The pile section is generally the shape of the letter H, approximately 14 inches square, weighing 73 pounds per foot of pile length. The pile capacity was to be derived primarily from end bearing in the dense sands of a geologic formation common to the area. The assumed average pile length was 46 feet. The ultimate pile capacity was estimated to be 460 kips (230 tons). The geotechnical engineer specifically discouraged the use of high displacement piles (closed-end pipe piles, as shown in **Figure 5**) due to the proximity of the railroad to the proposed pile foundations (approximately 23 feet).

Figure 3
Newly constructed abutments with arch culvert segments in place.

Figure 4
Existing bridge removed with soil abutments exposed.

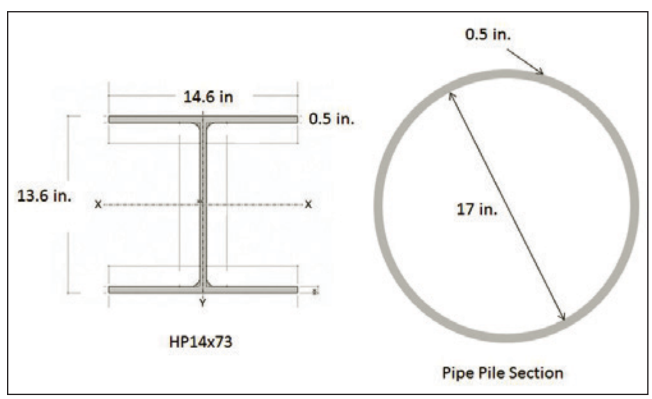

Figure 5
The 14-inch H-pile and 18-inch pipe pile sections.

The geotechnical engineer considered the installation of high displacement piles and associated lateral soil and track movement as a potential concern.

The geotechnical engineer recommended a program of dynamic testing during pile installation (index piles) using a pile driving analyzer (PDA), as shown in **Figure 6**. The purpose of the testing was to determine both the drivability of the piles and provide a refinement of the pile capacity. Generally, this is an acceptable procedure in lieu of static load testing, particularly in a design-build situation. Based on the engineer's analyses, estimated pile penetration rates, ranging from 139 to 258 blows per foot (bpf), were calculated to achieve the desired capacity for the proposed pile type and driving equipment. The analysis was based on the equipment used to drive the index piles. No pile refusal rate was established for the testing program.

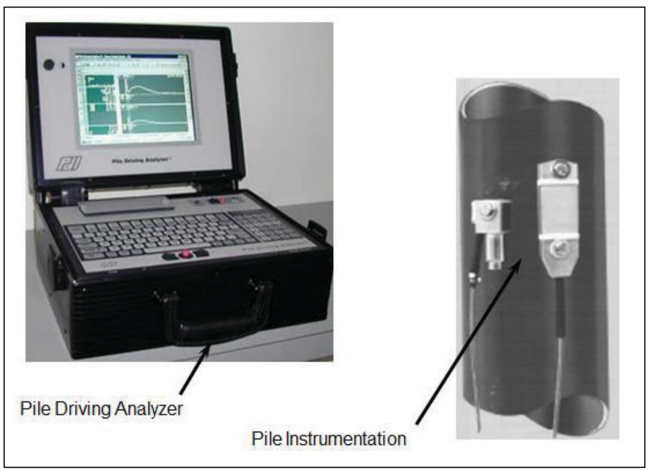

Figure 6
Pile driving analyzer readout box and instrumented pile.

The bid submission did not account for the skewed angle of intersection between the roadway alignment and the railroad alignment. The skew geometry resulted in an extended abutment foundation from 45 feet to nearly 90 feet. The number of piles increased from a total of 32 piles based on the geometry assumed at bid submission to 74 piles for the 50% design submission. At the time of the 50% design submission, no consideration was given to pile support of the retaining walls associated with the abutments. For this submission, the geotechnical engineer still provided recommendations for shallow support of the retaining walls on either side of the bridge abutments. Based on the information reviewed, it appeared that the omission of the skew angle in the calculations supporting the bid was an oversight.

Final Design Submission

Approximately eight weeks after the contract was awarded, the geotechnical engineer provided the final report in support of the design engineer's final design submission. The geotechnical engineer provided additional analyses but continued to rely on the subsurface data obtained from the initial two borings. The ultimate pile capacity for piles supporting the abutments was increased from 230 tons to 262 tons, which increased the predicted pile length from 46 feet to 52 feet. The engineer revised the number of piles to support the abutments down to 56 piles; however, pile support of the retaining walls associated with the abutments was determined to be required, increasing the overall number of piles to 83.

Based on the engineer's lateral load analysis, the pile section was revised from HP14x73 to composite sections of HP14x102 and HP14x73 welded together or HP14x89 and HP14x73 welded together.

Construction

After approval of the final geotechnical report and associated design submission, pile installation began. Four instrumented test piles were driven to depths of 49 feet to 118 feet. A summary of the test pile driving is included in **Figure 7**.

Pile Designation	Pile Type	Depth Driven (ft)	Driving Resistance (bpf)*
Pile#1	HP14x73/ HP14x102	48	42
		49	56
		68	70
Pile #2	HP14x73/ HP14x102	48	55
		49	41
Pile#1A	HP14x102	57	25
Pile#2A	HP14x73	38	40
		78	58
		97	25
		118	145

*A driving resistance of 139 to 258 bpf was required for estimated design capacity.

Figure 7
Summary of test pile driving.

As a result of the pile test program, the geotechnical engineer drilled an additional boring at the pile line location at each abutment. Based on the lack of performance of the H-piles driven on-site and review of the additional boring data, the design team decided to use 18-inch-diameter closed-end pipe piles for support of the abutments. The geotechnical engineer never amended previous concerns regarding proximity of pile driving next to the railroad tracks. A revised wave equation analysis was performed, and a new driving criterion of 50 to 55 bpf was established for the pipe piles. The result was that the production pipe piles achieved the bearing criteria with an average embedment of 35 feet to 40 feet.

The Case

A design-build contract affords the contractor very limited ability to modify the accepted bid. By its very nature, the design-build contract requires that the design-build team perform sufficient design analyses prior to bid release to establish a comprehensive bid for execution of the scope of work. The issuing authority must provide the bidders with sufficiently accurate details of the conditions and scope of work. One of the most common sources of inaccurate bid information in the traditional design, bid, and build contract, "the design documents" are not part of the bidding process for a design-build contract. Therefore, the contractor has very limited recourse to the owner should the bid turn out to be insufficient for the scope of work. In this case, the contractor claimed the excess construction cost was the result of errors made by the contractor's design team. The contractor claimed the designer breached the standard of care with regard to providing an accurate design and estimate of quantities prior to bid.

The cost issues associated with the foundation system for the bridge fell into two major categories: 1) the number of piles required to support the bridge loads; and 2) the misjudgment of the load capacity of the chosen pile system.

The choice to replace the bridge with a floorless culvert option significantly influenced the size and uncertainty associated with the foundation system. The footprint of the pile-supported foundation given to the contractor as a basis for bid was approximately 40% of the pile-supported foundation footprint used in the final submission.

Part of the discrepancy can be attributed to the fact that the designer did not account for the skew between the alignment of the roadway and the alignment of the bridge until after bid submission. A major portion of this discrepancy related to the fact that the retaining walls to either side of each abutment also required pile support and a modification of the pile section with depth. This was primarily the result of the geotechnical engineer changing the estimate of the lateral load imposed on the abutments and retaining walls from active earth pressure to at-rest earth pressure, an increase of nearly 50%. This revised recommendation of lateral load came over two months after bid submission.

The second issue that caused significant impact to the project was the inability to attain the predicted load capacity with the chosen H-pile foundation system. The geotechnical engineer recommended and performed a case method analysis (CAPWAP, Case Pile Wave Analysis Program) in conjunction with the test piles to judge nominal capacity and confirm the driving criteria. This is standard practice in the industry. The methodology uses information obtained during pile driving to modify parameters assumed in the wave equation analysis program (WEAP) until calculations match conditions measured during driving. The modified analysis is used to generate a relationship of pile capacity and driving resistance. The driving resistance (number of blows per foot) required to achieve capacity was not attained for the test H-piles.

The use of dynamic analysis (CAPWAP) to predict a static bearing capacity of H-piles in a layered soil environment is difficult. Various researchers (Seo et al. 2009) have questioned whether full bearing (bearing across the entire area circumscribed by the pile section) can be realized in such environments. A multi-layered environment, such as the one at this site, may prevent the soil "plug" from developing at the base and along the sides of the pile.

The geotechnical engineer did not drill additional borings or perform additional field testing along the proposed pile lines but rather throughout the design relied on two borings that were significantly offset from the proposed pile lines. It was only during construction — after the chosen pile system did not attain the required bearing capacity — that additional borings on the pile lines were drilled. Even though the geotechnical engineer classified the geologic formation boundaries as consistent across all of the borings, the layers of sands and clays at each boring location varied in elevation and affected pile driving resistance — and therefore the predicted capacity. It was also evident that significantly more clays were encountered in the two additional borings than were recognized in the original borings, which added to the difficulty of predicting capacity and driving resistance.

Using the wave equation to dynamically analyze piles assumes that sufficient strain occurs during driving to mobilize the assumed parameters in the soil profile. The ASTM standard test method for dynamically testing deep foundations (ASTM D4945-2012) recommends at least 2 millimeters of pile movement per blow to remain within a range of movement consistent with the analysis. The penetration rate (139 to 258 bpf), resulting from the geotechnical engineer's analysis of the H-piles (equated to movements of 2.2 mm to 1.2 mm), was largely outside the range recommended by ASTM. One test pile that was driven to more than twice the predicted termination depth (118 feet) attained the required driving resistance. Only then did the geotechnical engineer decide to change the pile type from H-piles to closed-end pipe piles. Once the change was made, construction proceeded without further delay.

It was evident from the communication documents recovered during discovery that both the design engineer and the geotechnical engineer performed as if the contract was a traditional design, bid, build contract. The design effort prior to bid consisted primarily of rough sketches of proposed geometry and design assumptions based on past experience with little or no application to the specific site. Low-displacement pilings, such as H-piles, were not generally used for bridge support in this geologic environment. The geotechnical engineer's reluctance to obtain more boring information resulted in a dependency on a dynamic test method to determine pile capacity that could only be validated during construction, resulting in an expensive change of materials and equipment to the contractor. The case was settled out of court with a negotiated settlement.

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