COVER STORY

Foundation Innovations Ensure Successful Bridge Replacement

Rhode Island's new $163.7 million, 2,265 ft (690 m) long, four-lane Sakonnet River Bridge sits just south of the existing bridge in Portsmouth/Tiverton. The bridge, a critical transportation system link between Massachusetts and Rhode Island, has a steel I-girder main span and concrete New England Bulb Tee approach spans. The foundation work was done between October 2009 and July 2010, and the bridge was completed in February 2014.

Foundation design and construction challenges make the project noteworthy. There were thick layers of silty glacial soils with bedrock as deep as 400 ft (122 m) below the waterline, coupled with high foundation capacity demands at the river piers in 50 ft (15 m) of water. The Sakonnet was one of the first major bridge projects in the country to incorporate AASHTO Load and Resistance Factor Design (LRFD) guidelines for foundation design and construction. Because of these and other challenges, the engineers conducted two design-phase load test programs on several foundation elements. These programs were successful and allowed the engineers to adjust the final foundation design prior to the start of construction. During construction, the contractors drove thirty 6 ft (1.8 m) diameter steel pipe piles, each with a novel recessed steel plate insert, to depths of 130 to 200 ft (40 to 61 m) at the three river piers. The insert provided increased resistance of the steel pipe piles and saved about $9 million. Also, 457 14x117 end-bearing or friction H-section piles were driven to between 50 and 190 ft (15 to 58 m) at five land piers. All piles were driven relatively close to the existing bridge, which remained in service during construction, due to the project team's precautionary use of instrumentation and the installation of a jacking system.

Area Geology

The Sakonnet River is up to 60 ft (18 m) deep along the bridge alignment and is underlain by a deep bedrock valley. The bedrock valley is buried by at least 350 ft (107 m) of soil, which includes a complex sequence of interbedded glacial soils (glacial till, glaciolacustrine deposits and glaciofluvial deposits), overlain by geologically recent estuarine deposits. The soils having the greatest impact on the foundation resistance are the glaciolacustrine (fine sandy silt or silt) and glaciofluvial (silty sand with gravel, cobbles, and occasional boulders less than about 2.5 ft [0.8 m] in size). The soil overburden decreases toward the east and west banks of the river, as the bedrock surface rises.

The existing bridge, constructed in 1956, has deep and shallow foundations. The river piers are supported on HP14x73 steel piles. As-built construction information for the bridge, including any previous static load test data, was not available. However, based on interviews with one of the design engineers

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involved with the original design and construction, the project team learned that final as-built lengths of the piles were two to three times the design lengths.

The engineers developed preliminary foundation designs for the new bridge for the river piers (Piers 4, 5 and 6) and land piers (Piers 1, 2, 3, 7, 8 and 9). The factors influencing foundation type selection were depth to rock, loading, predicted scour, pier/pile cap locations and constructability considerations, among others.

At the river piers, bedrock is about 350 ft (107 m) below mudline. Pile caps for the river piers were planned at the water line (about 50 ft [15 m] above mudline), and the design considered predictions of as much as 30 ft (9 m) of scour. Consequently, stiff foundation elements were a requirement at these locations. Initial design alternatives included 6 ft (1.8 m) diameter concrete-filled steel pipe piles driven open-ended 120 ft (37 m) below mudline and 8 ft (2.4 ft) diameter uncased concrete drilled shafts embedded 160 ft (49 m) below mudline. Foundation elements would be embedded in the glaciofluvial and glaciolacustrine deposits to generate resistance through a combination of side friction and end bearing. The design team also considered post-grouting beneath the concrete plug in the steel pipe piles to increase end-bearing resistance. They developed a layout of eight elements per pier (either pipe piles or drilled shafts) and estimated initial loading to be approximately 3,300 kips (1,497 tonnes) per element (all loads shown are strength limit state factored loads).

At the land piers, depth to rock ranges between 220 and 280 ft (67 and 85 m) below ground surface. Piers 3 and 7 were at the shoreline, and the bottom of the pile caps were within several feet of the mudline. The team planned permanent sheeting around these pile caps to mitigate scour effects. Initial design included steel HP14x117 friction piles to depths of approximately 110 ft (34 m). The initial number of piles and loading varied from pier to pier, but in general there were approximately 80 piles per pier, and loads were as high as 374 kips (170 tonnes) per pile. Depth to rock at Piers 1 and 8 ranged between 50 and 110 ft (15 to 34 m), so the engineers planned to use end-bearing steel HP14x117 piles for these locations. At Pier 9 (not shown on profile), spread footings on soil were considered adequate.

Design Phase Test Programs

After consulting with the Rhode Island Department of Transportation (RIDOT) and Federal Highway Administration (FHWA) regarding the difficult nature of the silty soils at the site,

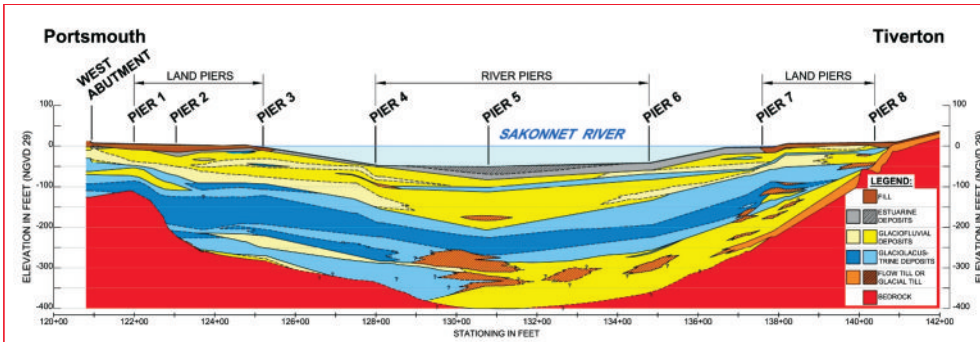
Cofferdam for HP pile installation

the project team recommended that design phase load test programs be implemented to accomplish the following:

- Determine resistances of H-pile, pipe pile and drilled shaft elements by static load testing and dynamic testing.
- Compare predicted resistances from static prediction and dynamic methods to the static load test results.
- Determine unit skin friction and end-bearing resistances for H-pile, pipe pile and drilled shaft elements.
- Examine drivability and constructability characteristics of the test elements.
- Use test program data to evaluate foundation types and capacities, and estimate tip elevations for foundations of the proposed piers.

Ultimately, the engineers implemented two design-phase load test programs (over $4 million), allowing the project team to test innovative pile designs and make critical design adjustments before construction began. The first test program (TP1) was in 2006. TP1 consisted of installing and statically load testing in axial compression one HP14x117 and one 3.5 ft (1 m) diameter concrete-filled open-ended steel pipe pile (before and after internal pile grouting). A 6 ft (1.8 m) diameter open-ended steel pipe pile was also installed, but a static load test was not performed because the engineers expected the failure load to be too high to achieve economically. The engineers planned to construct a drilled shaft and statically load test it, but the shaft was not successful and was therefore eliminated from the design. Based on the static load test results of TP1, the engineers increased the number of friction H-section piles per pier. In addition, the engineers recommended static load testing of 6 ft (1.8 m) diameter pipe piles, as the dynamic testing indicated lower than expected resistances.

Subsequent to TP1, Dr. Samuel Paikowsky put forth an innovative design for pipe piles as an attempt to increase the resistance of the steel pipe piles. (At the time, Paikowsky was with GTR and is currently with GeoDynamica, Inc.) His suggestion was to install an internal, recessed plate



Soil profile at Sakonnet River Bridge

New piers under construction

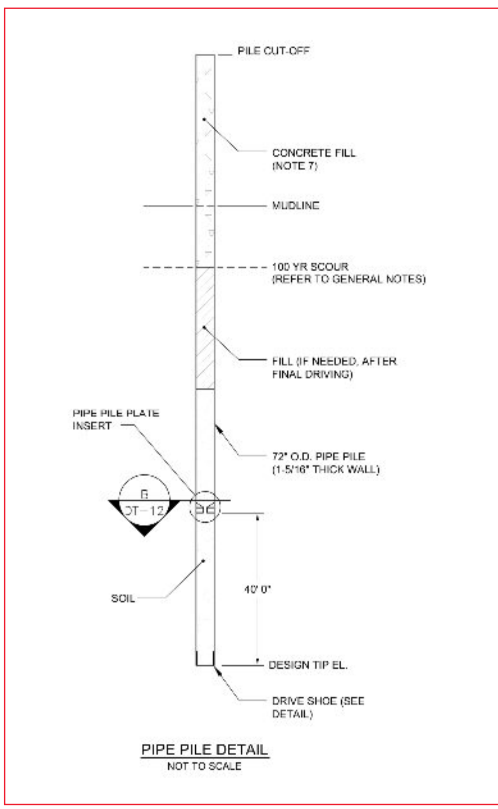
insert with a 14 in (356 mm) central hole in the 6 ft (1.8 m) diameter pipe pile to develop plugging, while at the same time, allow the piles to be driven to the minimum embedment required for lateral capacity.

In 2000, the team conducted the second test program (TP2). This included installing and conducting static 6,000 kip (2720 tonne) and dynamic load tests on one 6 ft (1.8 m) diameter open-ended pipe pile (tested at two different depths), and one 6 ft (1.8 m) diameter open-ended pipe pile with a plate insert welded 40 ft (12 m) from the pile tip (also tested at two different depths). The TP2 results indicated that the recessed plate insert was a successful and innovative design for this site, generating soil plugging yet allowing the piles to drive to sufficient depth for lateral capacity. The pipe pile with the recessed plate insert (plate insert pile) was selected as the foundation element for the river piers because it generated greater resistance at the same penetration depth. The use of the plate insert helped avoid having to drive the piles to rock as deep as 400 ft (122 m).

Final Design and Installation

Following the test programs, the engineers estimated the final number and design lengths of H-section and pipe piles, based on the static load test results. They calibrated dynamic testing results with static load test results for use during production pile driving.

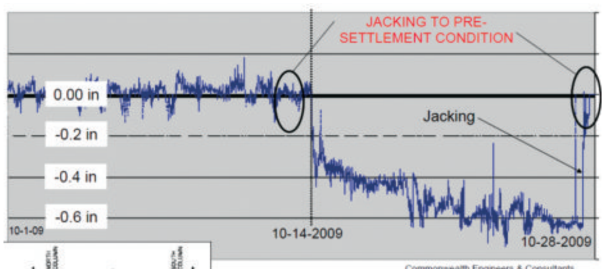
The team designed the three river piers for the new bridge to be supported on ten 6 ft (1.8 m) diameter plate insert piles each, for a total of 30 piles. The plate insert was manufactured with a 14 in (325 mm) central hole and welded 40 ft (12 m) from the tip. The piles were driven into the glacial silt and sand to a maximum depth of 170 to 220 ft (52 to 67 m) below mudline. The required factored resistance ranged from approximately 2,853 to 3,758 kips (1,294 to 1,705 tonnes). The specified pile wall thickness is 1-5/16 in (33 mm), which included an allowance for a sacrificial corrosion thickness. The design also called for the toe to be reinforced with double-wall thickness for a height of 9 in (229 mm).

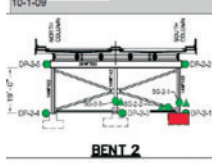


Before starting pile driving, the contractor performed sonic core borings to 110 to 150 ft (34 to 46 m) below mudline at each pipe pile location to search for obstructions. The sonic cores obtained continuous recovery of the entire length of boring, and no boulders greater than 2 ft (0.6 m) thick were seen.

The contractor installed the plate insert piles in two to three 50 to 75 ft (15 to 23 m) long sections, using a hydraulic hammer that delivered approximately 375,000 ft-lbs (508,430 N-m) to the top of the pile. Dynamic testing was performed on each pile for the entire driven length to monitor stresses. The team installed two indicator piles to completion at each river pier prior to production pile driving for the remaining eight piles at each pier. Production pile driving commenced following acceptance of the indicator piles. To confirm capacity, the contractor performed restrikes on the piles three and seven days following end-of-drive.

Per specifications, final driving criteria consisted of driving the pile to either a blow count resistance relative to hammer energy, to refusal or to a design tip elevation, whichever occurred first. However, final pile acceptance was based on achieving the required factored resistance as measured using CAPWAP on restrikes. The actual driven depth below mudline ranged from 130 to 200 ft (40 to 61 m). Following installation, the piles were filled with sand to approximately scour elevation, and then with concrete to pile cutoff elevation. As an added precaution against corrosion, the contractor installed a passive cathodic protection system, in the form of aluminum-zinc anodes, on the exterior of the piles below the river level.





Vertical settlement data at Bent 2 prior to and after jacking

Detail and photo of plate insert pipe pile

A total of 457, 14x117 H-section piles support the five new bridge land piers. The contractor outfitted all piles with a pile tip coated with coal tar epoxy on the top 30 to 40 ft (9 to 12 m). Piles at Piers 1 and 8 were driven to end-bearing to the required factored resistance of 495 to 568 kips (225 to 258 tonnes). Final driven lengths varied between 50 and 190 ft (15 and 58 m). Piles at Piers 2, 3 and 7 were friction piles driven to an embedment depth of approximately 120 ft (37 m). Required factored resistance of the friction piles ranged from approximately 193 to 230 kips (88 to 104 tonnes). The contractor used a hydraulic hammer that delivered approximately 70,000 to 120,000 ft-lbs (95,000 to 163,000 N-m) to the top of the piles. Dynamic testing was done on indicator piles to monitor driving stresses and confirm capacity during restrikes, as assessed by CAPWAP. Out of 457 piles, only three piles encountered conditions that required adjustment during construction.

Maintaining Existing Bridge Service

The existing bridge remained in service during construction. The project team was particularly concerned about potential settlement of the existing bridge due to nearby pile installation, pile cap construction and abutment earthwork filling. During the design phase test programs, settlement extensometers, piezometers and inclinometers were installed in the ground and strain gages were installed on several of the steel bents of the existing bridge to monitor effects of pile driving on the ground and existing bridge. Data generated from this instrumentation in combination with empirical assessments led the project team to discuss contingency plans in the event the existing bridge settled during foundation construction. As a result, RIDOT authorized installing an extensive instrumentation program of strain gages, vertical survey points and seismographs on the existing bridge. Each instrument could be monitored remotely and nearly continuously. As a complement to the instrumentation program and prior to the start of foundation construction, RIDOT included in the contract a jacking system at many of the existing bridge's steel bents supported on shallow foundations.

The forethought regarding the instrumentation and jacking system turned out to be critical in ensuring the continued service of the existing bridge. On several occasions during construction, instrumentation alerts indicated that a pier's settlement and truss member's strain/stress were approaching action limits set by the project team. Almost immediately, the engineers halted the work temporarily while the contractor jacked the pier back to near its original height and stress state (In each instance, existing bridge service was not impacted, and construction resumed shortly after jacking was completed.) If the instrumentation and jacking systems had not been in place and ready to employ at a moment's notice, the existing bridge would have been put out of service and foundation construction halted indefinitely at a large economic loss and inconvenience to the public.

Night view of the newly constructed bridge

Conclusion

Constructing a new bridge adjacent to an existing bridge, and generating high-capacity foundation elements in deep silty soils proved to be challenging. However, innovative design solutions were created through close collaboration of all teaming partners. The design phase test programs allowed the design team to develop and select appropriate and innovative foundation systems prior to starting construction. The innovative use of a recessed, internal plate inside 133 to 200 ft (41 to 61 m) long, 6 ft (1.8 m) diameter steel pipe piles saved the project about $9 million in driving and furnish costs, plus additional savings in time by eliminating the need to drive pipe piles to rock. Furthermore, preconstruction outfitting of the existing bridge with an extensive instrumentation program and jacking system allowed existing bridge service to continue uninterrupted and avoided construction stoppage.