Philadelphia Dock Story—Pile Challenges at Delaware River

A new ship dock at a Philadelphia area refinery will be capable of docking the largest tanker to travel the Delaware River, the Stena V-MAX, which will induce significant lateral loads. The loads at the dock, a system of mooring dolphins and platforms, will be resisted by over 150 pipe piles, including some 20- and 30-in diameter, reinforced, concrete-filled pipe piles and H-piles. Construction included driving the pipe piles to the required ultimate capacity, flushing the pipe pile casing clean of overburden materials, followed by drilling rock sockets into the underlying Wissahickon Formation. The Wissahickon Formation is a complex subsurface that includes variations in depth to bedrock, rock quality, degree of weathering and the presence of very hard quartzite lenses or inclusions. Because of the problematic subsurface, the designers and client requested extensive pile dynamic analysis (PDA) testing by **TRC Engineers** (TRC).

Before beginning, the contractor requested that TRC perform the WEAP (wave equation analysis program) to evaluate the proposed hammer (APE D30-32 open-end diesel) to drive the piles into the proposed bearing strata while maintaining allowable compression stress levels. The WEAP provided a prediction of blow counts and stresses for various ultimate capacities, and showed that for the HP14x89 piles with a required ultimate capacity of 480 kips, a blow count of at least four blows per in at a stroke of 8.0 ft was necessary.

New Approachway Ramp

The PDA testing began at the new dock approachway ramp, parallel to the existing one. The new structure is a 300-ft-long by 21-ft-wide concrete deck supported on seven bents; each has two 24-ft-diameter steel open-ended pipe piles. Every pipe received an HP 14 x 89 x 80-ft pile that was later driven beyond the pipe pile tip to create a composite pile. The pipe piles were later cleaned of overburden materials and finally filled with concrete and rebar. At each bent, a cap was installed on top of each pair of pipe piles, and then a prefabricated concrete deck was added.

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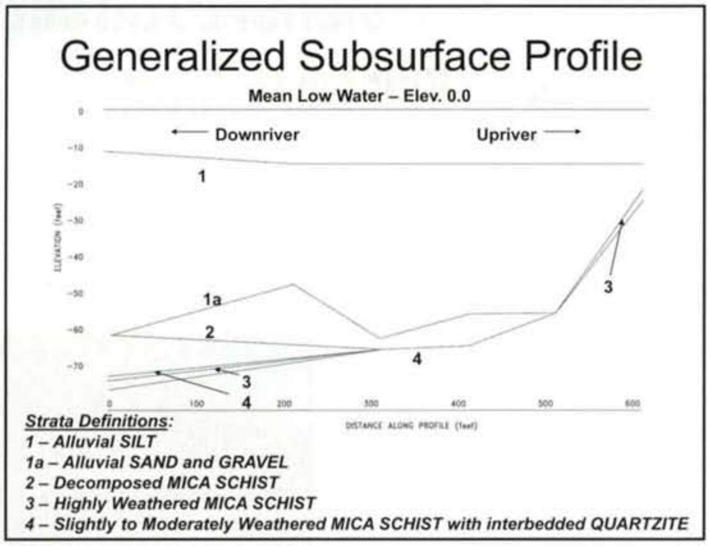
The PDA gages were installed near the pile heads to allow for maximum penetration depth without having to remove them when the top of the pipe pile was approached. As H-pile driving commenced, the PDA system recorded increased toe stress levels as the toe approached the pipe pile tip. The increase was probably due to a small pipe pile plug near the pipe pile tip. After the H-pile-tip penetrated below the pipe pile tip, the estimated toe stresses relaxed until suitable H-pile bearing strata was reached. This coincided with the H-pile achieving the required ultimate capacity at or below the required pile tip penetrations. At the end of driving, there was some variability in the calculated CAPWAP

Upriver approachway



Generalized Subsurface Profile: Ship Dock

(Case Pile Wave Analysis Program) shaft and toe resistance values, which was most probably caused by the variability in the subsurface weathering and quartzite inclusions.

The APE D30-32 hammer transferred approximately 45 ft-kips (64% of the rated hammer energy) during the driving of the bents, or above average performance.

Coordination Challenge

The project site owners scheduled a 90 day plant maintenance and operations repair program in early 2006. The upgrades were done in a three-shift operation, and the pile driving operations had to be scheduled around the ship dock needs; these had top priority. This meant that the PDA testing had to align with the pile driving schedule, regardless of the time of day.

During this period, two independent pile driving operations were underway. The scheduled construction sequence consisted of an out-shore dock section and three out-shore dolphin structures. When one pile driving crew was driving piles, the other was building forms and preparing decking for the next one. The crews had their own schedule and operational constraints, and the PDA test team was also supporting the planned test schedule for two simultaneous pile driving operations. The piles had to be kept prepared for testing by pre-drilling the PDA gage mounting holes in the pipe piles and H-piles. We also had to be on call for PDA testing at nights and weekends. Once the data was collected, it was analyzed as quickly as possible and CAPWAP analyses performed for on-site driving issues such as capacity, compression stresses and indications of pile damage.

The Wissahickon Formation is a complex subsurface that included variations in depth to bedrock, rock quality, degree of weathering and the presence of very hard quartzite lenses or inclusions.

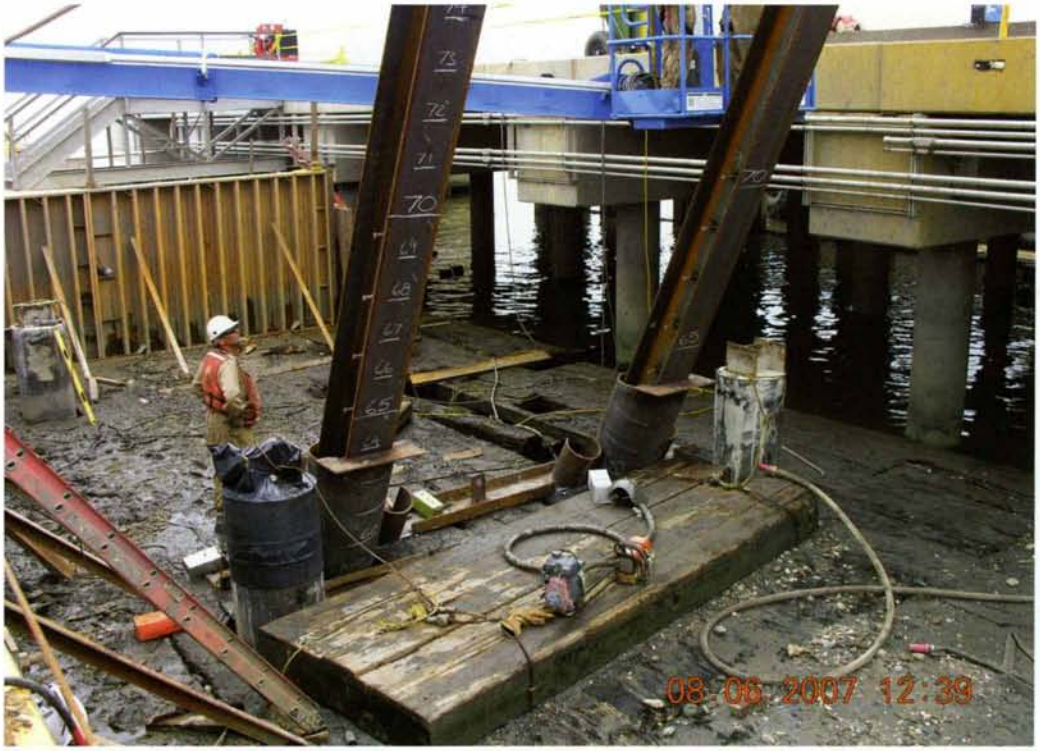
Another challenge during the 90-day turnaround phase involved the contractor's proposed use of a Vulcan 010 external combustion hammer to drive 90-ft-long HP14x89 piles at structure D-1. This hammer has a rated energy of 32.5 ft-kips when operating at a 3.25-ft stroke. During pile driving with the Vulcan hammer, the HP14x89 piles were driven short of the required pile tip elevation, and PDA measured approximately 650 kips, which was less than the required 800 kip ultimate resistance. The PDA also found that the Vulcan 010 hammer transferred approximately 22 kip-ft of energy during driving. With further investigation, it was found a WEAP analysis had not been performed for the Vulcan 010 hammer prior to driving the piles. Subsequently, the contractor asked TRC to review the drivability of the Vulcan 010 hammer, and it was found that the hammer would not achieve the required 800-kip capacity in a reasonable blow count. So the project team decided to use a larger hammer, an ICE I-36 open-end diesel hammer, with a rated energy of approximately 90.1 kip-ft.

The TRC team performed a new WEAP analysis for the ICE I-36 hammer and found that it could safely drive the piles; however, the predicted blow counts could become excessive at or near the 800-kip-capacity requirement. The project team continued driving the remaining HP14x89 piles with the ICE I-36 hammer and achieved

PDA testing at Bravo

the required capacity and penetration depths. The CAPWAP analyses showed that calculated shaft resistances ranged from 37 to 46% at the end of driving.

The out-shore dock structure A piles were driven with an ICE I-46 hammer (107.7 kip-ft rated energy) and the driving characteristics of the pile/hammer system were reasonably consistent across this structure. The biggest challenge during driving was overcoming some of the subsurface penetration issues encountered during driving at two areas within this structure. These two areas exhibited deeper weathered layer thicknesses and required additional pile length to obtain suitable bearing strata. Corresponding ultimate capacities ranged from 900 to 1,070 kips, and blow counts averaged approximately 11 blows per in. The ICE I-46 hammer operated at an approximate energy transfer ratio of 49.3% (52.8 kip-ft), which was above average.



Dock Section B

Yield Strengths of 135 ksi

The upriver accessway bents and dolphin structures D6, D7, D8 and Alpha were installed between October 2006 and July 2007. New challenges were encountered prior to driving the pipe piles during PDA pile preparations due to the use of pipe piles with very high yield strength. Independent test reports of sample material from the piles showed some yield strength properties as high as 135 ksi! The high yield strength caused problems with drilling and tapping the pipe pile for the PDA sensors. The TRC team implemented special drilling operations for this material, and were able to successfully drill and tap the holes for PDA testing using specialty drill bits, cutting oils and low-speed drilling techniques.

The pile driving operations along the upriver accessway bents commenced in an upriver direction from the main dock. It was found that high blow counts coincided with piles that had high end bearing with little penetration into either the quartzite or decomposed mica schist layers. Typically, when blow counts were above 10 blows per in, the piles had most of their CAPWAP resistance at the pile toe. Conversely, when blow counts were less than 10 blows per in, the CAPWAP resistance had more of the ultimate resistance distributed along the shaft—approximately 50 to 69% of the total capacity. The upriver bents had ultimate capacities ranging from 813 to 1,713 kips, and corresponding blow counts ranged from 5 to 14 blows per in. During pile driving, the PDA system monitored the driving compression stresses, which were kept below 39 ksi. An ICE I-46 hammer was used at the accessway bents and transferred approximately 38% of the rated hammer energy, which is above average.

The pile driving at dolphin structures D6, D7, D8 and Alpha had approximate pile tip elevations ranging from –53.7 to –77.2 ft. The variable pile tip depths were mostly due to the different batter orientations. Ultimate capacities ranged from 700 kips at D6 to 1,360 kips at D8, blow counts ranged from 6 to 15 blows per in, and calculated shaft resistances ranged from 18 to 37% at the end of driving. It was found that approximate penetrations into the decomposed mica schist ranged from 1 to 18 ft during impact driving with an ICE I-46 hammer.

There was one instance of irregular rock socket drilling. During installation, the socket wall just below the pile tip collapsed, and seawater and overburden materials flooded the pipe pile. The project team decided that additional pile penetration was needed to get a stable rock socket wall. An additional 10 ft of pipe pile was welded onto the pile head, and the pile was advanced deeper into the subsurface—approximately 5 ft—using blow counts on the order of 24 blows per inch. The project team also requested TRC to perform PDA testing on the redrive to evaluate the compressions stresses and capacity. Fortunately, the compression stresses stayed below 28 ksi, the capacities were approximately 1,075 kips, and the subsequent rock socket drilling operation was successfully completed.

> ***The project encompassed five different pile types driven with three different hammers into a problematic subsurface.***

PDA testing

Trouble in Bravo Town

Driving the 28 pipe piles at the Bravo structure revealed some of the shortest pile tip elevations due to higher quartzite inclusions and mica schist layers. Initially, the piles were vibrated into position approximately 3 to 8 ft before impact driving. The plumb piles had penetrations of 5 to 10 ft using the ICE I-46 impact hammer, while the battered piles had impact hammer penetrations of only 1 to 3 ft. Pile capacities ranged from 850 to 1,560 kips for the plumb piles and 870 to 1,190 kips for the battered piles. The compression stresses stayed within 36 ksi.

In March 2007, during the initial driving operations for one of the Bravo piles, the PDA recorded signs of impedance changes approximately 3 ft from the pile toe. After discussion, the project team decided to remove the pile, and the damage was verified at the pile toe. The extracted pile was redriven to a final driving resistance of 10 blows per in and was successfully drilled out for a rock socket. It is believed the pile hit an obstruction due to the hard quartzite layers that created local stress concentrations and consequently, the pile damage.

Overall, the pile driving operations at the Bravo structure were slightly more difficult than the other dolphin structures due to (1) the orientation of the batter piles that limited the sequential pile installation; and (2) the mica schist/quartzite layers were problematic due to the rock quality, degree of weathering and the presence of very hard quartzite inclusions. Both issues prolonged construction times. The PDA provided real-time QA data regarding the pile capacity, driving stresses, hammer performance and pile integrity.

Pipe Support Rack

When the upriver Bravo structure was completed, the operations returned to the main dock area and the remaining inshore dock structures. These structures were B, C and D. The pipe piling used to the decking were 30-in outside diameter by 0.625 in wall thickness by 80-ft long. Part of this construction phase included an additional structure called the pipe support rack, which used 90-foot-long HP14x89 piles, installed through a 24-in outside diameter by 60-ft-long pipe pile shell.

Piles at these structures required an 8-ft embedment into the weathered mica schist using the APE D30-32 impact hammer. During driving, some piles reached high blow counts of more than 12 blows per in to achieve the required embedment. These likely encountered a quartzite inclusion within the mica schist. The pipe piles at dock structure C had CAPWAP capacities ranging from 600 to 1,300 kips. The lowest occurred where the pile blow count was 5 blows per in and resulted from insufficient pile length to continue PDA testing above the nearest obstruction. The highest CAPWAP capacity occurred when penetration was close to the 8-ft embedment requirement and the blow count approached 24 blows per in. During impact driving of these piles, the hammer and lead system occasionally became out of plumb at the pile head. This minor instability was monitored by the PDA and, once recognized, the hammer was stopped and the leads were adjusted.

Pile damage during impact driving at dock structure C occurred when an old timber pile/structure joint was struck. The PDA showed potential issues with the integrity of the pile at approximately 2 ft from the toe that could impact future rock socket drilling operations through the bottom of the pipe pile. The pile was extracted, repaired and successfully redriven. Using the PDA as a QC tool saved the piling contractor time because the obstruction would have been encountered later during drilling operations.

Using the PDA as an effective quality control tool and WEAP analyses for quality assurance provided real value to the client through reduced construction costs and final verification of pile capacity.

Conclusion

This project encompassed seventeen structures and five different pile types that were driven with three different hammers into a problematic subsurface. Using the PDA as an effective quality control tool and WEAP analyses for quality assurance provided real value to the client through reduced construction costs and final verification of pile capacity. Without the use of these two QA/QC tools, pile driving and rock socket construction issues would have been encountered early and often.