INNOVATIVE RIVERBANK EROSION CONTROL RETAINING WALL SYSTEM FOR THE BRAZOS RIVER

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Abstract: An innovative retaining wall design consisting of tangent drilled shafts with supplementary seal piles was used to limit continuing bank erosion along the Brazos River in Southeast Texas. The riverbank erosion had progressed to where it was threatening the stability of both the bridge abutment and corresponding approach embankment of the heavily travelled Highway 99 bridge at this location. A tangent pile design was selected because it was both much faster to install and more cost effective than a secant pile system. The design included both 5.5-ft and 10-ft diameter shafts with depths up to 130-ft and comprised both anchored and cantilevered sections. Supplementary seal shafts were also installed between the structural tangent drilled shafts to help plug any gaps between the tangent shafts. The plumbness and diameter of the shafts were tested using a sonic caliper to make sure the shafts were installed within the specified tolerance. The initial design had to be revised when a record flood from Hurricane Harvey impacted the site during construction.

Introduction

The Fort Bend Grand Parkway Toll Road Authority (Owner) needed to protect the north bridge abutment with a retaining wall system due to rapidly eroding conditions of the Brazos River banks within the 300-feet-right-of-way of the State Highway 99 Jodie Stavinoha Bridge. The extent of the local scour and erosion along the north bank of the Brazos River has caused concern for the structural integrity of the bridge. The magnitude of the erosion along the north bank at the location of the bridge has been measured at about 120 feet over three recent hydrologic flood events locally referred to as Memorial Day 2015, Memorial Day 2016, and Tax Day 2016. During construction, a new record flood level occurred due to Hurricane Harvey in August of 2017 that resulted in a portion of the retaining wall needing to be redesigned due to even more erosion occurring.

The Brazos River is an actively eroding and meandering alluvial river plain that naturally meanders and migrates over time. The processes of bank erosion and meander migration were ongoing before the bridge was constructed and will continue in the future. These recurring major flood events, however, rapidly increased the rate of erosion in just a few years.

Background. Due to the need to protect the bridge as soon as possible, the Owner selected a project team consisting of the designer, general contractor and specialty deep foundation contractor prior to final design to work together in developing a cost-effective design that could be implemented rapidly. The project team initially considered both a secant pile and tangent pile retaining wall system using drilled shafts. After reviewing various alternative designs, a tangent pile wall with seal piles was selected based on both cost effectiveness and speed of installation. The tangent pile with seal pile option was approximately 20 percent lower in cost and 50 percent faster to install.

Secant Pile Walls. Secant pile walls are formed by constructing intersecting reinforced concrete drilled shafts. The secant piles are reinforced with either steel rebar or with steel beams. Primary piles are installed first with secondary piles constructed in between primary piles once the latter gain sufficient strength. Pile spacing is typically between 0.7 to 0.9 times the pile diameter to provide the overlap.

The main advantages of secant pile wall construction are alignment flexibility; higher wall stiffness compared to sheet piles; they can be installed in difficult ground (cemented soils, rock, cobbles, boulders)
and in limited headroom conditions; and can be constructed with low noise and little vibration compared to sheetpiles. The main disadvantages of secant pile walls are verticality tolerances may be hard to achieve for deep piles and total waterproofing is very difficult to obtain in joints.

**Tangent Pile Walls.** In a tangent pile wall there is no pile overlap as the piles are constructed adjacent to each other with a design clear spacing ranging from a few inches to one foot depending on the diameter of the shaft. Factoring in shaft overpour (the volume actually placed relative to the theoretical volume) one pile can come into contact with the other. Compared to secant pile walls, tangent pile walls offer the advantages of better construction alignment flexibility; the ability to install larger diameter shafts with protective steel casings, easier and quicker construction; and lower cost. The main disadvantage of tangent pile walls is there is a small gap between the piles. Thus, they cannot be made watertight which could allow for groundwater flow and erosion to occur between the piles.

**Tangent Pile Wall with Seal Piles.** A third variant of the secant pile/tangent pile retaining wall options is a tangent pile wall with “seal” piles placed behind and between the structural tangent piles. The seal piles do not provide any structural support but are installed simply to plug the gap between the tangent piles. This is effectively a second row of unreinforced tangent piles typically of a smaller diameter. These seal piles can be installed as drilled shafts, but usually are installed faster and more economically as Augered Cast-in-Place (ACIP) piles. Pumping fluid grout under pressure with ACIP piles is considered to provide a better seal than tremied concrete used in drilled shafts.

**Highway 99 Bridge.** The bridge is situated where Texas State Highway 99 crosses the Brazos River just upstream of Sugar Land, Texas. State Highway 99 is known locally as the Grand Parkway, and is an important regional transportation corridor linking the Sugar Land area with southwest Houston and Katy. The 8-span, 1,200 foot long bridge structure was originally designed in the late 1980’s and constructed in the early 1990’s. Spans 1, 2, 3, 4, and 8 are 115-foot long approach spans comprised by AASHTO Type IV Girders supporting a cast-in-place (CIP) concrete deck with simple span configuration. Spans 5, 6, and 7 provided the original Brazos River crossing, and are comprised with 195-235-195 foot long continuous span steel plate girders supporting a CIP concrete deck. The substructures included concrete columns supported by a battered pile group foundation for the concrete spans, and concrete column pier walls supported by a battered pile group foundation for the steel spans. Change orders were executed during construction which modified the foundations at Bents 8 and 9 (abutment) to include four 5.5-ft-diameter concrete drilled shafts directly integral with the bent caps, in lieu of the pile-supported columns. The pile tip elevations for Bent 8 were located at -45.0 feet at Bent 8 and at elevation -35.0 feet at Bent 9. This change recognized that the river was moving to the north and was an important aspect for the design of the bridge.

**Brazos River Erosion.** The Brazos River is the 11th longest river in the United States, with a length of 1,280 miles and a combined rivershed of about 45,000 square miles. The geography and river morphology indicated that the Brazos River was meandering to the north at the river crossing. Since the completion of the bridge in the early 1990’s, the centerline of the approximately 200-ft wide river channel has moved nearly 250 feet from the midspan of Span 6 to a location just south of Bent 8. The north bank of the river has reportedly eroded about 120 ft in the past 3 years due to the multiple flood events. The river bottom grading has changed, and the former riverbank which was offset by 50 feet from interior Bent 8 is now encroaching directly on the riverbank immediately adjacent to Bent 9 and the approach roadway.

During flood events, the clays comprising the upper strata are in a saturated condition. Direct erosion and scour occurs from the flow of the river during the floods. In addition, rapid drawdown occurs as the floodwaters subside resulting in slope failures along the steep riverbank. This is a continual process with each flood event and as a result the river channel is migrating northward towards the bridge abutment. The continued erosion of the north riverbank threatened the abutment and roadway approach for the bridge structure, as well as the adjacent New Territory protection levee located just north of Bent 9.
Geology and Soil Conditions

Regional Geology. The site is located in the Northwestern (Texas) Gulf Coastal Plain geologic province of the continental United States. These Quarternary deposits form an outcrop belt about 100 miles wide generally parallel to the coastline. The stratigraphy to a few thousand feet consists of one Recent and five Pleistocene units. This site is located on an outcrop of the Beaumont formation that has a maximum thickness of 700 ft. The Beaumont formation was deposited at the beginning of the early Wisconsin glacial stage, approximately 75,000 to 100,000 thousand years ago. Beaumont sediments are deltaic and fluvial deposits laid down in distributaries and flood plains of rivers and in shallow lagoons. The soil at this site is non-marine and deposited by the Brazos River. The major streams changed courses frequently during the period of deposition, generating within the Beaumont formation a complex stratification of sand, silt and clay.

With the glacial advance of the Second Wisconsin Ice Age, the sea level lowered more than 400 feet, permitting the soil formation to desiccate for thousands of years. The desiccation process compressed the clays such that they became overconsolidated to a great depth. Subsequently, the sea level rose during the last 25,000 years and reached its present level approximately 5,000 years ago.

Soil Conditions. The soil conditions at the site generally consist of an upper stratum of stiff to very stiff clay extending to a depth of 53 ft below grade (top of wall). Below that a 22-ft-thick dense to very dense sand stratum with an average SPT blow count of 40 is present to a depth of 75 feet. A stiff clay layer is present below this sand to a depth of 83 ft and is underlain by another dense to very dense sand stratum extending to a depth of 103 ft. Very stiff clay was then encountered to a depth of 130 ft which was the maximum depth of the two closest borings. The groundwater level is typically about 30 ft below grade or slightly above river water level, but this can vary dramatically depending of the river level and rainfall.

Retaining Wall Design

The layout for the wall included enough length to protect the soil regions that supported the north abutment and roadway approach. The original design selected 5.5-ft-diameter concrete primary drilled shafts spaced at 6.5 ft center-to-center. Secondary seal shafts were 2-ft-diameter unreinforced Augered Cast-in-Place (ACIP) piles. Reinforced concrete tie beams and deadmen were included to anchor the main wall. The top of the drilled shafts was elevation +73.0, with the shaft tips located at elevation -51.0 ft. The embankment stabilization extended 100 feet on either side of the roadway as shown on Figure 1. The walls were extended approximately 75 additional feet to both the east and west flanks because of a local partnering agreement with the adjacent levee improvement district. The concrete anchor systems were not included in these extensions. However, the wall is constructed to the same specifications to facilitate installation of future anchors by the levee district. The retaining wall typical section is shown in Figure 2.

Since the Owner preferred a design that allowed at least one lane of traffic to remain open in each direction during the construction, the original design included a section of wall located to the river side of existing Bent 9. The same primary drilled shafts and secondary seal piles formed the substructure of this wall section, with top of drilled shaft at elevation +45.0 ft. A reinforced concrete retaining wall with soil nail anchors was selected to protect the soil around the abutment and roadway approach.

The project design criteria established that the wall would be designed for typical design requirements and safety factors for scour to elevation +25.0, and to a safety factor of 1.0 to 1.1 for the extreme scour condition to elevation +0.0. The top of the wall was at elevation +75.0, which lead to design wall heights of 50 feet and 75 feet.

The factored design loads of approximately 50 kips per foot for the in-service condition and 80 kips per foot for the extreme condition were driven by active earth pressure, hydrostatic water pressure, and nominal 250 psf surcharge load.
The drilled shaft reinforcement included bundled No. 11 reinforcement steel, with shaft spiral spaced between 6 and 12 inches. The longitudinal shaft reinforcement was placed eccentrically in the section, and cut off in several locations based on the unidirectional nature of the applied loads. SP Column was used to determine the structure capacity of the shafts based on the soil-structure interaction analysis performed using LPILE+. The maximum design loads in the shaft were approximately 600 kips shear and 12,500 kip-feet for bending moment. The point of maximum bending moment was located at about 5 times the shaft diameter below the ground elevation.

Construction began in July 2017 on a 24-hours per day, 7-day a week schedule with one drilled shaft installation crew positioned on each side of the roadway. Anticipated completion for the entire project was scheduled for early 2018. With the arrival of Hurricane Harvey at the end of August 2017, the site topography was radically changed from that which existed during the final stages of project planning and the first phase of construction. Early in September, the project stakeholders determined that the elements of the retaining wall located under the end of the bridge were no longer constructible due to erosion and poor soil conditions.

Two primary elements were redesigned post-Harvey. The first item was the design of the wall anchors changed to high-strength steel tie rods with a steel sheet pile deadman system in lieu of the concrete grade beam anchor system. The typical anchor details are shown in Figure 3. Note that while the vibrations

![Site Layout per the Original Design pre-Hurricane Harvey](image-url)
associated with the driving of the steel sheet piles were a primary concern due to the erosion and soil conditions, the steel sheets were not installed until the drilled shaft tangent wall installation was complete, thereby the harmful effects of vibration on precarious soil slopes were already mitigated.

The rapid erosion also required redesign of the wall within the footprint of the existing roadway corridor. It was determined that 10'-0" diameter shafts could be installed using the equipment already on site. Subsequent engineering studies showed that the 10'-0" shafts could resist the lateral earth pressures as a cantilever wall system and did not require installation of an anchor system. This modified layout is shown in Figure 4.

Further studies showed that anticipated erosion of the soils surrounding existing Bent 9 required analysis to confirm it was adequate for a transition from a closed abutment to an interior bridge bent. Original
ground elevations near Bent 9 were approximately elevation +70, while the anticipated scour elevation was considered to at least elevation +25.0 and ultimately to the final river flowline elevation. Bent 9 was determined to be adequate to support the bridge as an interior bent.

After consideration and study, it was concluded that the new cantilever wall system crossing to the north (land) side of Bent 9 would provide the required erosion protection without affecting shaft stability at Bent 9. While this required the removal and replacement of the bridge approach slab, it eliminated the requirement to build the complex retaining wall and soil nail system under the bridge profile.

Figure 3- Typical Anchor Wall Details

Figure 4 - Modified Site Layout - post-Hurricane Harvey
Hurricane Harvey

Hurricane Harvey made landfall along the middle Texas coast near Rockport Aug 25. Harvey generally spared the site and the Brazos watershed during its first few days, as Sugar Land fell between hurricane bands rotating through the Houston area. The Brazos River had been running at minimal levels prior to the storm. Based on the projected storm path the nearest NOAA river height projections in nearby Richmond were raised to a record 59.0 ft (gauge level) Sunday, August 27 with an extended flood level duration. Mandatory evacuations were ordered that evening for the adjacent New Territory subdivision. Between August 26 and August 29 (4 days) Hurricane Harvey dumped 35 inches of rain at this location and similar amounts were recorded over the entire region, although some areas received up to 52 inches of rain during this time.

The Brazos River actually peaked at 55.2 ft gauge level (also a record) on August 31 and the evacuation order was changed to voluntary on September 2. The drilling equipment was moved to the top of the roadway embankment and edge of levee prior to stopping work due to the hurricane and fortunately none of the equipment was damaged by the floodwaters. A picture of the flooded jobsite is shown in Figure 6.
Installation of Drilled Shafts and ACIP Piles

The structural drilled shafts used to form the wall were typically 5.5-ft-diameter and 120-ft-long spaced at a 6.5-ft center-to-center spacing except where the wall alignment went through the highway embankment. Since those shafts could not be tied back they were designed as a cantilevered wall. Those 12 shafts were 10-ft-diameter and typically 130-ft-long, and were spaced at an 11.0-ft center-to-center spacing. Both shaft diameters thus had a plan 1 foot clear spacing between them (see Figure 4). All of the shafts included a 40-ft-long permanent steel casing in the upper portion of the shaft which penetrated below the bottom of bank level. This protected the shafts from blowing out laterally through the bank during drilling and concreting. In some areas the bank erosion had already encroached to the shaft alignment.

Drilled Shaft Installation. The drilled shafts were advanced using a bentonite slurry to keep the holes open during drilling. Once the final depth was reached, the slurry was de-sanded and the bottom of the hole was cleaned out with a clean out bucket. The full length rebar cage was then installed and the shafts were then concreted using a tremie pipe. The slurry was returned to the slurry tanks and re-used on the next shaft.

ACIP Seal Pile Installation. The seal piles were 24-inch-diameter and 95-ft-long and were placed immediately adjacent to the gap between the 5.5-ft-diameter structural drilled shafts. These seal piles were installed using ACIP pile installation techniques. A 24-inch-diameter hollow stem auger was used to drill down to 95 ft where fluid grout was then pumped under pressure through the hollow stem of the auger and out the drill bit. Prior to withdrawing the auger a 5 ft grout head was pumped in the bottom. Once the grout head was established the auger was continuously withdrawn while pumping at least 115 percent of the theoretical volume in each increment until grout was observed flowing from the ground surface, which is defined as the grout return depth. The grout return depth should be at least the same at the initial grout head but was typically 10 ft or more.

When initially spotting up on each drilling location the bit and auger were placed directly against the two adjacent steel casings for the structural drilled shafts. The leads were then plumbed and adjusted to maintain verticality. The auger then drilled down beside both casings with the casings acting as a guide below grade.

The total volume pumped in the seal piles averaged 132 percent of the theoretical volume with an average grout return depth of 12 ft. The average in-situ pile diameter based on the actual volume pumped in the piles was 27.5 inches. All piles were installed using a Pile Installation Recorder (PIR) to automatically monitor and record key aspects of the pile installation process. The PIR monitors depth, time, incremental and total grout volume, grout pressure and hydraulic pressure (torque) at the gearbox. The operator is able to monitor these values in real time as the pile is being installed and make any required adjustments. The PIR also provides a digital record of this information for each pile.

Drilled Shaft Seal Pile Installation. The nine seal piles between the 10-ft-diameter structural drilled shafts that went through the embankment were 30-inch-diameter and 100-ft-long and were installed using slurry displaced drilled shaft techniques. This was done primarily for schedule issues as the drilled shaft rig was already in place on the roadway since it had just installed the structural drilled shafts. One direction of the highway had to be shut down to install these shafts and all traffic was being detoured so speed of installation was a primary concern to meet the schedule. A high slump and flowable concrete was used for these seal shafts. The concrete was placed with a full length enclosed system tremie. During concrete placement we first established a concrete head outside of the tremie prior to lifting the tremie pipe. The concrete depth in the seal shaft was monitored to make sure the tremie pipe was always in the concrete a minimum of 5 ft. In this sense, the drilled shaft seal piles were installed similarly to the ACIP pile seal piles. A larger diameter seal pile was used for drilled shaft application than the ACIP seal piles for both constructability and conservatism.

SoniCaliper Testing. The project specifications listed a vertical tolerance for the shafts at 1 inch off center per 10 ft vertical (0.83%) out of plumb consistent with TxDOT specifications for drilled shafts. Because
these are part of a wall that utilizes seal piles it was important to measure both the shape (diameter) and verticality of the shafts to determine what the clear spacing was between the shafts. Per the specifications, if the clear spacing between shafts was greater than 18 inches at the maximum depth where a seal is still required of 95 ft then a larger 30-inch-diameter seal shaft would be required.

The verticality and shaft diameter was measured using the SoniCaliper tool. The SoniCaliper™ is a quality assurance tool for drilled shafts that has the ability to virtually "see" foundation excavation shapes prior to placing concrete in dry or slurry conditions. This sonar calipering technique provides results in real-time display and it creates "as-constructed" images and calculations immediately after the excavation has been profiled. This information gives the engineer and contractor confidence that the end product is manufactured according to specification. Utilizing sonar technology, the SoniCaliper provides a full 360-degree profile and can determine diameter, assess verticality and calculate volume.

The initial phase of the testing plan was to run a SoniCaliper test on the first 10 shafts to check the verticality and diameter. The project team would then evaluate the data to determine if continued shaft testing would be necessary. We actually tested the first 13 shafts to provide a little extra data to evaluate. The center offset measured at 100 ft ranged from 0.25 inches to 5 inches with an average of 2.6 inches on the first 13 shafts. The offset standard deviation was 1.6 inches. The tolerance at 100 ft was 10 inches so all the shafts were well within tolerance. The direction the shafts were off center were primarily perpendicular to the wall alignment so the clear spacing between shafts had not increased to the point where a larger seal shaft would be needed. Based on these excellent results the project team determined that further SoniCaliper testing was not required.

Figure 7 shows the erosion of the riverbank post hurricane flooding along the retaining wall.

![Figure 7. Post Hurricane Erosion Along Retaining Wall Under Construction](image)
Summary and Conclusions

Even with a record hurricane impacting the site resulting in major design changes the project was quite successful. The work was done on budget and completed ahead of schedule. Even the lane closures that required traffic detours were completed ahead of schedule in both instances. Everyone on the project team should be commended for working together to achieve this level of success under such challenging circumstances. Our conclusions are as follows:

- An innovative retaining wall design consisting of tangent drilled shafts with supplementary seal piles was used to limit continuing bank erosion along the Brazos River in Southeast Texas. The riverbank erosion had progressed to where it was threatening the stability of both the bridge abutment and corresponding approach embankment of the heavily travelled Highway 99 bridge at this location.
- The tangent pile with seal pile retaining wall system selected for this project was not only more cost effective and faster to install than secant shafts, it also allowed for better flexibility in design, which ended up being needed due to design changes resulting from Hurricane Harvey.
- The Owner’s selection of the entire project team prior to final design proved to be very prudent in this case. It allowed both the designers and contractors to develop a more effective design by putting together the best ideas from all parties.
- This excellent working environment between the project team created from the very beginning of the project continued throughout the entire project and was equally useful in quickly coming up with the required re-design.

Acknowledgments

The following main project team members were involved with the project.

- Fort Bend Grand Parkway Toll Road Authority (Owner)
- BGE, Inc. (General Engineering Consultant, Project Designer Post Harvey)
- NBG Constructors (General Contractor)
- A.H. Beck Foundation Company (Specialty Deep Foundation Contractor)