MARC BASNIGHT BRIDGE - PRECAST SOLUTIONS FOR A CHALLENGING BRIDGE SITE

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ABSTRACT

Traveling the scenic North Carolina Outer Banks on NC Highway 12 requires crossing Oregon Inlet, one of the most dangerous inlets on the Atlantic coast, where treacherous currents, constantly shifting bathymetry and violent storms are normal occurrences. Since its completion in 1962, the Herbert C. Bonner Bridge served as that critical link between Hatteras and Bodie islands. Unfortunately, the Bonner Bridge has suffered from severe scour and deterioration in the harsh marine environment, and has required nearly continual maintenance, repair and retrofit. In 2011, NCDOT awarded a design-build contract to replace the bridge, requiring a 100-year service life, design for up to 84' of scour and minimal environmental impacts. The associated design and construction challenges created opportunities for innovation and creativity. The resulting 2.8-mile long bridge, recently christened the Marc Basnight Bridge, features extensive use of precast concrete construction for quality, durability, economy and constructability, a first-of-its-kind driven pile foundation verification method, and innovative, environmentally-sensitive construction approaches. The use of precast bent caps and columns instead of CIP concrete for the 44 pile bents and 25 two-column bents resulted in substantial savings for both overall schedule and cost.

Keywords: Precast, Bridge, Coastal, Scour, Foundations, Viaduct

INTRODUCTION

The North Carolina Outer Banks consist of a series of barrier islands on the Atlantic coast of North Carolina, essentially a 200-mile long series of sandbars several miles offshore. The area has been a recreational destination for decades, featuring beautiful beaches, cool breezes, historic lighthouses, great fishing and abundant natural flora and fauna. Isolated from the mainland by Pamlico Sound, the Outer Banks were originally only reachable by boat. By the early 20th century, a series of regular ferries facilitated automobile access. In the mid- to late-20th century, the North Carolina Highway Department (now the North Carolina Department of Transportation, NCDOT) constructed several extremely long viaduct bridges to improve access to the many popular tourist destinations in the area. One of these was the Herbert C. Bonner Bridge, carrying North Carolina Highway 12 (NC 12) across Oregon Inlet. The 2.3-mile long, two-lane bridge consisted of 201 pre-stressed concrete girder approach spans leading up to a high-level three-span steel plate girder unit over the designated navigation channel. This iconic structure was completed in 1962 and connects Hatteras Island to the south with Bodie Island to the north, thus providing highway access to eight communities on the southern Outer Banks, including Rodanthe, Avon, Buxton and Hatteras, and further on to Ocracoke Island via ferry.

However, within a few years of opening, the Bonner Bridge began to suffer from various types of deterioration and damage. Oregon Inlet, while beautiful, is a relatively inhospitable place, unkind to structures. Severe scour undermined the bridge's multiple pre-stressed concrete piles, and salt spray contributed to corrosion of steel, leading to spalling and deterioration of the concrete bents and pre-stressed concrete girders. Repairs and retrofits became a routine occurrence as NCDOT repeatedly patched spalls on the superstructure and substructure and constructed a variety of "crutch bents" – adding new, deeper piles to reinforce foundations scoured to nearly zero embedment into the channel bottom. During a severe nor'easter in 1990, the dredge *Northerly Isle* broke loose of its moorings and collided with the bridge, causing the collapse of six spans. An emergency repair project reconstructed the damaged bridge, but by this time it was clear that the Bonner Bridge was in need of complete replacement by a more durable structure. NCDOT undertook a planning study to evaluate alternatives for replacement of the Bonner Bridge. The problem was more complicated than simply replacing the bridge in place; NC 12 south of the Bonner Bridge runs through the Pea Island National Wildlife Refuge, and in this area Hatteras Island has proven to be susceptible to breaches and washouts during storm events. The entire NC 12 corridor needed study. Eventually, in 2008, NCDOT advertised a design-build project to replace the existing bridge, as the first step in what was called the phased alternative approach for the overall NC 12 corridor. Various obstacles to the completion of the environmental studies and the Record of Decision delayed the procurement process, but in August of 2011, a Design-Build Team (DBT) led by PCL Civil Constructors, with HDR as the lead design firm, won the contract to design and build the replacement for the Bonner Bridge. PCL's actual bid was \$215.8 million, approximately \$64 million less than the second-place bid, and its quality-adjusted price was \$194.2 million, nearly 20% lower than the second-place bid. Design and permitting activities were largely completed by early 2012, but the start of construction was delayed until resolution of litigation in the summer of 2015.

Mobilization and preconstruction activities started in late summer, and PCL was on-site by January 2016, with the official groundbreaking occurring in March of that year. The new 2.8-mile long bridge, recently christened the Marc Basnight Bridge in honor of North Carolina State Senator Marc A. Basnight, a long proponent of the project, was opened to traffic on Feb. 25, 2019, with the official grand opening ceremonies held on April 2, 2019.

CHALLENGES

Oregon Inlet is not a site conducive to the construction and maintenance of large infrastructure. Often-cited as one of the most dynamic and dangerous inlets on the Atlantic coast, Oregon Inlet is subject to frequent and heavy hurricane and nor'easter storm activity. The inlet itself is extremely dynamic; the bathymetry is constantly changing as tides and storm action move the loosely deposited sand and shift the size, shape and location of the natural channel from day to day, and sometimes from hour to hour. In order to maintain navigation under the single navigation span of the existing Bonner Bridge, the U.S. Army Corps of Engineers (USACE) must dredge a navigable channel virtually nonstop, year-round. Further, since the site is on the Atlantic Ocean, any structure in Oregon Inlet is subjected to a constant barrage of salt-spray wetting and drying cycles, leading to significant potential for corrosion and structural deterioration.

These conditions contributed to unprecedented design criteria for the bridge. The foundations were to be designed and constructed to experience anywhere from 0 to 84' of scour in some regions, combined with flow velocities of up to 12.4 fps, wind velocities of up to 105 mph (measured as "fastest mile of wind") and vessel impact forces of up to 2151 kips. Due to the constantly shifting location of the natural channel, the USACE and the U.S. Coast Guard (USCG) requested that the bridge be designed to accommodate a "navigation zone" with a minimum width of 2500'; all spans within this zone were to provide a minimum of 70' of vertical and 200' of horizontal navigation clearance, so that the marked navigation channel could be easily relocated to minimize the need for dredging. In addition, in hopes of being able to avoid the nearly continuous and expensive maintenance and repair needed to keep the current Bonner Bridge operational, NCDOT specified numerous prescriptive durability criteria. The general theme was to achieve a 100-year service life.

Construction was similarly constrained and challenged at the site. High winds, rapid tidal flows and frequent storms hamper construction, particularly in late fall, winter and early spring. In addition, nearly the entire project site is considered environmentally sensitive in one manner or another. The south end of the bridge lands within the Pea Island National Wildlife Refuge, operated by the U.S. Fish and Wildlife Service. The construction easement within the refuge is extremely narrow. Meanwhile, the remaining length of the project site to the north is within the Cape Hatteras National Seashore – again with a tightly constrained easement. Exacerbating the challenges of limited work area is the proximity of the existing bridge, which must remain in service until completion of the new bridge. Much of this area is also designated as Submerged Aquatic Vegetation (SAV) habitat; in those areas neither dredging nor causeways are permitted, forcing the use of a temporary work trestle. The project site is also fairly remote, without nearby access to a concrete batch plant and with only the two-lane NC 12 highway available for overland material deliveries.

DESIGN AND CONSTRUCTION APPROACH

DESIGN AND CONSTRUCTION CONDITIONS, CONSTRAINTS, AND CRITERIA

While this project certainly presented a plethora of daunting, even unprecedented, challenges, the DBT also recognized significant opportunities for enhancing quality, durability, economy, speed and environmental stewardship. The consistency of the site conditions and the nature of the project as a single, long, viaduct-type bridge allowed for a focused approach to design and construction, which features several simple, complementary and mutually supportive themes.

Early during the pre-bid engineering phase of the project, the DBT recognized that replacement of the Bonner Bridge was not a “bridge job.” It was a large marine foundation project, with a bridge stuck on top. This realization allowed the DBT to focus on foundation design and construction as key to the success of the project. The structural and geotechnical engineering teams created a color-coded longitudinal plot of the project, illustrating the subsurface conditions, the scour profile, the vessel collision zones and the navigation clearance zones (Fig. 1). Examination of this plot allowed the project to be partitioned into five regions: North Approach Spans, North Transition Spans, Navigation Unit, South Transition Spans and South Approach Spans. These regions corresponded to both the scour profile (which also features five regions, each with a prescribed minimum design scour depth), and the vertical geometry profile of the bridge. Coincidentally, the subsurface soil conditions, which are remarkably consistent throughout the length of the project, primarily fall into two regions, which roughly align with the five bridge regions. Vessel collision forces, a primary loading consideration for the deep foundations of the bridge, also varied along the length of the bridge, with smaller forces in the North and South Approach Spans, larger forces in the North and South Transition Spans, and the largest forces in the Navigation Unit.

SELECTION OF PRECAST CONCRETE

Considering all of the various parameters, each of the regions lent itself to a tailored design approach that allowed for widespread use of repetitive construction elements. The salt-water environment and the RFP’s emphasis on durability, corrosion resistance and a 100-year service life indicated the need for a concrete structure, while the remote location of the project site also suggested broad use of prefabricated elements and modular construction. All indicators pointed to the use of precast concrete as the optimum design solution.

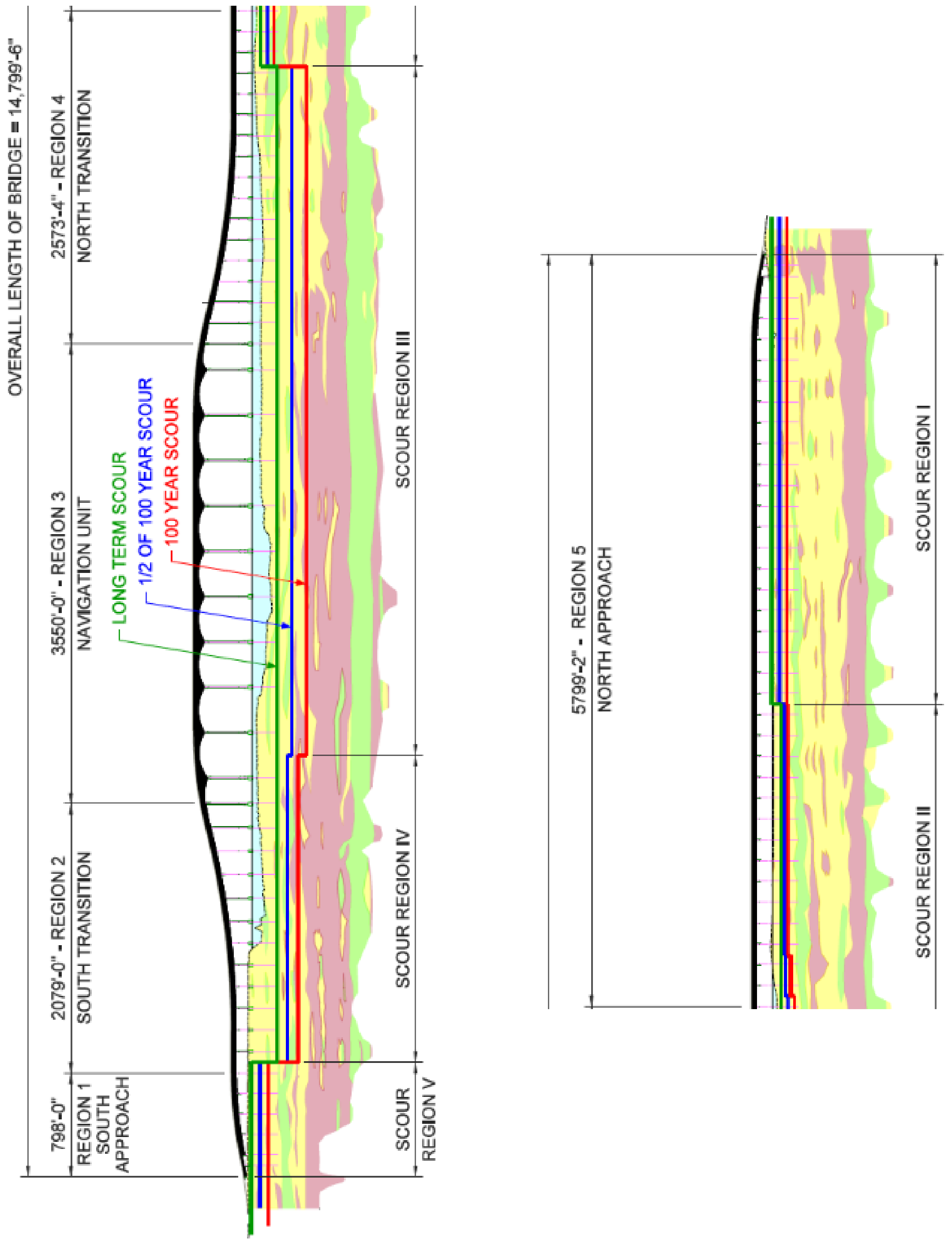

Fig. 1 Longitudinal profile showing bridge regions, scour regions and subsurface conditions (yellow is loose to medium dense sand, pink is dense sand, green is clay/silt).

The extensive use of precast concrete elements offered multiple advantages. First among these were durability and quality. Precasting FIB girders, box girder segments, bent caps, columns and piles in an off-site precasting yard, under controlled conditions, results in the production of extremely high quality, extremely durable concrete elements. These levels of quality and durability would have been difficult to achieve in the harsh marine environment of Oregon Inlet.

These precast elements are also very economical: fabrication off-site is much less costly than trying to deliver and place CIP concrete to the remote project site. Minimizing field construction work from barges and work trestle also leads to much faster, much safer construction. Last, but certainly not least in this project, minimizing field construction work, construction duration and the placement of CIP concrete on-site is also very environmentally friendly, reducing the duration and extent of temporary environmental impacts.

The precast elements used in this project are generally very simple and employ significant repetition of detailing. This repetition of detailing led to significant economies of scale in terms of fabrication and familiarity in terms of construction, again reducing costs and speeding up construction. Since the design regions also roughly correspond to land-based, water-based and SAV-based regions of the project, construction activities could similarly be tailored by region. These focused, tailored approaches to design and construction, combined with extensive use of precast construction, result in an extremely high quality, durable, economical and constructible structure.

SUBSTRUCTURE DESIGN

NORTH/SOUTH APPROACH SPANS

The North and South Approach Spans represent approximately half of the total bridge length, and have design 100-year return period scour elevations from -22 feet to -34 feet. Foundations in this region are precast concrete pile bents, with three or four vertical 54” diameter cylinder piles for each bent (Figs. 2 and 3). Typical cylinder piles are approximately 135 feet long, and the total length of these cylinder piles on the project is over 3.4 miles. The piles are made with 8.0 ksi concrete and have 6” walls, with 2.5” minimum concrete cover. Pre-stressing was applied with 32 0.6” diameter grade 270 strands. The piles were cast monolithically, not spun cast in segments as is sometimes selected with cylinder piles. The use of spun-cast piles would have required greater wall thickness for post-tensioning duct and strand, which was not desirable due to the considerable weight of these piles. In addition, corrosion in the salt water of the Oregon Inlet was a concern for segmental pile joints.

The cylinder piles are connected directly to innovative precast bent caps via reinforced cast-in-place (CIP) concrete infill. This infill extends 30 feet into the hollow piles to provide stiffness in cases of severe scour, and transfer both moment and axial loads to each pile. The infill also provides strength locally to prevent damage to the pile wall from a vessel strike. Using precast bent caps greatly increased the quality and durability

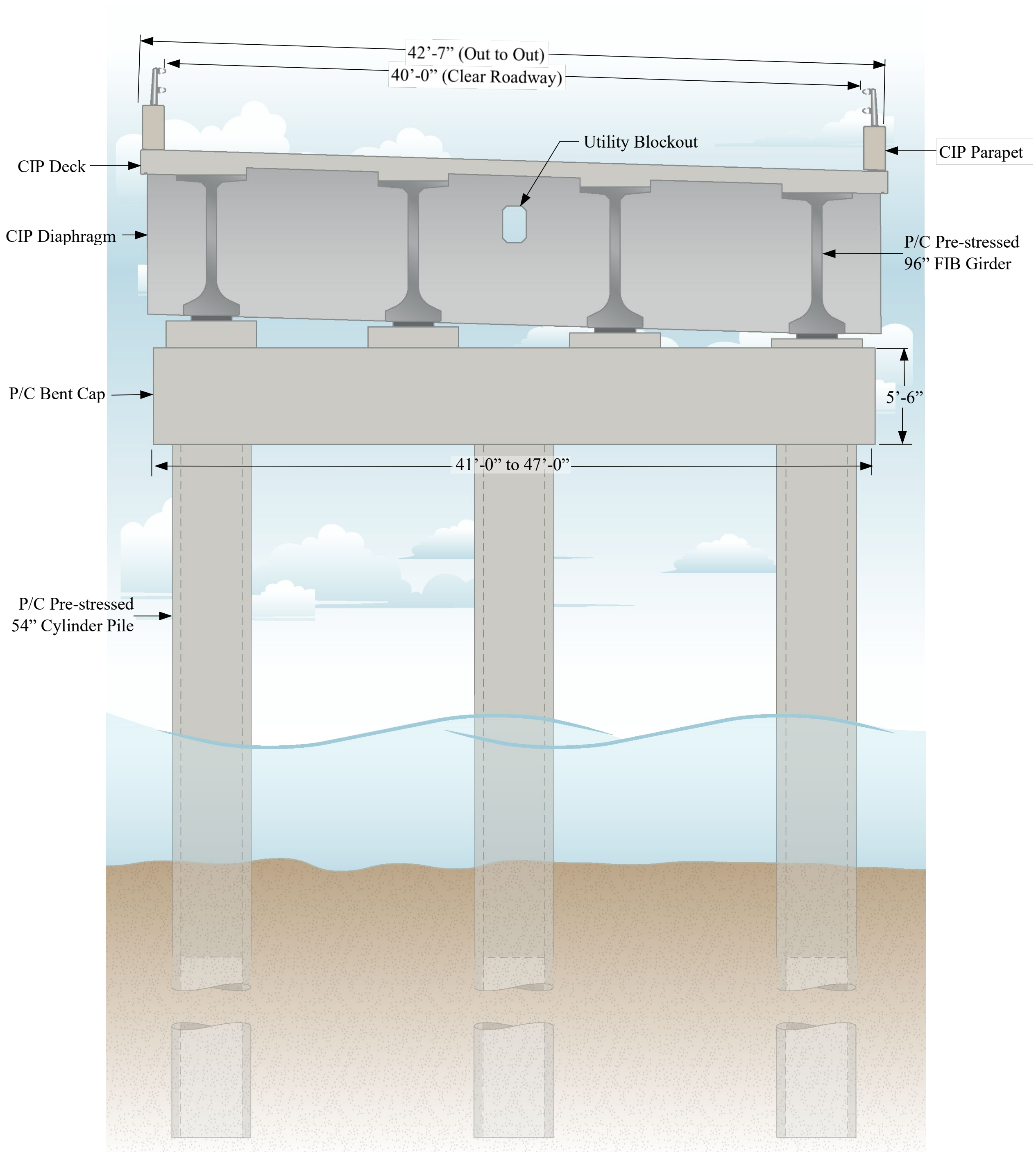

Fig. 2 Typical Section View of the North Approach Spans, showing the CIP concrete deck, P/C FIB girders, P/C bent cap, and P/C cylinder piles. The South Approach Spans are similar.

Fig. 3 Setting of the first precast concrete bent cap on 54” diameter precast concrete cylinder piles in the North Approach Spans, creating an all-precast substructure unit.

of the substructure. The bent caps were designed with voids to reduce shipping weight and include nominal pre-stressing to address transportation and handling stresses. The voids are filled with CIP concrete when the caps are connected to the cylinder piles. Following connection of the caps with the piles through placement of a CIP concrete infill, CIP pedestals are used to meet final plan bearing elevations and support the precast superstructure girders. In accordance with project requirements, stainless steel reinforcement was used in all CIP concrete.

NORTH/SOUTH TRANSITION SPANS

The North and South Transition Spans represent approximately one quarter of the total bridge length and have design 100-year return period scour elevations from -71 feet to -

84 feet. Foundations in this region include six to 16 36” square precast concrete piles, with a 4.5 ksi CIP waterline pile cap. All piles were battered on a 2:12 slope for greater stability, especially in cases of extreme scour. The remainder of the substructure was completely precast, using precast, post-tensioned two-column bents supporting a precast pier cap (Fig. 4). Some of these pier caps included voids to reduce trucking weight, but most were solid precast concrete, delivered by barge.

Typically, the 36” square piles were approximately 130 feet long, and over 12 miles of these piles were used on the project. The piles were fabricated using 8.0 ksi concrete with 2.5” minimum cover to the reinforcement, and include a central 21” circular void away from the ends of the pile to reduce weight for handling. Pre-stressing was applied 36 0.6” diameter grade 270 strands. The piles are embedded four feet into the CIP pile caps to develop a full moment connection at the pile head. Pile layouts and batter configurations were optimized to resist bent-specific transverse and longitudinal loadings. To control the constructed geometry of the battered piles, PCL used a sophisticated pile template system that included oversized steel casings installed up to 60’ deep; a vibratory hammer was used, which facilitated precise control of the location and orientation of the casings. The 36” square piles were then tripped into the casings and guided by rollers inside the casing during jetting and driving to depths up to 130’.

Above the waterline pile cap, substructures in this region include post-tensioned two-column bents with column heights up to 50’. These 8.0 ksi columns were assembled using 5’ square or 6’ square, solid, match-cast precast concrete segments, post-tensioned together. 1.75” diameter, 150 ksi post-tensioning bars are used in the columns, with bars ending at various segments based on design moment demand. Column segments are typically 12’ tall, but each bent includes a single unique segment to achieve the correct bearing elevations.

To meet project durability requirements, stainless steel bars were used for all post-tensioning below the splash zone, defined as 12’ above Mean High Water level. The NCDOT RFP had prohibited the use of any post-tensioning in the substructure in the splash zone, due to corrosion concerns, but the DBT proposed an Alternate Technical Concept (ATC) in which the columns would use solid stainless steel post-tensioning bars based on recommendations in the report *New Directions for Florida Post-Tensioned Bridges, Volume 7 of 10: Design and Construction Inspection of Post-Tensioned Substructures*, (*1*).

A precast bent cap was post-tensioned to the top of the columns. A 2” grout bed between the top of column and bottom of cap was provided to accommodate construction tolerances. CIP concrete pedestals were used to meet final plan bearing elevations and support the precast superstructure girders. For all column post-tensioning on the project, PT bars were anchored in the CIP pile caps, just above the bottom mat of mild reinforcement. A dead-end anchorage assembly with a stainless steel nut and anchor plate was placed above the reinforcement, followed by a standard plastic PT duct sealed to the bar, with a grout inlet pipe. The PT duct extends up the full height of the column and cap, with standard duct couplers used for joints between segments. For locations where the PT bar is coupled, short lengths of oversized PT duct were used to accommodate the couplers. The bar couplers were staggered, with no more that 50% of the PT bars coupled at a given elevation. At the top termination of each bar, a grout cap was used to seal over the top anchor plate and nut.

NAVIGATION UNIT

The 11-span Navigation Unit extends 3,550’ and includes 12 substructure bents, with design 100-year return period scour elevations from -71 feet to -84 feet. Foundations in this region include 18 to 30 36” square precast concrete piles, with a 4.5 ksi CIP waterline pile cap. All piles are battered on a 2:12 slope for greater stability, especially in cases of extreme scour. On top of the pile cap, precast post-tensioned hollow box columns support a rectangular precast column cap (Figs. 5 and 6).

The foundations in the Navigation Unit are similar to those in the Transition Spans, with more piles and larger pile caps. The single columns are 16’ by 11’, with heavily reinforced CIP column bases extending 17’ above mean water level. Above this CIP base, 12’ (typical) hollow precast box column segments were assembled, topped by a rectangular precast column cap. These 8.0 ksi precast sections were match-cast and post-tensioned together with 2.5” diameter 150 ksi post-tensioning bars, with bars ending at various segments based on design moment demand. The column segment walls are 1.5’ thick. Like the transition columns, stainless steel bars were used for all post-tensioning below the splash zone.

Design of the Navigation Unit included individual FB-Multipier bent models and a global 3D LARSA model of the entire 3,550’ unit with superstructure and substructure. This LARSA model permitted staged analysis to capture time-dependent effects from superstructure creep and shrinkage. Due to the length of this continuous unit, displacement-driven loads like temperature, creep and shrinkage were significant and could potentially apply huge forces to piers with fixed bearings. All piers needed to be designed for both maximum scour and the case of re-deposited sand up to the pile cap. The second case results in an extremely stiff substructure, so two fixed bents were used to keep displacement-driven forces low. Sliding disk bearings are used for the other 10 bents, reducing superstructure longitudinal loads to static friction only.

During design, iteration was required between substructure and superstructure development, as changes to the pile foundation layout altered the boundary conditions of the global 3D LARSA model. Close coordination was particularly important in developing the jacking force and displacement requirements for Span 24, between the fixed bents. Just prior to placing the central closure pour in this span, jacking forces were applied to push Bents 23 and 24 apart. This jacking was optimized to offset half of the long-term superstructure creep and shrinkage. The stiffest possible foundation condition (re-deposited sand) was used in establishing the maximum applied jacking force.

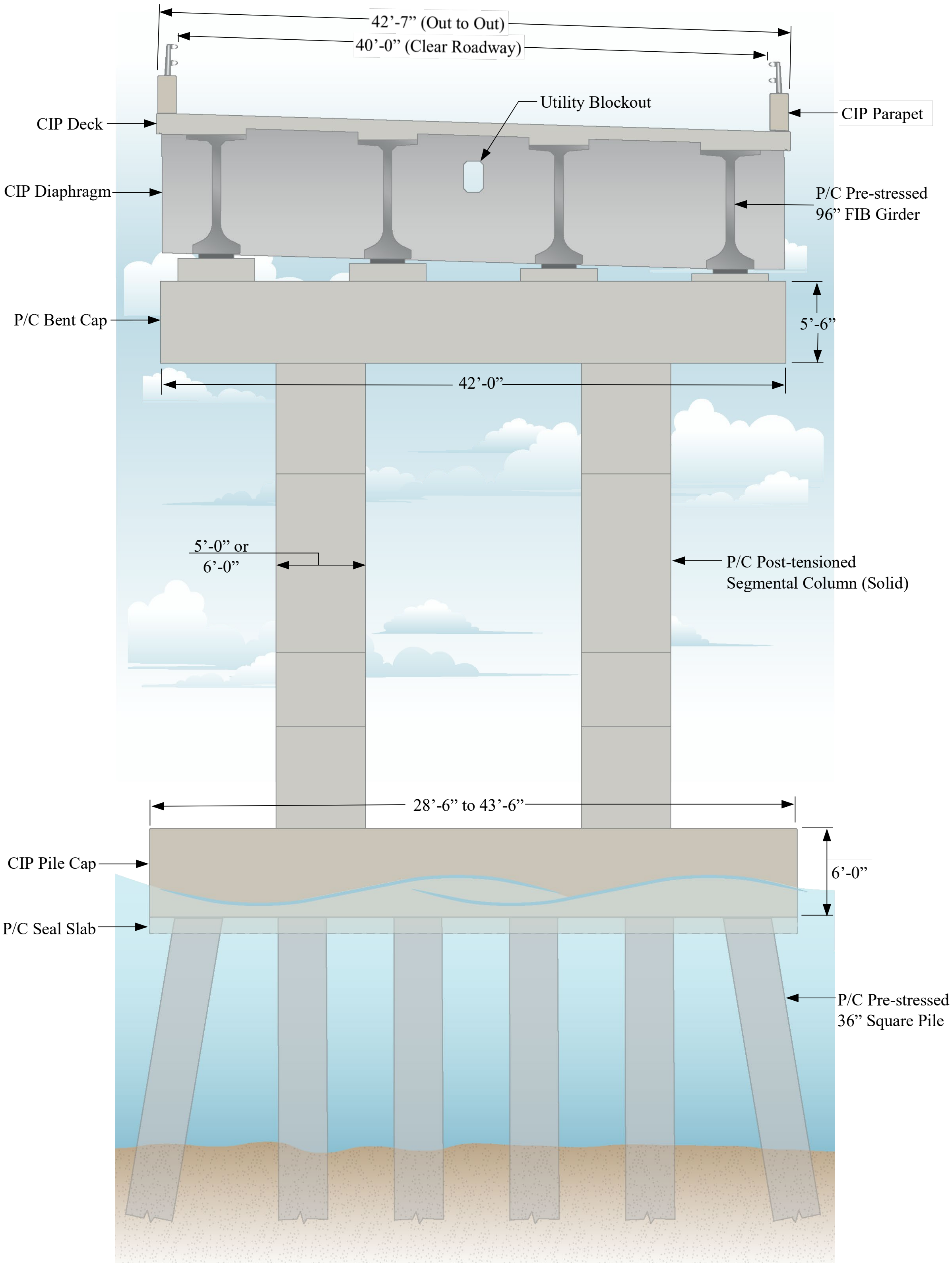

Fig. 4 Typical Section View of the North Transition Spans, showing the CIP concrete deck, P/C FIB girders, P/C bent cap, P/C post-tensioned columns, CIP footing and P/C square piles. The South Transition Spans are similar.

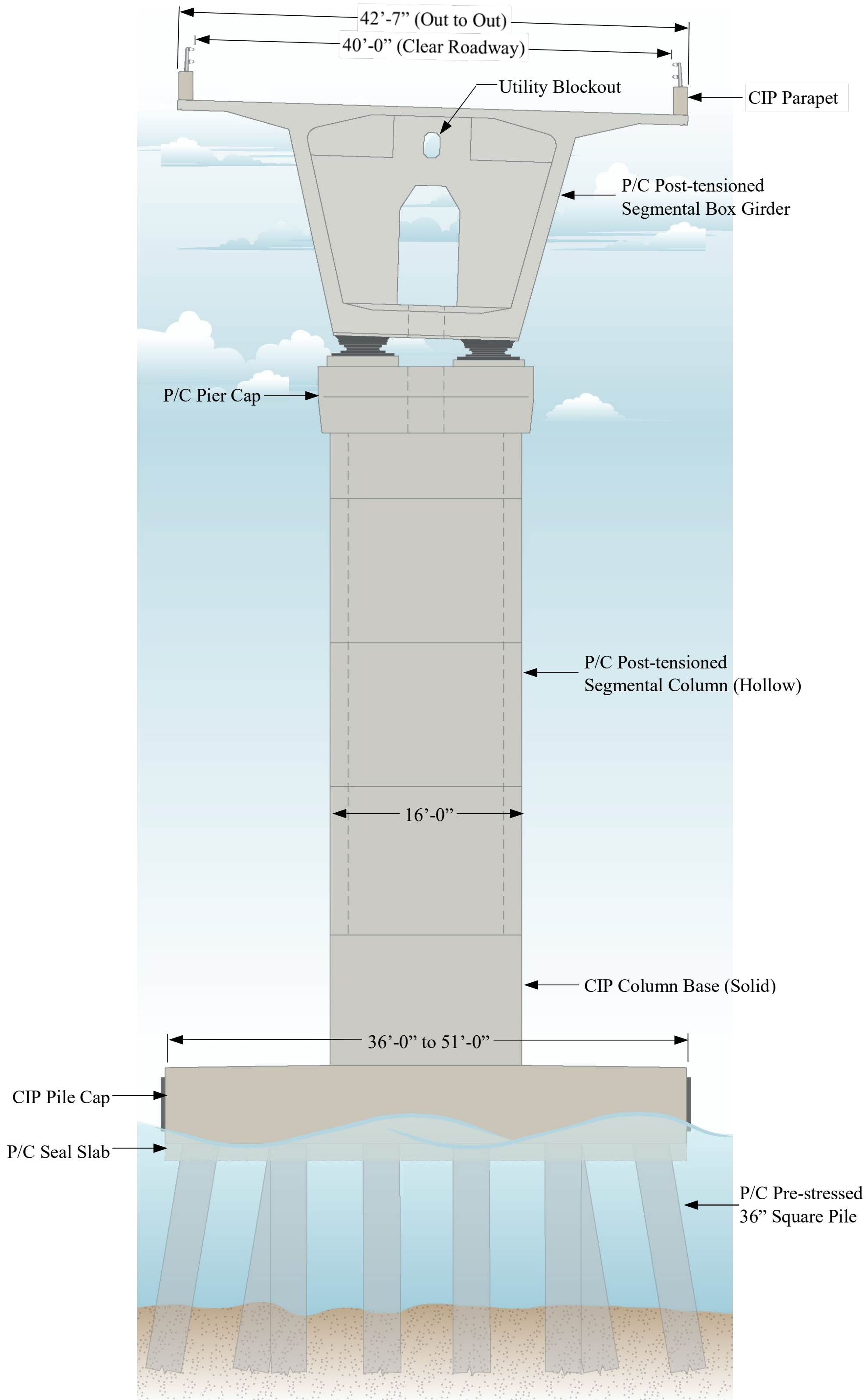

Fig. 5 Typical Section View of the Navigation Spans, showing the P/C post-tensioned segmental box girder, P/C pier cap, P/C post-tensioned hollow box columns, CIP footing and P/C square piles.

Fig. 6 Navigation Spans construction, showing installation of 36” precast concrete square piles in foreground and balanced cantilever construction of precast concrete segmental box girder superstructures on precast concrete box columns in the background.

SUPERSTRUCTURE DESIGN

FIB GIRDER SPANS

For the majority of the bridge – all of the North and South Approach Spans and the North and South Transition Spans, representing 2.1 miles of the total 2.8-mile length of the bridge – the superstructure consists of a conventionally-formed CIP lightweight concrete deck supported by precast, pre-stressed concrete FIB girders (Figs. 2, 4, and 7). Approximately 8.75 miles of FIB girders were used. The CIP lightweight concrete deck is a simple, conventionally reinforced design with stainless steel reinforcing. The majority of the bridge has a roadway cross-section with two 12’ lanes and two 8’ shoulders, with a total out-to-out deck width of 42’-7”. The most common span configuration features a four-girder cross-section and a span length of 160’-10”. In the South Transition Spans a number of spans feature a six-girder cross-section and spans up to 182’. Typical continuous units consist of up to six spans, with a unit length of 965’ between expansion joints. Permanent intermediate diaphragms were not provided in any FIB girder spans, but full depth end diaphragms are used at expansion bents, along with the full depth continuity diaphragms at the interior bents. All of the FIB girder spans are supported on steel-laminated elastomeric bearing pads with stainless steel sole plates and anchor bolts. In some cases, when desirable to allow redistribution of vessel collision loads to adjacent bents, reinforced concrete shear keys are provided.

The FIB girders were designed as simple spans for dead load and live load, but are detailed as continuous for live load using typical NCDOT continuous for live load continuity diaphragms at the interior piers. Two spans at each end of the bridge use 45” deep FIB girders, while the remaining spans use 96” deep FIB girders. All girders were designed with a 6.4 ksi release strength and 8.0 ksi final strength and use 0.6” diameter, 270 ksi low-relaxation pre-stressing strands. The concrete strengths were intentionally limited to 8.0 ksi for easy fabrication; higher concrete strengths would require either longer cure times (hampering the ability of the precaster to quickly cycle girders out of the precast beds, a key consideration given the need to cast over 300 girders), or would require the use of more challenging mix designs with increased risk of thermal cracking, etc. All girders were heavily pre-stressed, generally using over 60 0.6” diameter strands, resulting in a design that experiences no tension under service load conditions (AASHTO Service III Limit State) to enhance durability. A combination of both debonding and draping was used to control bursting and tension stresses in the ends of the girders at release. To address the anticipated high variability in pre-stressed girder camber, four different camber prediction methods were used to envelope the anticipated minimum and maximum camber; the highest camber prediction was used to set the girder build-up (haunch) dimension, and the lowest camber prediction was used to evaluate whether the girder had sufficient pre-stressing to provide positive camber after deck placement.

Fig. 7 South Approach Span construction, showing 96” deep precast concrete Florida I-Beam (FIB) girders supported by precast concrete bent caps and 54” diameter precast concrete cylinder piles.

SEGMENTAL BOX GIRDER NAVIGATION UNIT

The 3,550’ Navigation Unit consists of 11 spans, with a typical span length of 350’ and end span length of 200’ and continues the 42’-7” superstructure width of the adjoining pre-stressed girder regions. The single unit is a post-tensioned concrete segmental structure comprised of 238 single-cell precast box girder segments supported on post-tensioned precast concrete columns (Figs. 5, 6, 8 and 9). The structure provides a minimum vertical clearance of 70’ above mean high water among nine of the 11 spans. Considering the vertical curvature with the variable depth superstructure, the bridge length meeting the aforementioned “Navigation Zone” vertical and horizontal clearance definitions is 3,090’, exceeding the USACE and USCG request for a 2,500’ accommodation.

The variable depth superstructure provides both an aesthetically-pleasing and economical solution, supporting the application of the balanced cantilever construction method that permitted the long 350’ typical spans. In this approach, the superstructure segments were erected in upstation and downstation pairs on either side of the pier to form balanced cantilever structures. At the site, the segments were hoisted into position with deckmounted segment lifters, their joints prepared with an epoxy, and stressed to the previously erected segments with temporary PT bars. After the epoxy was set for each upstation and downstation segment pair, permanent cantilever tendons were installed, anchoring at both cantilever tips, and the next segment was prepared for installation. After completion of two adjacent cantilevers, the structures were joined at the midspan by casting a concrete closure segment between the cantilever tips. Bottom and top slab tendons were installed within the span to achieve continuity of the structure.

Longitudinal post-tensioning consists of 18- or 22-strand cantilever and 12-, 16-, or 20-strand continuity tendons encased in plastic ducts and high-strength grout. One pair of contingency ducts is provided for each cantilever. Transverse post-tensioning in the segments uses four-strand tendons spaced at 3'-6" encased in flat 1"×3" I.D. ducts. All tendons are comprised of 0.6" diameter, 270 ksi low-relaxation pre-stressing strands. All diaphragms use vertical 1-3/4" diameter, 150 ksi deformed PT bars to resist vertical splitting induced by the longitudinal post-tensioning. Temporary PT blocks in the top and bottom slabs were provided to facilitate the reuse of temporary PT bars during segment erection.

Fig. 8 Navigation Spans construction, showing balanced cantilever construction of the precast concrete post-tensioned segmental concrete box girder superstructure.

The superstructure segments range in height from 9'-0" at the midspan to 19'-0" at the interior piers. In addition to the variable depth height, the bottom slab thickness varies along the first five segments of each cantilever from 2’-0” at the piers to 10” toward the midspan. Since the segments were delivered by barge, the segment lengths were not limited by roadway or truck restrictions, and a longer 14’-0” length was used to minimize erection operations, while staying within reasonable pick weights for the segment lifters and cranes. Pick weights varied from 94 to 132 tons for typical segments. Due to the greater weight of the superstructure pier segments from their included diaphragms, split pier segments were used to keep the lifting weights manageable. Each pier segment was formed from two 5’-0” long pier segment halves, weighing a more manageable 92 tons each, that were joined by temporary and permanent PT bars.

Fig. 9 Navigation Spans construction, showing balanced cantilever construction of the precast concrete post-tensioned segmental concrete box girder superstructure.

Cantilever erection was facilitated with the use of steel falsework towers bearing directly on the pile caps to resist the out-of-balance moments during segment installation. At the first and last interior piers, the structure and temporary towers were designed for a one-segment out-of-balance condition of 13 cantilever segments on the end span side of the pier and 12 segments on the other. This avoided the need for expensive falsework at each end of the navigation unit in the marine environment. Counterweights were used to reduce the imbalance on the substructure during construction of these particular cantilevers.

The superstructure is supported by two disc bearings at each pier, and the entire 3,550’ long navigation unit is longitudinally restrained at the two middle piers. Bearings at other piers are designed to slide longitudinally to relieve thermal, creep and shrinkage stresses in the long navigation unit. Sliding bearings were temporarily pinned to allow for cantilever erection and were unlocked once structural continuity was attained after casting of each successive closure pour and stressing of continuity post-tensioning. The construction procedure includes midspan jacking prior to closure of the central span to counter long-term creep and shrinkage effects on the two fixed piers in the middle of the unit.

CORROSION PROTECTION FEATURES

The desired 100-year service life for the replacement of the Bonner Bridge is achieved via a number of design and construction features, many of them prescribed in the NCDOT's RFP requirements for the project. The RFP included numerous prescriptive requirements for the concrete mix designs, which greatly enhance the durability and longevity of all concrete elements of the bridge, including the extensive use of fly ash or ground granulated blast furnace slag and silica fume, a low water-cement ratio, and the use of a calcium nitrite corrosion inhibitor admixture. In addition, the use of stainless steel reinforcing was required for all CIP concrete except the barrier rails, which use epoxy-coated reinforcing. The stainless steel reinforcing bars meet the requirements of ASTM A955-12, Grade 75. The stainless steel post-tensioning bars meet the requirements of ASTM A564, Allow S17400, Type 630, Condition H1025, with 150 ksi ultimate strength. Minimum concrete cover dimensions were explicitly spelled out for various elements and situations throughout the structure. Furthermore, stringent design criteria, such as a zero-tension stress requirement for pre-stressed concrete members under service load conditions, augmented the material and construction requirements. The DBT performed a service life analysis study using the LIFE-365 program and determined that all elements will provide the desired service life.

While the majority of the bridge is concrete (as required by the RFP), a number of secondary items are necessarily metallic and were also subject to a variety of prescriptive requirements. For instance, the two-bar metal railing atop the barrier rail concrete parapets were specified to be fabricated from solid aluminum. The sole plates for the elastomeric bearing pads supporting the FIB girders were fabricated from solid stainless steel, as were several other minor metal elements on the bridge. Metal elements that could not be practically or economically fabricated from solid stainless steel were metallized with a 99% aluminum thermal spray coating. When necessary for aluminum surfaces to be in contact with wet concrete, appropriate isolation details were specified.

PERMITTING, SCOUR ANALYSIS, AND FOUNDATION DESIGN

PERMITTING

The design-build contract called for the team to provide a final design, permit applications and agency coordination adequate for permit approvals within approximately 12 months of award, including coordination with other regulatory and nonregulatory agencies, including the U.S. Fish and Wildlife Service, National Park Service, National

Marine Fisheries Service and N.C. Division of Marine Fisheries. The project was able to greatly benefit from North Carolina's NEPA/404 Merger Process, which garners agency reviews throughout the NEPA planning and design process. When NCDOT provided a 404/401 permit application, the agencies were already aware of most (if not all) of the design constraints and alternatives, thus making the permit review a simpler task. The project team used the final stages of the merger process to present the intricacies of the bridge design and the construction process to agency staff, allowing regulators the opportunity to ask questions, offer feedback and gain a "sneak peek" of what they would see in their respective permit applications. All parties embraced this proactive partnering approach to the design, permitting and construction process. The permits were all obtained on schedule, and construction proceeded relatively smoothly.

SCOUR ANALYSIS

The location of the bridge, adjacent to both the Atlantic Ocean and Pamlico Sound, subjects the bridge foundation and superstructure to storm surge, local wind setup and waves during tropical systems and nor'easters. To develop the design conditions, the analysis employed a modeling procedure that used the latest hindcasting technology (coupled ADCIRC+SWAN model) to hindcast the hurricanes that have affected the Oregon Inlet area over the past 160 years for three inlet configurations. Local pier scour computations employed the equations and methodology in the Florida Department of Transportation (FDOT) *Bridge Scour Manual*, Reference (*2*), and physical model scour test results (performed at the Hydraulics Laboratory at Colorado State University) for some of the more complex piers. Scour elevations predicted for the proposed bridge were higher than the RFP-required minimum scour elevations. As the RFP required, design of the replacement for the Bonner Bridge employed the more conservative scour elevations presented in the RFP.

Although the minimum low chord of the bridge superstructure exceeds the 100-year wave crest elevation along the length of the bridge, the substructure is within the wave crest. Wave impacts on a pile cap can generate a substantial moment at the seabed. The AASHTO *Guide Specification for Bridges Vulnerable to Coastal Storms*, Reference (*3*), provided the methodology to calculate wave forces on those elements.

FOUNDATION DESIGN

Design and construction of the bridge foundations proved to be quite challenging, beginning with selecting the most viable options and continuing through installing and verifying completed bents. With design scour depths up to 84' and high lateral loads including wind loads, wave loads and ship impact loads, the foundations had to extend to significant depths through a consistent layer of dense sand to obtain adequate lateral resistance. Following an in-depth review of various foundation options, including traditional drilled shafts and innovative systems such as hybrid pile-shaft foundations, the DBT elected to use jetted then driven pre-stressed concrete piles. The challenges presented by the need to construct very deep foundations to address exceptionally severe design scour envelopes led to development of a highly innovative, first-of-its-kind procedure for determining the piles' required driving resistance (R_{ndr}). This procedure, based on bent-specific in-situ measurements of the axial resistance of the piles incorporating the specific jetted and then driven installation method, removed excessive conservatism from the process, while at the same time increased confidence in the final results.

CONCLUSION

The 2.8-mile long Marc Basnight Bridge is a monumental structure built in a challenging marine environment and designed for a 100-year service life, with minimal maintenance. Through the flexibility of the design-build process, the DBT was able to develop an extremely economical, durable, constructible design and was able to foster a spirit of partnership with NCDOT and various affected agencies. Such collaboration resulted in construction approaches that will minimize temporary and permanent environmental impacts in this pristine coastal location.

Bridge construction involved approximately 90,000 cubic yards of concrete, of which approximately 60,000 cubic yards was in the form of precast concrete structural elements. Extensive use of precast concrete elements, including 3.4 miles of precast cylinder piles, 12 miles of precast square piles, 0.58 miles of precast bent caps, 0.30 miles of precast columns, 8.75 miles of precast FIB girders and 0.67 miles of precast segmental box girders, greatly enhanced the quality and durability of the structure, while simultaneously facilitating faster, safer and more economical construction. Use of precast bent caps and columns – instead of CIP concrete for the 44 pile bents and 25 two-column bents – resulted in substantial savings in overall schedule and cost. The value of this approach was demonstrated by the bid prices for the project: The PCL team's bid was $64 million less than its nearest competitor.

REFERENCES

1. Corven Engineering, Inc., *New Directions for Florida Post-Tensioned Bridges, Volume 7 of 10: Design and Construction Inspection of Post-Tensioned Substructures*, September 1, 2001.
2. Sheppard, M. and Renna, R., *Florida Department of Transportation Bridge Scour Manual*, 2005.
3. American Association of State Highway Transportation Officials (AASHTO), *Guide Specification for Bridges Vulnerable to Coastal Storms*, 2008.