INTO THE DEEP

The foundations of a new 4.5km-long crossing in North Carolina were the key to a complex marine project in a challenging environment, write Domenic Coletti, Dominick Amico and Elizabeth Howey

The Marc Basnight Bridge has been designed with a 100-year service life

After nearly three decades of planning, the new Marc Basnight Bridge on North Carolina's Outer Banks has overcome a remote location and a challenging, constantly changing channel to maintain a connection for residents who live, work or vacation in this scenic area. The US$252 million, 4.5km-long bridge conquers the treacherous currents of one of the most dangerous inlets on the Atlantic coast, with constantly shifting bathymetry and violent storms, while resisting up to 26m of scour below sea level, 169km/h winds, and vessel collision forces.

Some of the pile tips are 40m below the water surface

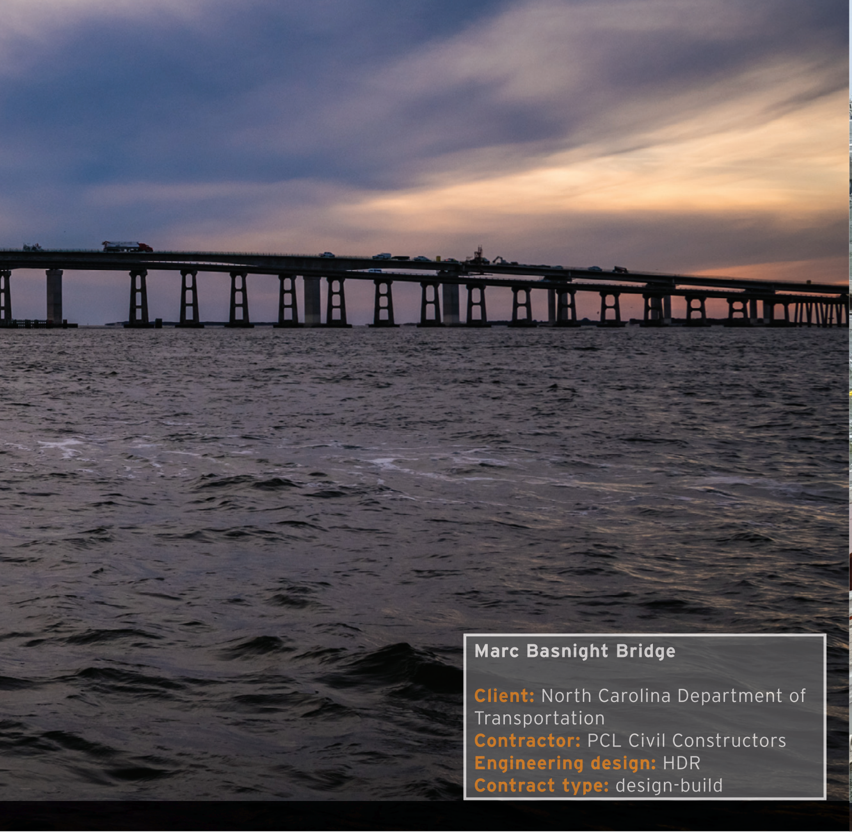
The new bridge, designed with a 100-year service life, faced a number of challenges, but foremost was creating the right foundation. To achieve a more durable structure, the bridge incorporates concrete piles jetted and driven as deep as 40m below sea level, with their required depth verified in the field using a first-of-its-kind method to determine long-term pile axial capacity after significant scour loss. In many ways, the project wasn't a bridge job – it was a complex marine foundation job with a bridge on top. Given the harsh environment and strict requirements for durability, the foundations were the key to the entire project.

A series of barrier islands, the Outer Banks are essentially a 322km-long series of sand bars, several miles offshore, known for their beautiful beaches, historic lighthouses, and abundant flora and fauna. The islands were reachable only by boat for decades until a series of bridges were built in the mid- to late-20th century to improve access for the many tourists who visit the area each year. One was the Herbert C Bonner Bridge, opened in 1963, which carried North Carolina Highway 12 across Oregon Inlet.

The Bonner Bridge improved access to eight communities in the southern Outer Banks. However, the bridge began to suffer from deterioration and damage within just a few years of opening. Oregon Inlet, while beautiful, is inhospitable, and subject to harsh storms including hurricanes and Nor'easters. Severe scour undermined the bridge's concrete piles, while salt spray corroded its steel. For the next five decades, the North Carolina Department of Transportation regularly completed repairs and retrofits to maintain the bridge. After a dredge struck the bridge during a storm in 1990 and collapsed several spans, the need for a new structure was clear.

After decades of study by NCDOT, a team composed by PCL Civil Constructors and HDR was chosen in 2011 to design and build the replacement for the Bonner Bridge. As the lead design firm, HDR provided all roadway, geotechnical and bridge design as well as environmental permitting services. Design and permitting was largely completed by early 2013, but litigation delayed the groundbreaking until March 2016. Less than three years later, the bridge was opened to traffic on 25 February 2019.

The highly dynamic environment proved to be one of the most challenging aspects of the project for both the designers and the contractor. The location of the bridge, adjacent to both the Atlantic Ocean and Pamlico Sound, subjects the bridge foundations and superstructure to severe scour, storm surge, and strong wind and wave forces during tropical systems and Nor'easters, along with vessel collision force effects. The inlet itself is also very dynamic, constantly changing as tides and storms move the loosely deposited sand, shifting the size, shape, and location of the natural



Marc Basnight Bridge

Client: North Carolina Department of Transportation
Contractor: PCL Civil Constructors
Engineering design: HDR
Contract type: design-build

The piles were installed by a combination of jetting and driving

channel from day to day, and sometimes from hour to hour.

To maintain navigation under the Bonner Bridge, which had a single 40m-wide span high enough for ships to pass under, the US Army Corps of Engineers dredged the channel nearly non-stop, year-round. Part of the requirement for the new bridge was to create a much wider navigation zone. The replacement Basnight Bridge features nine 107m-wide spans, which each provide sufficient vertical and horizontal clearance for navigation. As the inlet's natural channel shifts, lights and other markings can be moved from one span to another to indicate which channel should be used by ships, reducing dredging needs.

The varying conditions across the Oregon Inlet led the team to divide the bridge into five regions – north and south approach spans, north and south transition spans, and the centre navigation unit – with each region's design tailored to fit its distinctive subsurface and scour conditions, span length and height requirements, and load demands.

To facilitate delivery of the massive bridge at a practical cost, each design features an assembly of simple, but proven and reliable, structural elements – piles, pile caps, girders and bents. Each of the regions lent itself to a design approach that included widespread use of repetitive construction elements. The saltwater environment and the owner'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 the broad use of prefabricated elements and modular construction. All indicators pointed to the use of precast concrete as the optimum design solution.

The extensive use of precast concrete elements offered multiple advantages. Precasting Florida I-beam girders, box girder segments, bent caps, columns and piles in an off-site precasting yard, under controlled conditions, resulted in the production of extremely high quality and extremely durable concrete elements; these levels of quality and durability would have been difficult to achieve in the harsh marine environment of Oregon Inlet. The precast elements were also very economical: fabrication off-site was much less costly than using cast-in-place concrete at the remote project site. Minimising field construction work from barges and a work trestle also led to much faster, much safer construction while reducing the duration and extent of temporary environmental impacts in a very environmentally sensitive area.

Multiple refined soil-structure interaction analysis models were run for every bent on the bridge using FB-Multipier soil-structure interaction analysis software, considering various scour depths from no-scour to full-scour conditions. The design of the centre navigation unit in particular included multiple individual FB-Multipier software models and a global 3D Larsa model of the entire 1km-long unit with superstructure and substructure. The superstructure and substructure design teams conducted 14 full design iterations to determine the bridge's ideal articulation scheme and optimise the design. The final design features a scheme with two fixed piers and match-cast, post-tensioned, precast hollow box column piers.

To analyse the hydraulic design conditions, the team considered the hurricanes ▶

Most of the bridge deck is supported by precast Florida I-beams

that have affected the Oregon Inlet area for the past 160 years, using a modelling procedure based on the latest storm hindcasting technologies. Local pier scour computations employed the most modern equations and methodology, including validation by means of physical model scour tests performed at the Hydraulics Laboratory at Colorado State University for several of the more complex piers.

Scour depths varied considerably along the length of the bridge, with the approach spans subject to shallower depths, the transition spans subject to deeper scour, and the centre subject to the deepest scour and highest vessel collision forces.

With design scour depths as deep as 26m below the water's surface and high lateral loads including wind loads, wave loads, and ship impact loads, the foundations had to extend to a significant depth, 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 design-build team elected to use jetted and driven prestressed concrete piles.

To verify how future scour affected each pile's required long term axial resistance, the HDR team developed a first-of-its-kind method for calculating predicted scour loss incorporating the jetting and driving installation procedure. To the knowledge of the design team, driven pile bridge foundations subject to scour as deep as 26m below sea level have not previously been designed and constructed in the USA with consideration of this type of long-term scour evaluation. Traditional methods of estimating the loss of pile capacity due to scour would have been extremely conservative, especially considering the planned pile installation method, as well as extremely difficult to achieve in the field without damage to the concrete piles.

The geotechnical engineering team instead developed a simple procedure for taking an in-situ measurement of the actual pile resistance at a given bent, incorporating its jetting-then-driven installation method, using dynamic analysis with the Pile Driving Analyser system. This field-measured resistance was then used to calculate the long-term pile capacity under the design scour conditions. The procedure was thoroughly vetted by geotechnical engineers within both HDR and North Carolina DOT, as well as independently reviewed by two separate international experts in pile foundations. Because it used the actual, measured resistance of the pile, rather than a conservative calculated value, the method helped avoid the risk of being over-conservative and driving the pile to a much higher load, which would have resulted in increased construction durations, longer piles, and greater risk of damaging the piles during installation.

Foundation work began amid the choppy waters in the middle of the inlet with jetting used to advance each pile through the inlet deposits. Upon reaching 3-6m from the required tip elevation for adequate lateral resistance, the team switched to driving the piles the final distance. The piles' final tip elevations are as deep as 40m below the water surface – significantly deeper than required under normal conditions.

The transition spans and navigational unit feature up to thirty $2.3m^2$ piles in a battered configuration to provide greater lateral resistance against wind, water, and ship impact loads under deeper scour conditions. Meanwhile, the approach spans, with significantly less scour and ship impact loads, are supported by pile bents with three or four 1.4m-diameter cylindrical vertical piles. In total, there are 669 piles measuring more than 24km of pile length combined.

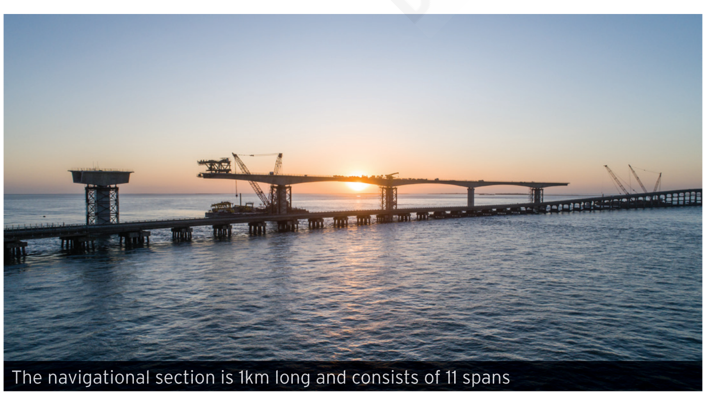
For the majority of the bridge – all of the approach and transition spans – the superstructure consists of a conventionally-formed cast-in-place lightweight concrete deck supported by precast, prestressed concrete FIB girders. The deck is conventionally reinforced with stainless steel reinforcing. The majority of the bridge has a roadway cross-section with two 3.7m lanes and two 2.4m shoulders, with an out-to-out deck width of 13m.

The 1km-long navigational unit consists of 11 spans constructed as a single unit, with a typical span length of 107m and end span length of 61m. 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, and is believed to be the third-longest continuous precast, balanced-cantilever segmental concrete box girder unit in the USA.

The new bridge was officially dedicated on 2 April 2019, during a rainstorm that exemplified the challenging marine environment it was built in. The extensive use of precast concrete elements greatly enhanced the quality and durability of the structure, while simultaneously facilitating faster, safer, and more economical construction. In total, over 40km of precast concrete structural elements were used in the construction of the bridge – 5.5km of precast cylinder piles, 19km of precast square piles, 1km of precast bent caps, 0.5km of precast columns, 14km of precast FIB girders, and 1km of precast segmental box girders. In terms of concrete volume, two thirds of the 69,000m3 of concrete used in the structure was precast.

The former bridge is scheduled to be demolished by early 2020, with much of its material reused to create artificial reefs to enhance fish habitats. Designed to last well into the next century with minimal maintenance, the Marc Basnight Bridge will be a lifeline for communities during hurricanes, an economic boon for an area reliant on tourism, and an iconic structure that will be used for generations

Domenic Coletti and Dominick Amico are senior bridge engineers at HDR; Elizabeth Howey is senior geotechnical engineer, also at HDR



The navigational section is 1km long and consists of 11 spans

The Bonner Bridge that opened in 1963 is due to be demolised in 2020