Iterative Substructure Design for the Marc Basnight Bridge Navigation Unit

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The navigation portion of the new Marc Basnight Bridge is an 11-span, 3550-ft-long continuous precast, post-tensioned concrete segmental box-girder unit, which is believed to be the third-longest continuous unit of its type in the U.S. (for more information on this project, see the Project article in this issue of *ASPIRE*®). For a segmental unit of this length, a primary substructure design challenge was determining the number of piers to have fixed bearings. This article outlines the unique approach the design team used to determine the number of fixed bearings and arrive at a pier design that would satisfy the array of requirements.

Design Process

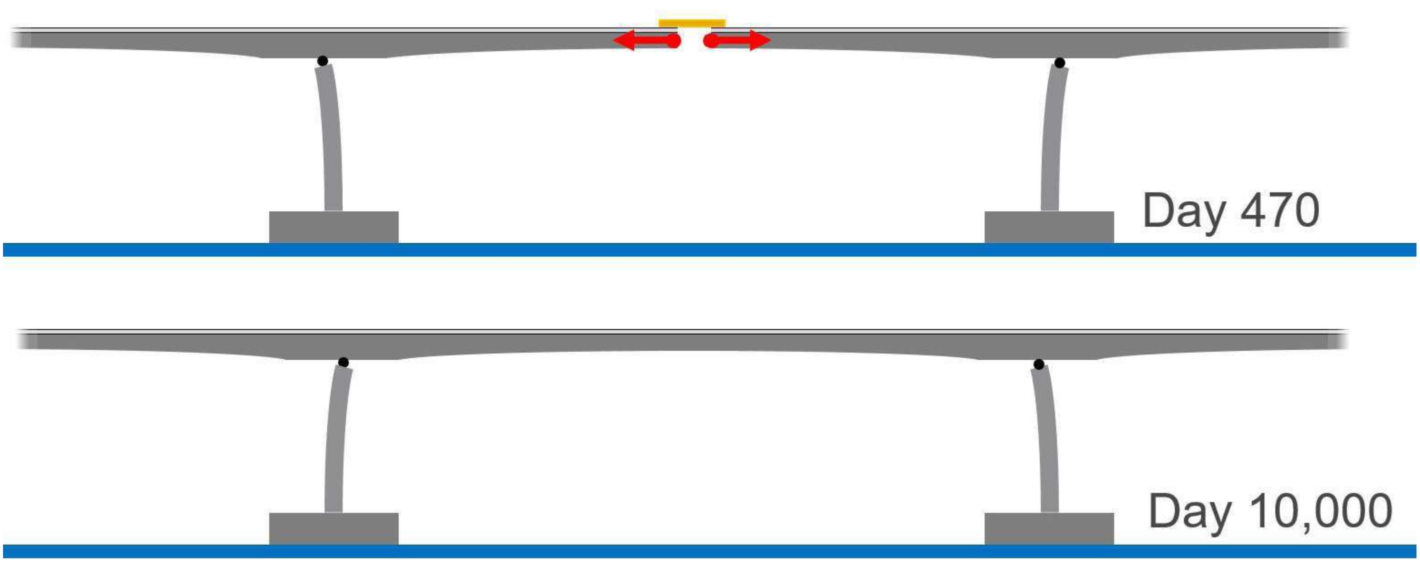
Fixed bearings are necessary to resist the significant longitudinal forces caused by wind and braking. While using several fixed-bearing piers would help distribute these forces, other forces due to creep, shrinkage, and thermal deformations accumulate and increase as a function of a fixed-bearing pier's distance from the center of the unit. On a long, continuous bridge these displacement-driven forces are substantial and increase over time.

To offset the effects of these forces, the design team decided to "preload" the structure by jacking the segmental cantilevers apart in the longitudinal direction between fixed-bearing piers before the cast-in-place (CIP) closure segment was placed. This process induced a shear force in the columns in a direction opposite to the column shear loading produced by creep and shrinkage of the superstructure.

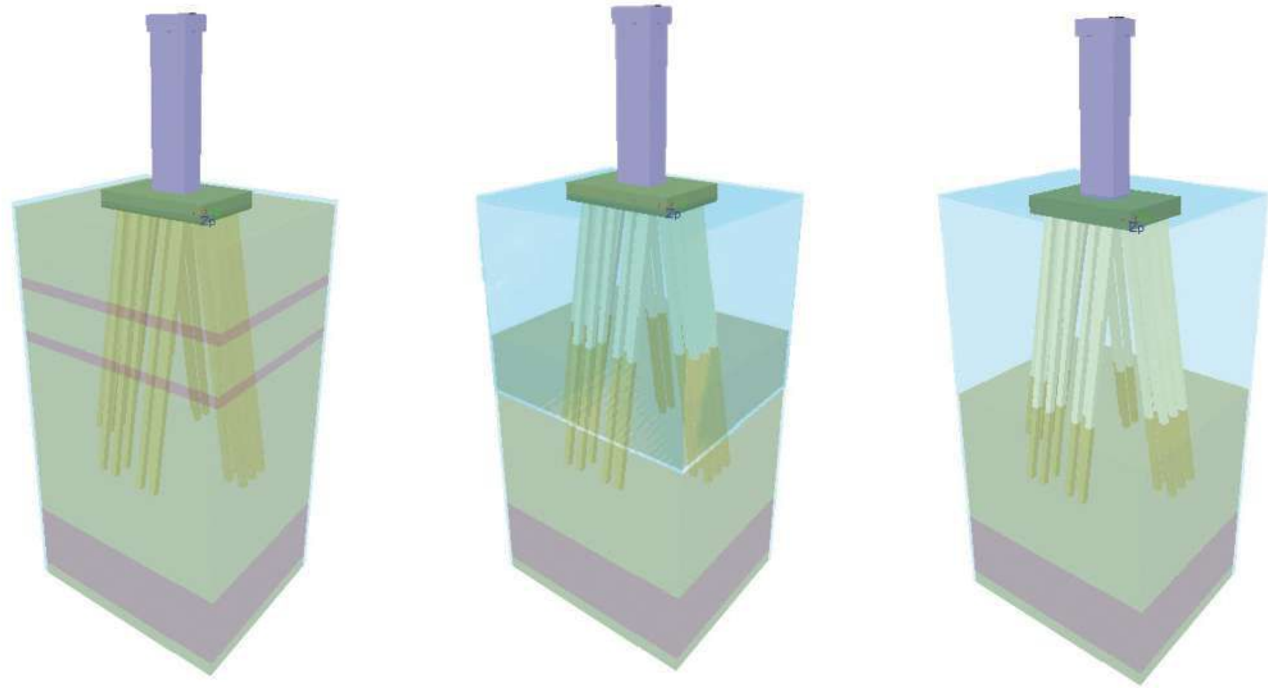
An added complication to the design was the potential for extreme scour, ranging up to 84 ft deep for the 100-year scour, which significantly changes the foundation stiffness. The structure had to be designed to resist longitudinal force-driven loadings due to wind and braking, and longitudinal displacement-driven loadings caused by creep, shrinkage, and thermal deformations of the superstructure at both the zero-scour and maximum-scour conditions. The zero-scour scenario represents the stiffest foundations and thus produces the largest displacement-driven longitudinal forces on the piers.

Over a dozen iterations of superstructure and substructure designs were performed to determine the optimal pier fixities, column and foundation designs, and superstructure jacking force.

The segmental superstructure was designed using a three-dimensional, time-dependent, staged-construction



At midspan of the Marc Basnight Bridge's navigation unit, the two 1825-ft-long halves were jacked apart with a 600-ton jacking force prior to midspan closure (top). This effectively "preloaded" the pier columns with a 600-ton shear force in the direction opposite to the anticipated creep and shrinkage deformations of the superstructure and helped offset the maximum design creep, shrinkage, and thermal contraction case (bottom). All Photos and Figures: HDR.



FB-MultiPier models of the foundation showing the range of design scour levels: zero scour, long-term scour, and 100-year scour of 84 ft.

model developed with LARSA 4D. This model included the pier columns down to the pile caps, where 6 × 6 stiffness matrices were used to represent the stiffness of the foundations. The analysis included steps during construction for the erection of the segments, post-tensioning, and longitudinal jacking of the segmental cantilevers between the fixed-bearing piers before placing the last CIP closure segment at the center of the unit. For design of the completed structure, this model considered two key time steps: Day 470, which was the completion of the last bridge span, and Day 10,000, when all creep, shrinkage, and post-tensioning relaxation are assumed to have occurred. The displacement-driven forces on the fixed-bearing piers increased by approximately 75% over this period.

The navigation unit substructure consists of precast, post-tensioned, 16-ft-wide, 11-ft-deep, and 70-ft-tall hollow concrete columns. These columns are on a CIP pile cap and battered, 36-in.-square precast concrete piles. The substructure was modeled using FB-MultiPier (see the Concrete Bridge Technology article in the Summer 2019 issue of *ASPIRE*) to assess the soil-structure interaction and nonlinear geometric and material effects. Each pier was modeled individually with appropriate design scour levels for strength, service, and extreme event (vessel collision) load combinations. A stiffness matrix representing the foundation stiffness of the pile pattern and a given scour level for each fixed pier was exported from FB-MultiPier and used to represent the foundation stiffness in the LARSA model for each design iteration.

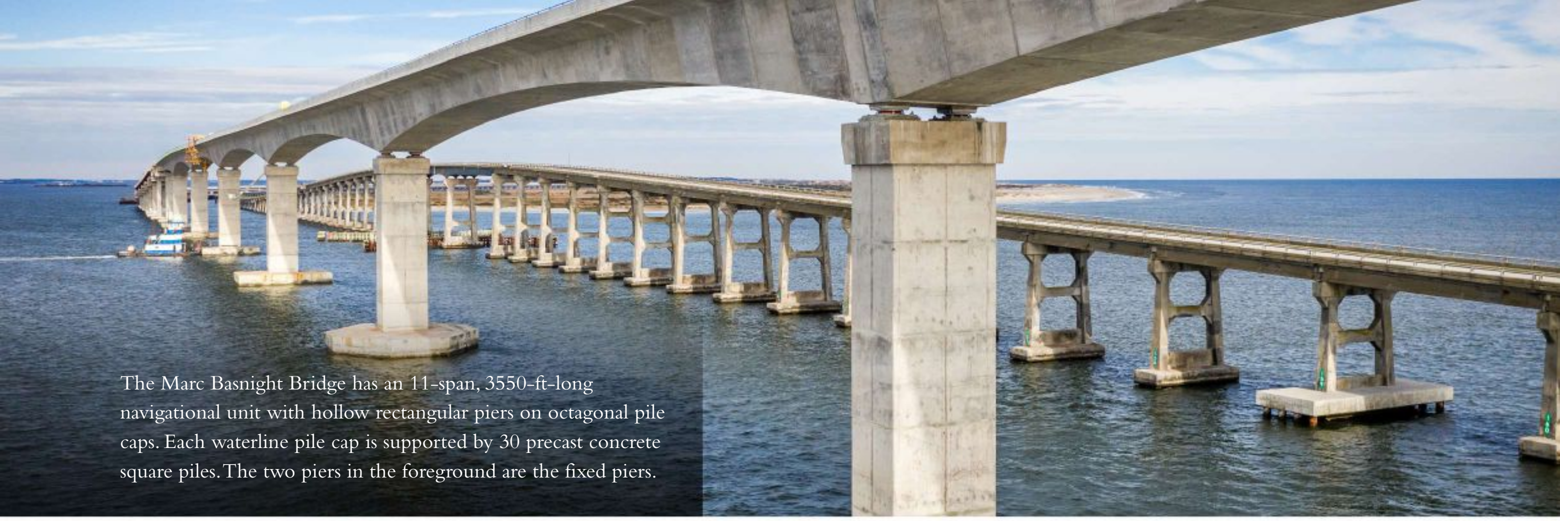
Each change in bearing articulation or substructure stiffness required a full design iteration of the global LARSA model. The bearing articulation in the model would be changed, pier sections updated, and new 6 × 6 stiffness matrices for the foundations provided. For substructure evaluation, the LARSA model was used primarily to evaluate bearing reactions for the stiffest substructure condition (zero scour) at Day 470 and Day 10,000. Following full, staged LARSA analysis, the resulting bearing reactions were summarized for incorporation in the FB-MultiPier models; this represented one design iteration.

The Optimal Number of Fixed-Bearing Piers

Initial designs of the 12-pier navigation unit considered the central six piers fixed, with the intent of distributing force-driven longitudinal loads among more piers to limit foundation sizes, especially for the 100-year-scour condition. For cases of zero scour, however, the foundations are extremely stiff and the box columns do not provide much flexibility. These stocky columns are further stiffened by post-tensioning designed to prevent tension in the columns under service loading. Given the lack of substructure flexibility, displacement-driven loads from the 1750 ft of superstructure between the outermost fixed piers were excessive.

The next design iteration was run assuming only four fixed piers. Resisting displacement-driven forces with the four fixed piers became difficult. Larger foundations (producing increased stiffness) were required at maximum scour, and several design refinements were attempted to address column overstress issues. A variety of pier column designs were investigated—including hollow rectangular sections with thinner walls, closer longitudinal pier spacings, and twin-wall pier configurations—in an attempt to reduce the longitudinal column stiffness for displacement-driven loading while maintaining adequate strength to resist the longitudinal force-driven column loads unaffected by column stiffness.

Also investigated was the construction sequence of jacking and closure segments for the three spans between the four fixed piers. The best jacking combination reduced loads on the interior fixed piers, but the outer fixed piers were heavily loaded and required very large foundations.



The Marc Basnight Bridge has an 11-span, 3550-ft-long navigational unit with hollow rectangular piers on octagonal pile caps. Each waterline pile cap is supported by 30 precast concrete square piles. The two piers in the foreground are the fixed piers.

In the end, none of these refinements proved satisfactory. It was not possible to reduce the column stiffness enough to decrease displacement-driven loads on the outer fixed piers without compromising their ability to resist these loads combined with the force-driven loads, which were divided evenly among the four fixed piers.

The optimal design solution incorporated only two fixed-bearing piers. This solution required that each of the fixed-bearing piers resist half of the longitudinal force-driven loads from the entire 3550-ft-long unit; as a result, larger foundations and significant column post-tensioning were necessary for those two piers. However, the two-fixed-pier solution significantly reduced the displacement-driven force effects by reducing the contracting distance to half the length of the 350-ft-long span between the two fixed piers. This meant that the increased substructure stiffness resulting from the larger columns and foundations required for these two piers to resist force-driven loading did not lead to excessive restraint forces under displacement-driven loading. This solution also limited jacking to one location between the fixed piers in the central span, where the application of a 600-ton jacking force was sufficient to offset a large portion of the displacement-driven forces occurring between Day 470 and Day 10,000.

Conclusion

This process of optimizing the number and type of fixed piers highlights the importance of close integration of superstructure and substructure design for longitudinal forces in segmental concrete bridges. Designers should understand how decisions made above and below the bridge bearings affect one another to produce an optimal design.

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