

The Chesapeake and Delaware Canal Bridge — Design-Construction Highlights



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Mr. Pate has worked 15 years for the Figg Engineering Group, primarily in the design and construction of concrete cable-stayed bridges. Six of these bridges have been completed. In the C&D Canal Bridge project, Mr. Pate participated as head technical engineer in the final design of the cable-stayed structure.

This award-winning \$58 million, 4650 ft (1417 m) long structure is the first major all-precast, prestressed concrete segmental cable-stayed bridge built in the northeast United States. Situated on the new state relief route (SR-1) near St. Georges, Delaware, the bridge will be a big step forward in alleviating traffic congestion on this important transportation corridor. This article will concentrate on the 1650 ft (503 m) cable-stayed portion of the the project which has a main span of 750 ft (229 m). A major feature of the design is the use of precast delta frames, trapezoidal box girder segments, box pier segments and piles — all precast components were barged 180 miles (290 km) to the bridge site. The innovative design features and new construction techniques contributed to making this bridge into a very efficient and economical structure. The author presents the conceptual design and structural design features of the bridge while discussing the production, transportation, and erection aspects of the precast concrete segments.

The Chesapeake & Delaware (C&D) Canal Bridge (see Fig. 1) is a 4650 ft (1417 m) long precast, prestressed concrete segmental cable-stayed structure situated on U.S. 13 near St. Georges, Delaware. The bridge is the first major precast, segmental cable-stayed bridge in the northeast United States. The \$58 million structure is part of a long awaited Relief Route, soon to be known as Delaware Route 1 (SR-1).

The SR-1 project is the largest high-

way project in the history of the Delaware Department of Transportation, with a total estimated construction cost of \$750 million. The 47-mile (76 km) highway will serve as a primary transportation corridor connecting Interstate 95 (I-95), south of Wilmington, and the existing Route 1 just south of Dover. The construction of the SR-1 project will improve the state's transportation system by alleviating traffic congestion along the heavily overburdened U.S. Routes 13 and 113 (see Fig. 2).



Fig. 1. Chesapeake & Delaware Canal Bridge. The last two segments were placed in the 750 ft (229 m) cable-stayed main span on April 3, 1995.

A key feature of the Relief Route is the crossing of the C&D Canal, a major shipping channel that serves as a vital link between the Chesapeake and Delaware Bays. To address the design challenges, a precast, prestressed concrete segmental bridge was selected. Of prime interest is the 1650 ft (503 m) cable-stayed bridge with a main span of 750 ft (229 m). This article will concentrate on the design-construction aspects of the cable-stayed portion of the project.

DESIGN ALTERNATIVES

Prior to presenting the design features of the bridge, the contract letting of the project will be discussed. Two complete bid documents were prepared for the Delaware Department of Transportation — a precast concrete segmental alternate and a structural steel alternate. Both alternates were designed using a cable-stayed system for the main span crossing of the C&D Canal.

Prequalified contractors were requested to submit bids for constructing either one or both alternates. In December 1991, Recchi America, Inc. submitted a low bid of \$57,869,004 for the precast concrete segmental alternate designed by Figg Engineering Group (FEG). The second lowest bid submitted for the project was for the

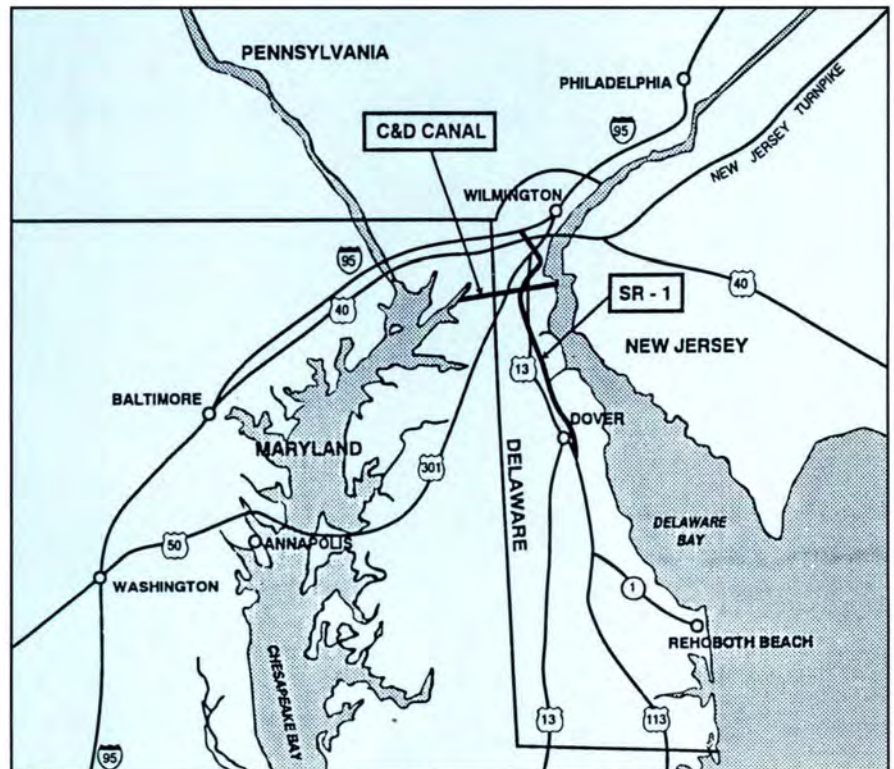


Fig. 2. Project location map showing C&D Canal Bridge in relation to the surrounding areas.

steel alternate at \$64,021,455 or about \$6.2 million more than the precast concrete alternate.

The cost of the precast concrete structure is \$64 per sq ft for the approach spans and \$117 per sq ft for the 1650 ft (503 m) cable-stayed main span unit.

DESIGN FEATURES

The bridge geometry was governed by the required 450 ft (137 m) horizontal and 138 ft (42 m) vertical navigational clearances in the canal. The main span length of 750 ft (229 m) was chosen so that the main piers

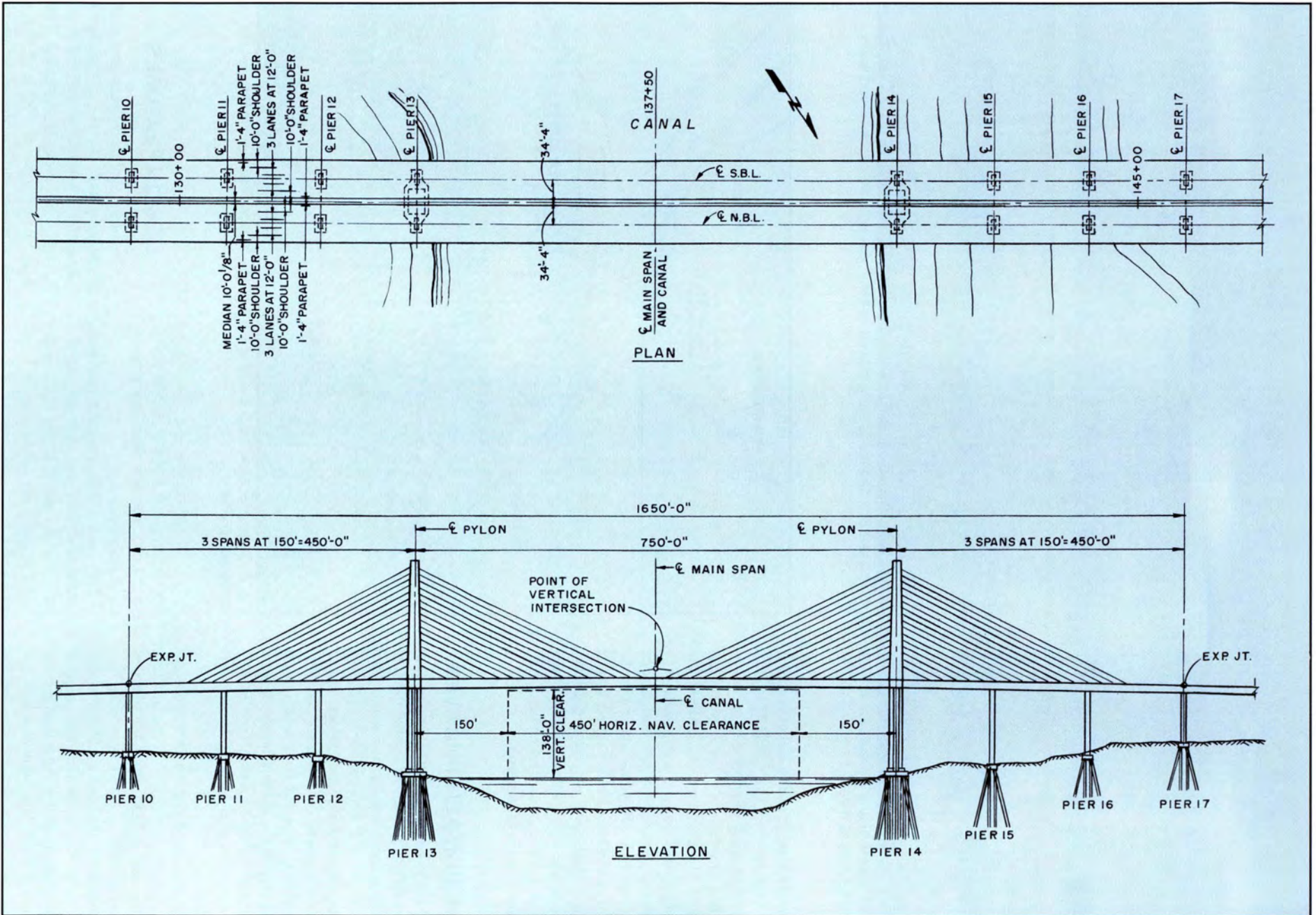


Fig. 3. Plan and elevation of the 1650 ft (503 m) main span of cable-stayed unit.

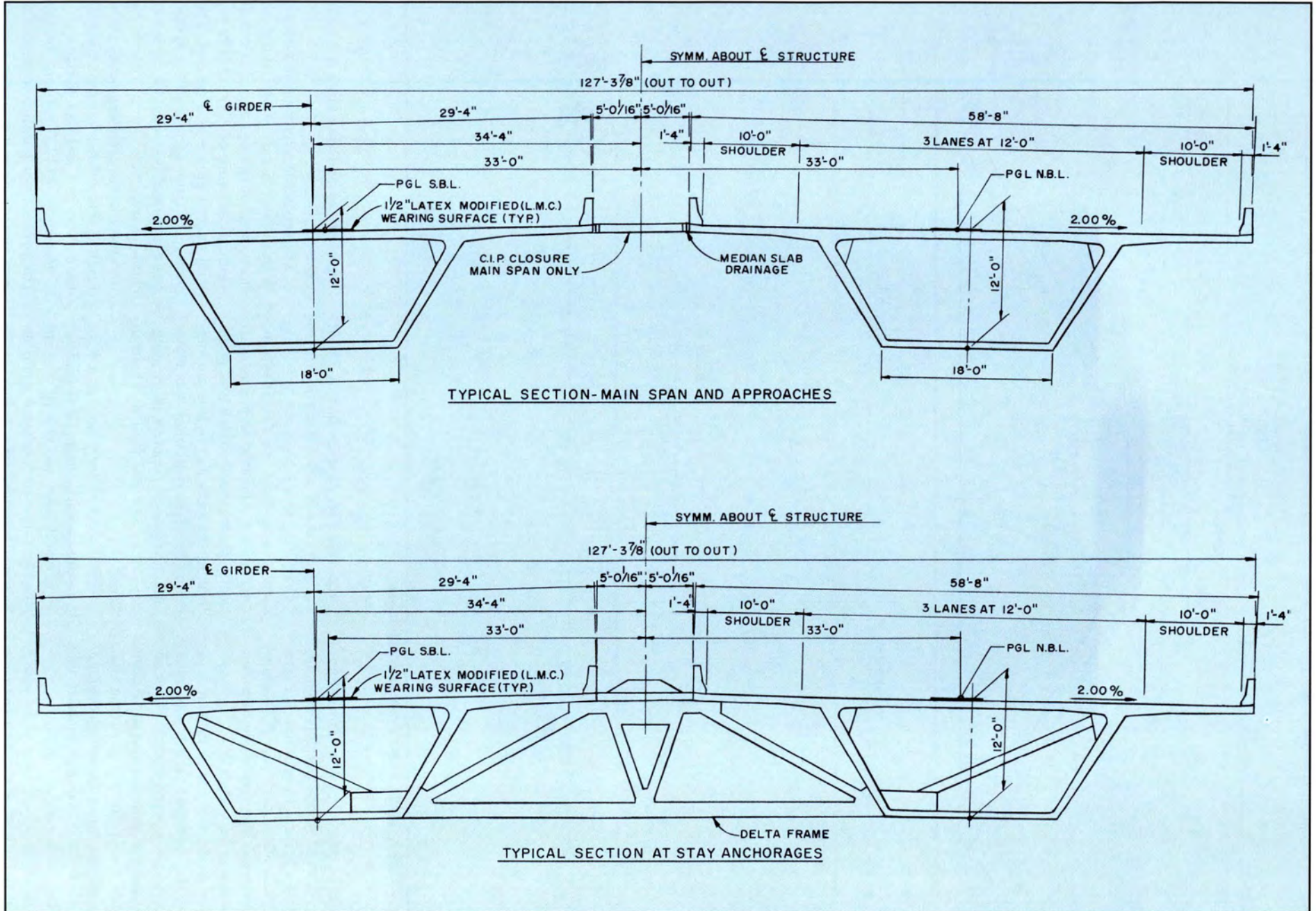


Fig. 4. Typical section of main span and approach spans (top) and typical section at stay anchorages (bottom).

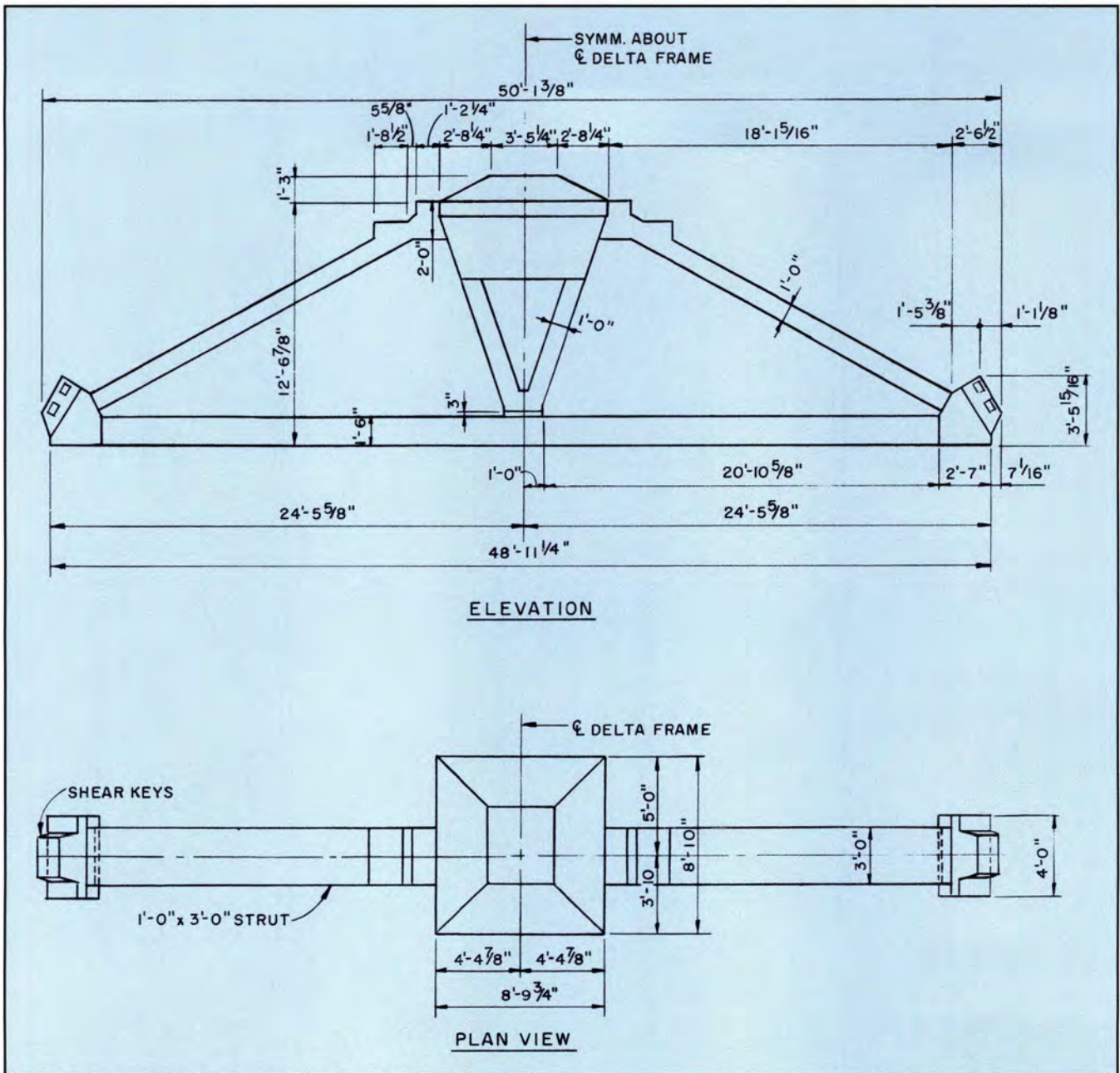


Fig. 5. Plan and elevation of precast delta frame.

would be on land to provide solid protection from vessels possibly colliding with the bridge. In addition, the construction of the main pier foundations on land was less expensive than construction in the waterway.

The most economical structural solution for this span length was found to be a cable-stayed bridge. The innovative use of a single plane of 16 cable stays at each pylon to support the main span creates a smooth and graceful appearance that blends the structure into the landscape and horizon.

The cable-stayed main span unit is 1650 ft (503 m) between expansion

joints (see Fig. 3), providing a 750 ft (229 m) main span from pylon to pylon. The spans between the abutments and pylons are 150 ft (46 m) long and are supported on precast, vertically prestressed, voided box piers. In turn, the piers and pylons are supported by 24 in. (610 mm) square precast, prestressed concrete piles, ranging from 23 to 102 ft (7 to 31 m) in length.

The project requirements called for a roadway with three 12 ft (3.7 m) wide travel lanes and two 10 ft (3 m) shoulders in each north and south direction. The bridge deck width (includ-

ing roadway and shoulder) is 127 ft (39 m).

The geometric alignment provides a high degree of safety by having no horizontal curvature and a minimal vertical curvature of 1900 ft (579 m) with tangent grades of 3 percent. The transverse cross section of the bridge has a constant cross slope of 2 percent with no super-elevation transitions into the roadway embankments. As a result of this geometry, a motorist will have a very safe and smooth ride.

The 4650 ft (1417 m) long bridge comprises twin parallel trapezoidal box girders. Each box girder is 58 ft

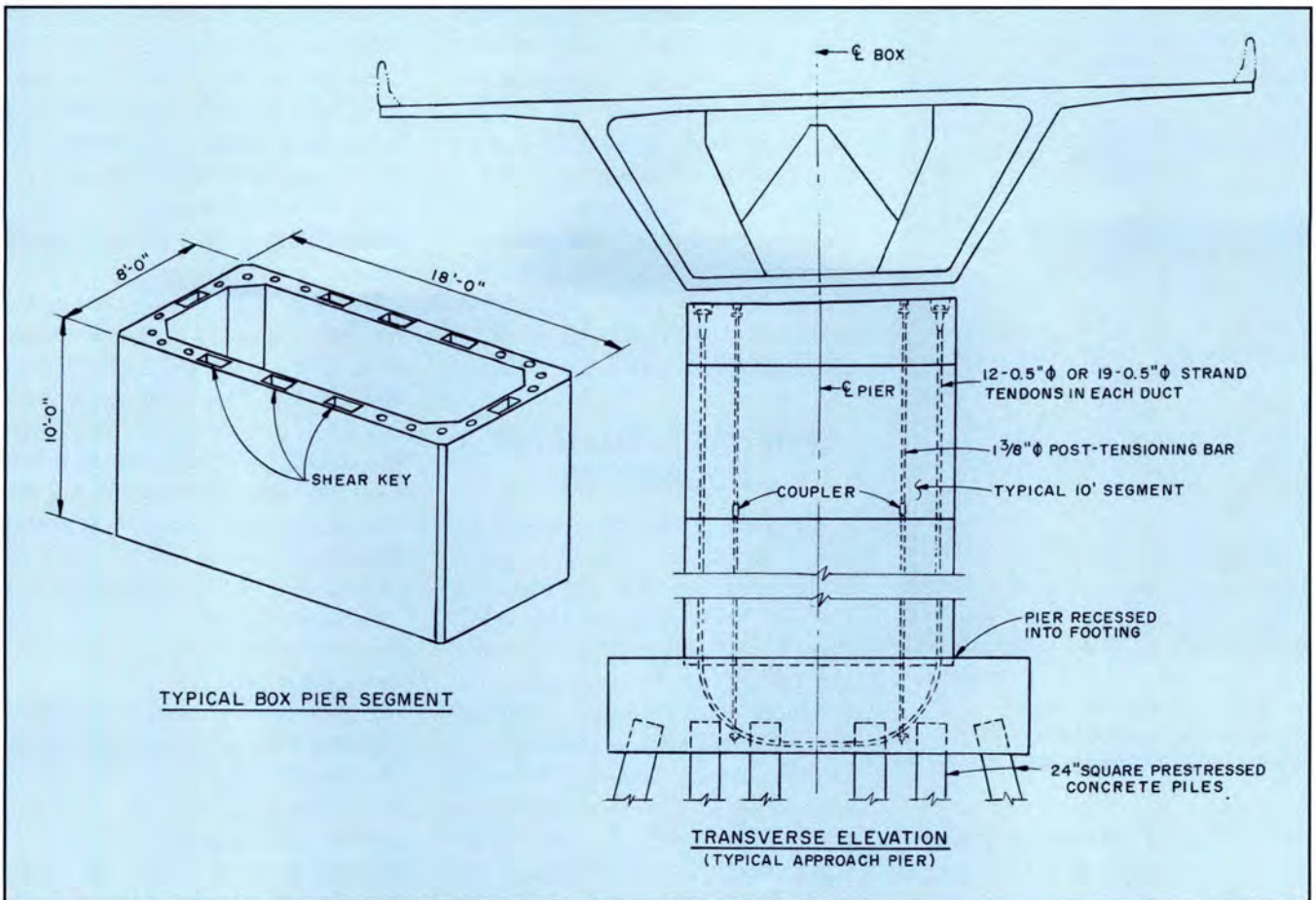


Fig. 6. Typical box pier segment (left) and transverse elevation of approach pier.

8 in. (18 m) wide and 12 ft (3.6 m) deep. A typical segment is 10 ft (3 m) long, has a cross-sectional area of 90 sq ft (8.4 m²), and weighs about 70 tons (63 t). In all, 984 superstructure box girder segments were used. Typical box girder spans have six external tendons with 31 1/2 in. (13 mm) diameter strands each, and two external tendons with seven 1/2 in. (13 mm) strands. It should be emphasized that the parallel box girder spans act independently in the approach spans but in the main span they are integrated with a cast-in-place median slab, as shown in Fig. 4 (top).

A major feature of the design is the use of precast delta frames to tie the box girders together in the main span unit. These delta frames not only provide a structural connection between the box girders but also provide the anchorage for the cable stays. Importantly, they allow the same cross-sectional shape of the box girders to be used in both the approach spans and the main span. The location of the delta frame is shown in Fig. 4 (bot-

tom) and a detailed plan and elevation of this element is depicted in Fig. 5.

Another major design feature of the bridge is the use of precast concrete box pier segments that are vertically

post-tensioned (see Fig. 6). These pier segments were match cast in lengths of 4, 5, 6, and 10 ft (1.22, 1.52, 1.83, and 3.05 m) and weigh up to 37 tons (34 t). A typical 8 x 18 x 10 ft (2.44 x

Table 1. Particulars of bridge and principal dimensions and other details of precast concrete components.

Total length of bridge including approach spans	4650 ft
Total area of bridge deck	562,100 sq ft
Number of superstructure spans	27
Length of main span	750 ft
Length of approach spans (typical)	150 ft
Navigational clearance	
• Vertical	138 ft
• Horizontal	450 ft
Box girder segment (typical)	10 ft long x 58 ft 8 in. wide x 12 ft deep
Number of box girder segments	984
Delta frames	48 ft 11 1/4 in. long x 13 ft 9 1/8 in. (weighing about 100 kips)
Number of delta frames	72
Box piers	8 x 18 ft (cast in 4, 5, 6, and 10 ft lengths)
Number of box piers	463
Piles	24 in. square
Number of piles	912

Note: 1 ft = 0.3048 m; 1 in. = 25.4 mm; 1 sq ft = 0.0929 m²; 1 sq in. = 645.2 mm²; 1 kip = 4.448 kN.



Fig. 7. Overall view of the precasting yard showing various precast components being prepared for shipment to the bridge site.

5.49 x 3.05 m) box segment is shown in Fig. 6 (left). The voided rectangular shape of the boxes provides the necessary strength to carry the superstructure while the low weight of the voided section reduces the number of required piles. In all, 463 precast box pier segments were used.

A total of 912 precast, prestressed concrete piles were used with a total driven length of 65,023 ft (19,820 m). The 24 in. (610 mm) square piles are pretensioned with 1/2 in. (13 mm) diameter strands to a force of about 700 kips (3,100 kN). A typical pile group has four vertical piles and eight battered piles.

The foundations for the main pylons have 118 vertical piles and 12 battered piles with a 4 ft (1.2 m) typical distance between the center of the piles. The pylon foundations also support the two adjacent box piers.

The main pylons have a six-sided cross section 10 ft (3.05 m) wide and a longitudinal length varying from 18 ft (5.5 m) below the deck to 12 ft (3.7 m) at the top. The pylon height is 322 ft (98 m) above the top of the foundation.

PRECAST CONCRETE OPERATIONS

All of the precast concrete components (see Table 1) for the entire bridge were fabricated at Bayshore Concrete Products Corporation, a PCI Plant Certified Member with many years of excellent performance. The Bayshore plant is located about 180 miles (290 km) south of the bridge site in Cape Charles, Virginia. This made it convenient to transport the precast concrete components by barge up the Chesapeake Bay and through the canal. Tow times were approximately 30 hours.

Four primary precast concrete components were produced by Bayshore:

- Piles (912)
- Box pier segments (463)
- Trapezoidal box girders (984)
- Delta frames (72)

Piles — All 912 24 in. (610 mm) square piles were fabricated within a 12-month period. They were cast in lengths of 23 to 102 ft (7.1 to 31 m) depending on the soil conditions. The casting of the piles required the use

of two 500 ft (152 m) casting beds. Steam curing was applied to the fresh concrete to achieve sufficient concrete strength [5000 psi (34 MPa)] to release and turnover the beds every day. Upon delivery to the site, the piles were driven with a single acting diesel hammer, all within a 13-month period.

Box pier segments — In all, 463 box pier segments were cast in lengths of 4, 5, 6, and 10 ft (1.22, 1.52, 1.83, and 3.05 m). They were cast within a 16-month period. The precaster used two casting cells for the production of these elements. Steam curing was also used to accelerate the strength gain of the concrete, which enabled each form to be turned over every day. The typical production rate for these elements was two segments per day or ten segments per week.

Jigs were used in staging areas to fabricate the reinforcing steel cage for the box pier segments. The use of these jigs created an assembly line process that increased the productivity and efficiency of the casting operation. The cages were pre-tied in the jigs and then set into place around the inner core form. After the cage was set, post-tensioning ducts were secured and the outer core form was placed. Concrete was then placed inside the forms and the segment was steam cured overnight. This cycle was then repeated the following day.

Trapezoidal box girders— A total of 984 box girders were fabricated. They were designed so that the basic external cross section of the approach spans and the main span were identi-



Fig. 8. Box pier segments had a one-day casting cycle. A total of ten segments were produced in a 5-day work week, using two forms.



Fig. 9. Trapezoidal box girder segments were match cast to ensure tight tolerances during erection. In all, 984 such girder segments were fabricated.



Fig. 10. Precast delta frames were designed to tie the main span box girder segments together and provide anchorages for the cable stays.

cal. Consequently, expensive modification to the forms by the precaster was not required, saving time and cost.

The box girders fall within two major categories, namely, the approach superstructure segments and the main span segments. The two major categories are further broken down by subcategories as follows:

- Approach superstructure segments:
 - (a) Typical
 - (b) Pier
 - (c) Deviation
 - (d) Expansion joint
- Main span superstructure segments:
 - (a) Typical
 - (b) Stay anchor (strut)
 - (c) Pier
 - (d) Deviation
 - (e) Expansion joint

Segments were cast in 10 ft (3.05 m) increments which were then used to produce the 150 ft (46 m) typical and 750 ft (229 m) main spans of the bridge. The precaster utilized two sets of forms to cast the typical, deviation and stay anchor segments for both the approach spans and main span. One superstructure pier form was used to cast the pier and expansion joint segments. Changes to the interior of the girder, however, were achieved through the use of the inner core forms.

Steam curing also enabled the typical forms to be turned over once per

day for an average production rate of 10 segments per week. The pier form was typically turned over at a rate of twice per week.

Similar to the box column casting, jigs were used in staging areas to fabricate the reinforcing steel cage separate from, and in advance of, the segment production. The cages were pre-tied in the jigs and then set into place within the outer core form. The inner core form was then moved into place.

The transverse deck post-tensioning ducts were secured and the concrete was placed. The following day, the as-cast survey was performed and



Fig. 11. One of the 463 match cast box pier segments being placed. After setting the last segment in place, the entire precast unit was vertically post-tensioned.

the transverse post-tensioning tendons were stressed.

Delta frames — As previously noted, the 72 delta frames are an integral part of the main span and played a significant role in the entire design of the bridge. A single form was used to cast the delta frames. On average, one segment was produced every 3 days.



Fig. 12. Special superstructure segments were designed to rest on the precast post-tensioned piers.



Fig. 13. Approach span erection truss moving several precast box girder segments.

MAIN SPAN ERECTION METHOD

For ease of construction and minimal disruption to navigational traffic, the bridge was built from above. Erection was accomplished using two methods; an overhead erection truss was used for the 150 ft (46 m) approach spans and twin 200 ton (181 t) crawler cranes for the unidirectional cantilevers of the 750 ft (229 m) main span.

The back span portions leading up to each pylon were completed with the use of an overhead erection truss. This allowed the back span portion of the main span structure to be completed using the span-by-span erection method. This time-saving solution allowed the main span segments to be delivered over the previously completed back span. It also allowed unidirectional erection of the center span from above, which provided minimal disruption to the navigational traffic within the canal.

The 150 ft (46 m) back spans are identical in length to the approach spans. Each span consists of fourteen 10 ft (3.05 m) segments, two 4 ft 6 in. (1.4 m) pier segments and two 6 in. (152 mm) closure joints. A longitudinal and transverse post-tensioning system precompresses the completed spans.

The typical erection cycle for completing a 150 ft (46 m) span took about 3½ days. This further empha-

sizes the advantage of using precast concrete elements and demonstrates the speed of erection that can be obtained with this type of construction. With the back spans complete up to the pylon or edge of the canal, the unidirectional scheme for erecting the cantilevers from each side began.

The erection of the main span cantilevers was accomplished through the use of twin 200 ton (181 t) crawler cranes that simultaneously erected the northbound and southbound trapezoidal box girders. The south cantilever of the center span was built first, cantilevering out 375 ft (114 m) over the canal. Both the northbound and southbound box girders of the



Fig. 14. Twin 200-ton (181 t) crawler cranes positioning trapezoidal box girder segments.

cantilevers have segments with 6 in. (152 mm) cast-in-place closure joints at four locations.

MAIN SPAN CANTILEVER CONSTRUCTION CYCLE

The construction method adopted using precast concrete elements allowed the erection of the bridge to exceed typical erection times for this type of structure. The erection cycle consisted of:



Fig. 15. Precast box girder segments cantilever from one of two main pylons.

- Erection of four precast roadway segments
- Erection of a precast delta frame
- Installation and stressing of a cable stay

In this way, each cycle completed 20 ft (6.1 m) of cantilever per cycle.

The cycle time on the north cantilever was less than the south cantilever, mainly due to the diminished construction learning curve. Even though the north cantilever was built primarily during the winter months, the cycle time was reduced on average by one working day.

The south cantilever was completed in 108 working days with an average working cycle of 5 days. The north cantilever was completed in 79 working days with an average working cycle of 4 days.

The stay cables of the C&D Canal Bridge were fabricated from up to 85 prestressing strands, 0.6 in. (15 mm) in diameter. They are continuous from one deck anchorage, over a curved concrete saddle in the pylon, down to the opposite deck anchorage. The stay cables are encased in a grouted steel pipe for corrosion protection.

Figs. 7 through 18 show various construction stages of the bridge from fabrication of the girder segments to erection of the superstructure.

Construction began in April 1992 with installation of the piles and foundation. The bridge is scheduled for completion in September 1995, as agreed upon in the contract.

ADVANTAGES OF PRECAST CONCRETE

Function, economy and aesthetics were the primary focus for the successful completion of the C&D Canal Bridge. Several key points regarding the overall design and construction solutions for this bridge merit emphasis:

- Precast concrete shapes saved \$6.2 million (or about 10 percent) of the total project cost at the time of bid, when compared to the low bid for structural steel construction.
- The use of precast concrete elements proved to be an efficient and cost effective method for the economical design solution of the bridge.
- This structure is the first precast



Fig. 16. Marine traffic proceeds unimpeded while construction continues above.



Fig. 17. Placement of final two box girder segments.

segmental cable-stayed bridge to be completed in the northeast United States.

- Construction proceeded routinely and on schedule without any undue difficulties.
- The unique method of erecting precast, prestressed concrete box girder elements from above using the twin 200 ton (181 t) crawler cranes resulted in minimal disruption of shipping traffic in the canal below.
- The unique design of the back span and approaches provided the contractor with unhindered access for uni-directional erection of the main spans.

- The use of precast delta frames allowed for a single plane of cable stays, use of one cross-sectional box girder shape and combined the twin box girders making the structure into a single bridge.
- Precast, prestressed box pier segments aided in the simplicity and timely construction of the substructure. Typically, 100 ft (30 m) of box pier was built in one day.
- All of the precast concrete components (including piles, pier segments, trapezoidal box girder segments and delta frames) were manufactured and delivered to the site by a PCI Plant Certified Member.



Fig. 18. Panoramic view of the nearly complete C&D Canal Bridge.

CONCLUDING REMARKS

The C&D Canal Bridge is a prime example of the efficient and economical use of precast, prestressed concrete for cable-stayed bridges with long spans and wide roadway sections. One advantage of this type of structure is that a common cross section can be used for the approach spans as well as the main span, thus permitting the casting of all the segments by the same set of casting machines.

Additional cost savings were obtained by constructing the transition spans in the same manner as the approach spans with the span-by-span method of erection instead of the relatively slow balanced cantilever method. The uni-directional cantilever erection of the center span is more efficient because the transportation of equipment, materials and segments can be done over the completed approach and transition spans.

The precast, prestressed delta frames are the single most important feature of the structure because they integrate the twin parallel trapezoidal box girders (making the main span into a single bridge), comprise a part of the cable-stay anchorage system that supports the main span, and allow the same cross-sectional shape of box girder segments to be used for both the approach spans and the main span.

The C&D Canal Bridge won PCI's Harry H. Edwards Industry Advancement Award for 1995. This was the jury's citation:

"This precast segmental bridge with a 750 ft (229 m) main span contains an innovative delta frame concept to reduce the size of the main span and back span boxes, and to provide the anchor for the cable stays at deck level. By keeping the same precast concrete box section in both the approach spans

and the main spans, weights and construction costs were significantly reduced."

Lastly, and most importantly, the design innovations and construction techniques employed in this bridge represent an advance in engineering design and technology that will carry precast, prestressed segmental cable-stayed bridges well into the next century.

CREDITS

Owner: Delaware Department of Transportation, Dover, Delaware

Structural Engineer (providing both design and construction engineering inspection services): Figg Engineering Group, Inc., Tallahassee, Florida

General Contractor: Recchi America, Inc., Miami, Florida

Precast Concrete Manufacturer: Bayshore Concrete Products Corporation, Cape Charles, Virginia