Northumberland Strait Crossing: Design Development of Precast Prestressed Bridge Structure

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The authors describe the design development process of the $840 million (Canadian dollars) Northumberland Strait Crossing Project from conceptual design in 1987 to the final project design. The 13 km (8 mile) long bridge links Prince Edward Island with New Brunswick and mainland Canada. The current design is based on main bridge spans of 250 m (820 ft) to minimize the number of piers and foundations in the Strait. Each span consists of a continuous precast, prestressed concrete variable depth double cantilever girder with a length of 190 m (623 ft) and a drop-in segment of 60 m (197 ft). The design took into consideration unusually heavy vehicle loads, high wind loads, seismic factors, very high icepack forces and possible ship collisions. Precast concrete production began in the summer of 1994 and the main spans will be erected beginning in September 1995. The project is scheduled for completion in the summer of 1997.

The Northumberland Strait Crossing Project (NSCP) is a 13 km (8 mile) long bridge (see Fig. 1), with associated approach roads and shoreside facilities, joining Prince Edward Island to New Brunswick and mainland Canada (see Fig. 2). The total capital cost of the project is approximately $840 million (in Canadian dollars).

Known to the local citizenry as the Fixed Link, it has been a desire of the island residents to have efficient and effective transportation to the mainland ever since Prince Edward Island joined Canada in 1873. In fact, in negotiating the Terms of Confederation, the Federal Government of Canada promised to promote efficient communication between the island and the mainland, a promise that has been fulfilled by the payment of annual subsidies to support the island ferry service from 1877 to the present.

This subsidy, which had reached $41.9 million annually by 1992, is not sufficient, however, to overcome the storms and ice conditions that plague the ferry in the winter (see Fig. 3) and the long lineups, which discourage travelers and disrupt commercial transportation in the summer. In addition,


Fig. 1. Artist's rendering of the Northumberland Strait Crossing Bridge.

increases in traffic demand and in operating costs guarantee that this subsidy will continue to increase over time.

The Federal Government of Canada, through Public Works Canada (PWC), has been studying the potential for a Fixed Link to replace the ferry service for many years. One such effort in the mid-1960s went as far as purchasing the right-of-way and constructing the approach roads on either side of the Strait (see Fig. 4).

In 1987, prompted by the receipt of three unsolicited proposals from private industry to build the link during the mid-1980s, PWC proceeded with a series of ten further studies to determine the economic, structural, environmental and financial viability of the link. In June 1987, PWC requested expressions of interest and qualifications from potential design-build-finance teams for the project. Twelve teams submitted proposals and seven were prequalified.

The successful bidder for the project was led by W. A. Stephenson Construction of Calgary, later to become known as Strait Crossing Inc. (SCI). This article describes the development of the Strait Crossing, especially the main bridge design, from the initial prequalification in 1987 up to the final project design in 1993.

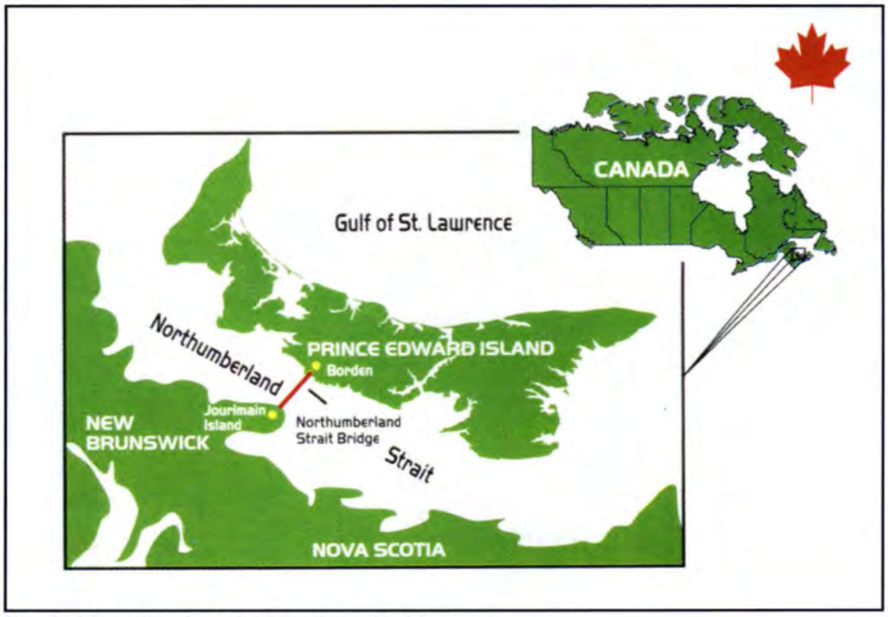

Fig. 2. Map showing site location of bridge.

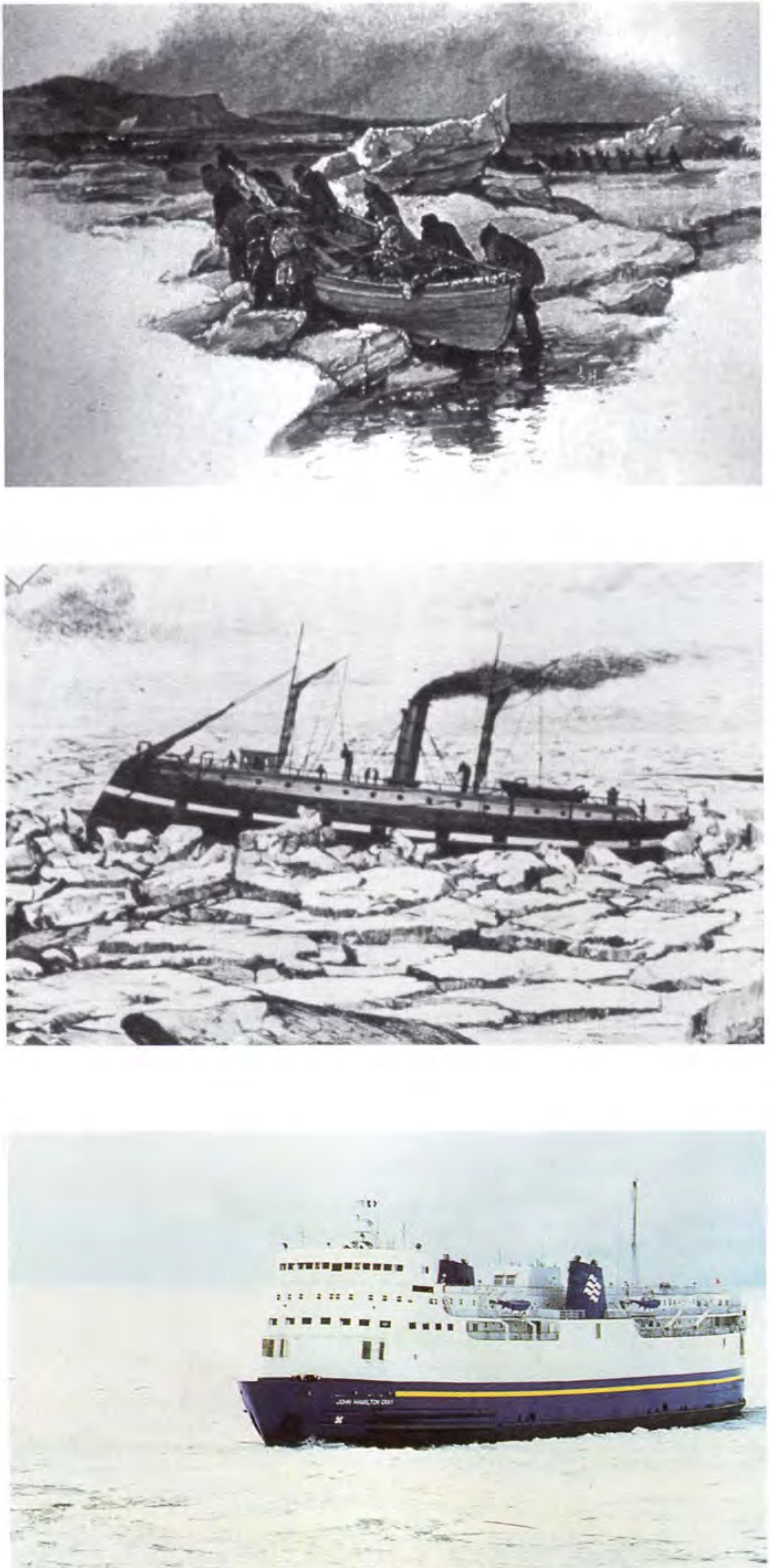

Fig. 3. Ferries in winter ice — a 100-year-old problem.

PROJECT REQUIREMENTS

A detailed set of project requirements, including design and construction specifications, operating and performance requirements, and environmental planning and assessment criteria, was first published by PWC in March 1988. As the project progressed through several years of studies, hearings, design and development, the detailed requirements were revised numerous times but the general content remained for the most part the same.

The bridge portion of the Link will consist of a two-lane roadway, 11 m (36 ft) wide between Cape Tormentine, New Brunswick, and Borden, Prince Edward Island (see Fig. 2). The bridge is to be financed, designed, constructed, operated and maintained by the Developer for a period of 35 years, after which ownership will be transferred in as-new condition to the government of Canada. The design service life of the bridge is to be 100 years.

In addition to carrying vehicle traffic, the bridge is also to act as a utility corridor for electrical services, telephone service and other utilities to the island. To minimize ice deposition on the roadway, the minimum height of the roadway above sea level at the approach spans is 16 m (52 ft). The typical spans require a minimum clearance below the structure of 28 m (92 ft) to allow for the passage of fishing and recreation vessels, while the navigation span was specified to have a vertical clearance of 49 m (161 ft) over a width of 200 m (656 ft). All piers subject to ship collision must be protected against damage from aberrant vessels. Minimum span lengths to avoid ice jamming during the winter and the delay of ice-out in the spring were specified to be 150 m (492 ft) for the typical spans and 80 m (262 ft) for the approach spans.

Roadway grades were specified to be a maximum of 4 percent with a desired grade of 2 percent. Design vehicle loads were based on the Canadian Standards Association S6 Code and on the Ontario Highway Bridge Design Code. A very critical element in the planning process was that a substantial amount of the information that was essential for

Fig. 4. Prince Edward Island in background; New Brunswick approach constructed in 1967 in foreground.

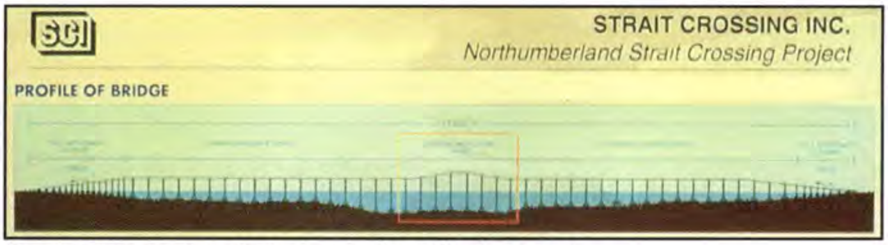

Fig. 5. Cross section of Northumberland Strait crossing.

the design of the bridge was neither known nor specified by PWC. Information with respect to geotechnical conditions, seismic factors, wind, waves and currents, ice loading, vessel collision loads and load or resistance factor calibration were all the responsibility of Strait Crossing and were the subject of extensive investigations and studies in the period from 1988 up to and including the final design. In order to determine the appropriate ice loading, for example, more than ten consulting firms and internationally renowned ice experts were retained for advice.

Appropriate experts were also retained to deal with each specific design parameter. Their input was utilized in a detailed calibration process that, based on the degree of certainty of both the loading and the resistance of the structure, determined the appropriate load and resistance factors to be used in the design. This process is considered far more rational than the application of arbitrary load and resistance factors, such as those specified in published bridge and building codes, but it is also an iterative process that cannot be finalized until the behavior of the structure to each load is predicted. This adds significantly to the complexity and schedule of the design.

The calibration process was aimed at achieving a target reliability index β of 4.0 for those portions of the structure considered to be multi-load path (such as flexural design of the deck) and 4.25 for those portions of the structure considered to be single load path (such as sliding resistance of the pier bases). Both ultimate limit states and serviceability limit states were analyzed probabilistically using the calibration process.

The reliability factor inherent in most North American bridge codes is approximately 3.5, making the NSCP the most reliable bridge structure design in North America. The safety and reliability of the Link is further enhanced by the specification of a 100-year design life vs. the normal 50-year life. This has a significant effect on both the number of cycles of load that must be resisted and on the durability requirements of the design.

Finally, the project requirements stated that the failure of any one span must not result in the progressive collapse of other spans, obviously a significant concern for such a long structure.

SITE DESCRIPTION

Northumberland Strait is a relatively shallow salt water channel separating Prince Edward Island (PEI) from Atlantic Canada. Water depths average 15 to 20 m (49 to 66 ft) with a maximum depth of 33 m (108 ft). Along each shore are shallows with depths up to 8 m (26 ft) (see Fig. 5).

The shoreline at each side of the Strait consists of low banks 3 to 5 m (9.8 to 16 ft) high of exposed weathered bedrock suitable for support of the abutments. In the shallow waters along each shore, medium span approach structures will be constructed to the point where the water depth reaches 8 m (26 ft), suitable for the operation of heavy marine equipment.

The length of the main bridge is approximately 11 km (6.7 miles). The PEI approach is 720 m (2362 ft) and the New Brunswick approach is 1440 m (4724 ft). Total length abutment-to-abutment is approximately 13 km (8 miles).

The sea floor generally consists of up to 3 m (9.8 ft) of clay till overburden over bedrock. The bedrock is made up of relatively soft layers of

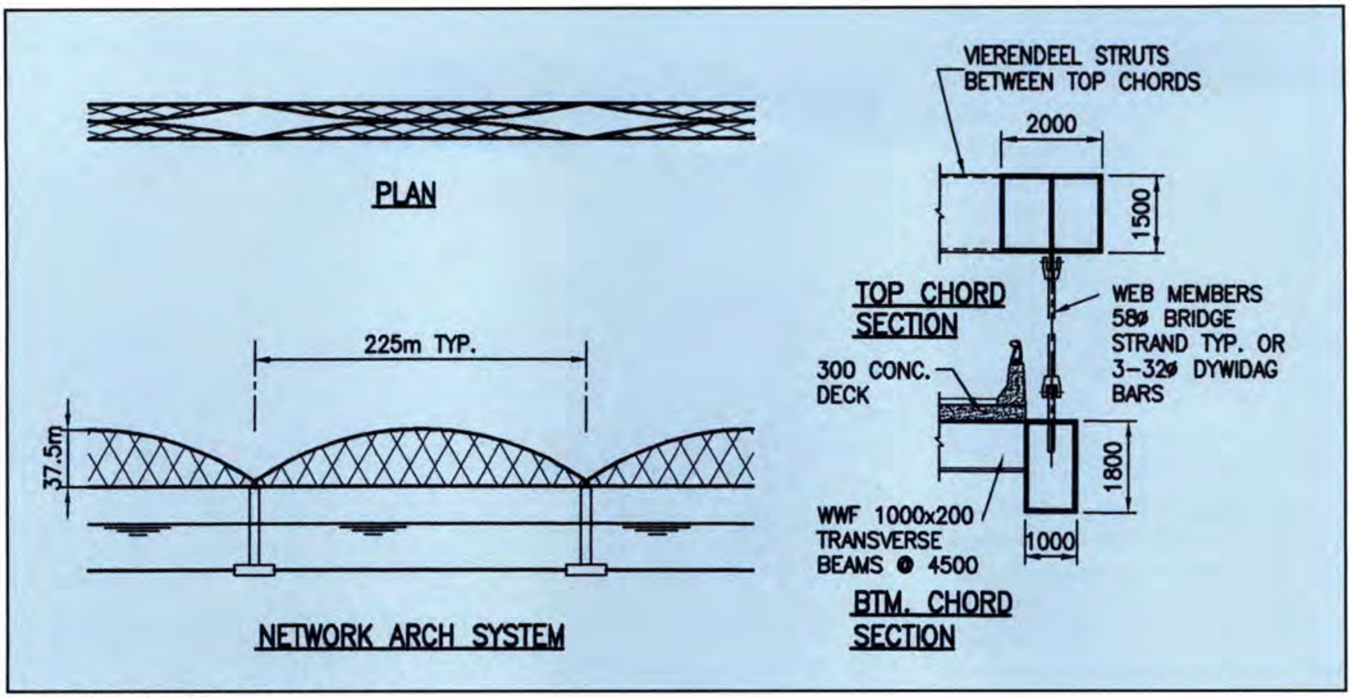

Fig. 6. Plan of network arch concept.

sandstone, siltstone, and mudstone. The mudstone, which is discontinuous, has very low shear strength and is a critical factor in the design.

Harsh climate conditions exist in the Strait, which freezes over in the winter. Stationary landfast ice forms along each shore while a shifting icepack, driven by wind and tidal currents, with extreme ridges up to 2 m (6.6 ft) thick, moves back and forth at speeds up to 2 m/s (6.6 ft per second). The presence of this ice dictates that any structure element placed in the Strait must be completed prior to the onset of winter.

Ice clearing generally occurs in late March or early April and marine construction operations are only possible from May to November. High winds, tidal variations up to 4 m (13 ft), and waves up to 2 m (6.6 ft) high must be dealt with during these operations.

A critical design condition is the very high lateral loads from pack ice in the Strait and from the wind. These loads, which were not fully determined until the final design stage, are in the order of 30 MN [3000 t (3307 tons)] per pier fully factored. They must be resisted by the bedrock below the Strait. Of critical concern was the need to prevent the layers of mudstone from sliding failure by either piling to pin the layers together or by clamping the layers with sufficient vertical force. Also of concern was the overturning of the piers by wind loads on the deck applied as high as 70 m (230 ft) above the foundation.

DESIGN CONCEPT DEVELOPMENT

The single source responsibility of the Strait Crossing team for design, construction, financing, operation and maintenance of the bridge was a critical aspect in the design development.

Not only must the bridge be economical in terms of construction materials, a normal requirement for all structures, but the design had to be constructible in the harsh weather conditions of Northumberland Strait, one of the windiest places in Canada, with a short construction season due to cold weather and ice in the Strait. Further, in order to attract private financing to the project, the design and the construction methods would have to be reasonably well known and relatively risk-free, a major concern for such a large project built in salt water. Finally, in order to avoid jeopardizing the long term financial plan, operation and maintenance costs must be predictable and absolutely minimized, thereby dictating maximum durability of all components.

Table 1. Original 1987 design team.

Principal consultants
Stanley Associates Engineering Ltd.
Speco Engineering (Dr. Gamil Tadros)
Simpson Lester Goodrich Partnership
Specialists
Leonhardt Andrä and Partner (Bridge Design)
Dr. Walter Dilger (Bridge Design)
Golder Associates (Geotechnical)
C-Core (Ice/Waves)
Boundary Layer Wind Tunnel (Dr. Davenport) (Wind)
Dr. James MacGregor/Dr. Laurie Kennedy (Load Factor)
Dr. Robert Dewar (Ergonomics)

The full design team met for the first time in September 1987 (see Table 1) and set out the objectives that the successful design must satisfy. In addition to being economical, it was essential that the design: (a) be constructible within the available weather windows; (b) minimize work in the water by prefabricating as much as possible on land; (c) be historically proven; (d) be durable for 100 years; and, of course, (e) satisfy the specific project requirements of Public Works Canada.

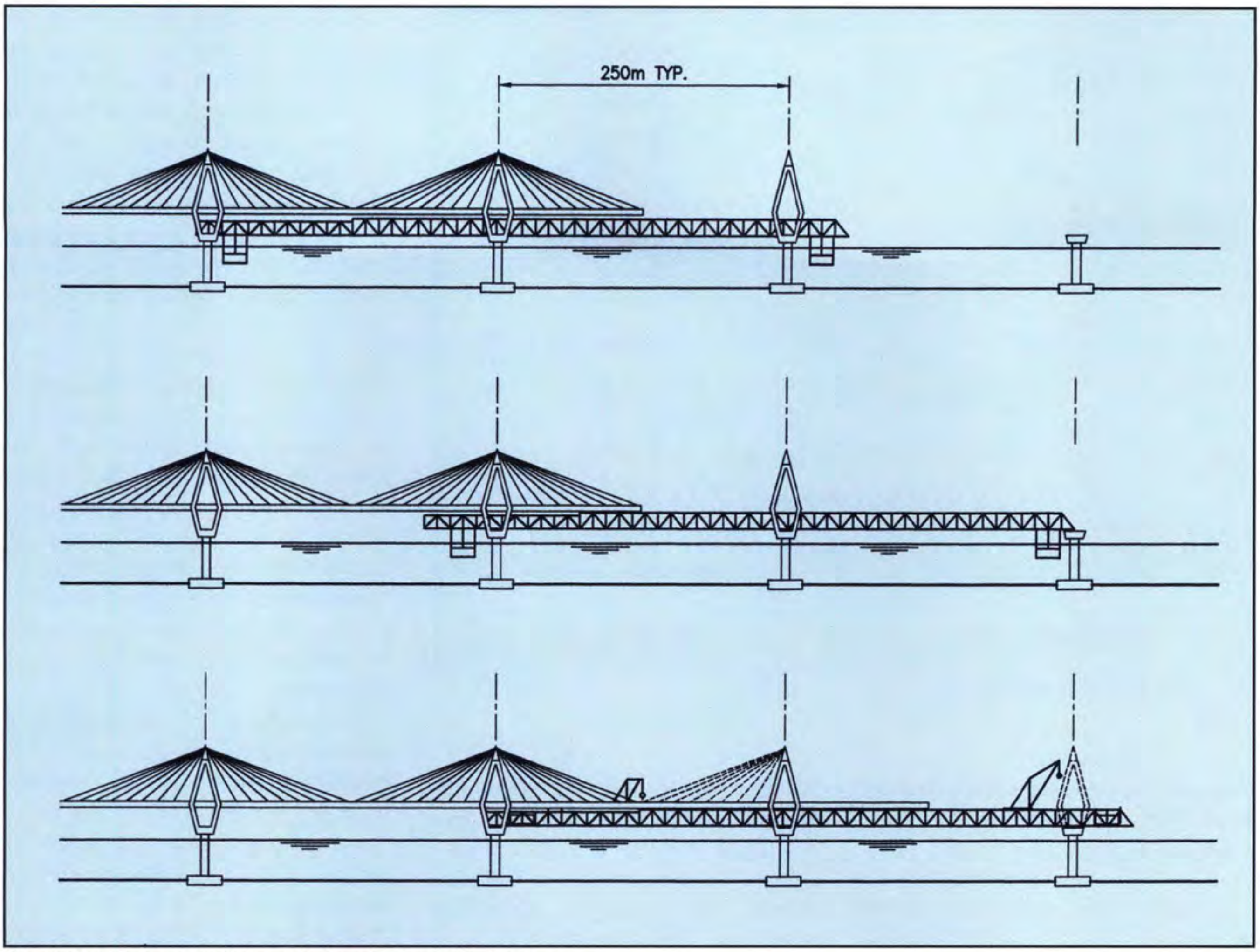

Fig. 7. Cable-stayed bridge with floating launching truss.

Superstructure Design Alternatives

A large number of options were reviewed during the winter of 1987-88. These alternatives included designs in different materials (steel, concrete, and steel-concrete composite construction); spans ranging from 150 to 275 m (492 to 902 ft); and a wide variety of different structural systems, including several cable-stayed solutions.

The design of the structure differs from conventional design in that there are many repetitive spans, unusually heavy vehicle loads, high wind loads, and very large ice forces. The large horizontal forces due to wind and/or ice required innovative solutions to the foundation design. In the following sections, the various alternatives that were studied are presented and the associated advantages and disadvantages are discussed.

Steel Design

Earlier design attempts in the 1950s and 1960s had concentrated on steel systems, and in the 1980s steel was again considered by the Strait Crossing team. Trusses, box girders and network arches were all studied in detail.

The steel options all shared many desirable advantages that fit the design team's criteria, such as prefabrication and proven technology. But there were also a number of serious drawbacks to steel including long-term maintenance costs, the need for expensive pile foundations due to the relatively light weight of the structures, and a lack of local Atlantic Canada content.

Through trusses and network arches (see Fig. 6), spanning up to 225 m (738 ft), were considered to be psychologically disturbing for drivers over such a long distance and were also relatively unstable due to the narrow roadway width. Steel box girders, while solving these problems, raised concerns with respect to vibration problems in the high winds prevalent at the site. No steel design was found that matched the economic advantages of concrete.

Concrete Design

Only two concrete options were considered: a simple span box girder system using constant depth 8 m (26 ft) deep girders spanning 150 m (492 ft), and a continuous variable depth box girder spanning up to 225 m (738 ft).

Although 150 m (492 ft) was the minimum specified span, it was desirable to minimize foundation work in the water as much as possible and, therefore, to maximize the span length of any system under consideration. The continuous variable depth girder offered obvious economic and aes-

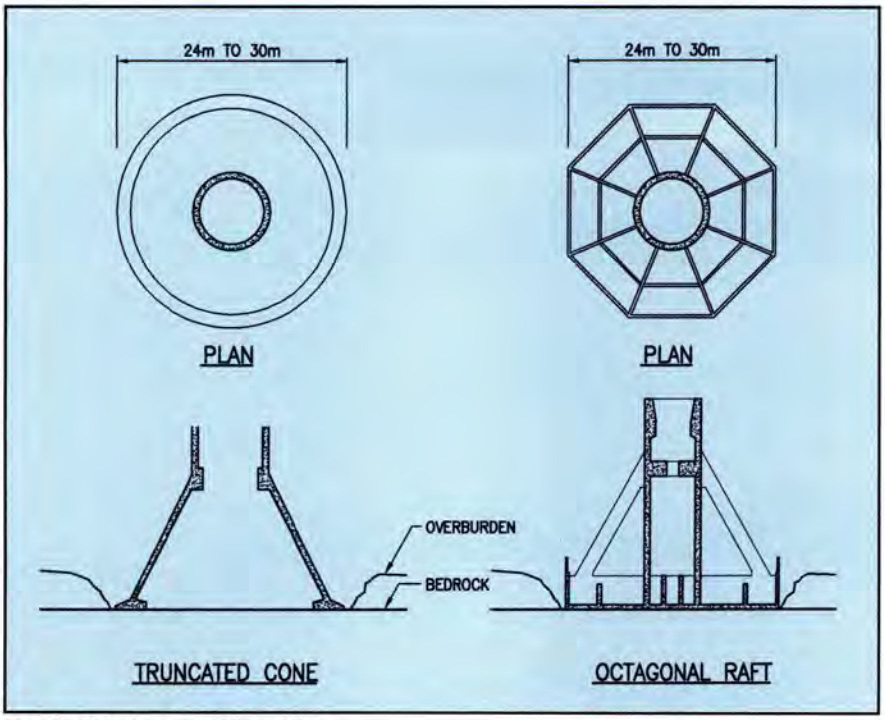

Fig. 8. Substructure alternatives.

thetic advantages over the constant depth girder.

Several different span lengths were analyzed in various combinations of continuous spans with and without drop-in sections. The conclusion was that the maximum possible span length would produce the most economical structure overall. In 1987, this maximum span length for a variable depth continuous concrete box girder was considered to be 225 m (738 ft).

Cable-Stayed Systems

Cable-stayed systems were also studied in detail. A cable-stayed bridge 13 km (8 miles) long differs from conventional cable-stayed bridges in that the back stays cannot be easily anchored. In addition, continuity of the cable-stayed spans was undesirable with respect to potential progressive collapse.

Two options were considered, one using a stiff tower system with a slender deck, the other using a stiff deck with a small number of cables.

Multiple Cable System With Slender Deck and Stiff Towers — For the stiff tower option, to provide the necessary stiffness for a 250 m (820 ft) span, a four-legged 45 m (148 ft) high framed tower, with the legs approximately 20 m (66 ft) apart in the longitudinal direction at the deck level was developed. With these geometric conditions, the unbalanced live load due to traffic did not generate any tension in the upper legs of the frame.

The framed towers would have sufficient flexibility in the longitudinal direction, however, to accommodate the deformations due to temperature, creep and shrinkage of one complete 250 m (820 ft) span. One 250 m (820 ft) span plus two 125 m (410 ft) cantilevers would form one structural unit with expansion joints at the ends of the cantilevers. The deck for this solution would consist of a slab with ribs in the transverse direction, edge beams 1.00 x 1.60 m (3.28 x 5.25 ft) in the longitudinal direction and a cable spacing of 12.00 m (39.4 ft) at deck level (see Fig. 7).

The head of the pylon would be built of steel. As an option, steel was also considered for the upper part of the frame. Corrosion protection of the stay cables would be provided by encasement in grouted polyethylene pipes. The very slender deck had the advantage of having a small wind resistance and a relatively small self-weight, which is beneficial with regard to the design of the cables and the towers.

Stiff Deck and Few Cables — The other alternative cable-stayed system was based on use of a stiff deck. For structures that derive their stiffness mainly from the deck, a reduced number of larger diameter cables can be used. Structures with one or two cables on each side were analyzed and designed for 250 m (820 ft) spans. The respective depths of the concrete box forming the deck were 4.0 and 2.5 m (13.1 and 8.2 ft). These decks are heavier but result in smaller forces in the towers. As in the multiple cable system with stiff towers, the flexibility in the longitudinal direction is such that the longitudinal deformations of a span up to 250 m (820 ft) in length can be accommodated. This means that the expansion joints and shear keys would be provided in the middle of every second span.

As a further option, a very stiff deck with five closely spaced cables, acting effectively as a single cable, supporting a 6.0 m (19.7 ft) deep box girder was considered. It would cantilever 110 m (361 ft) on each side of the tower and support 55 m (180 ft) long drop-in beams of 3.0 m (9.8 ft) depth at each end. The 6.0 m (19.7 ft) girder would be rigidly connected to the tower.

The advantage of this stiff girder is that it could be fabricated, together with the tower, on shore and floated into position as one unit. The 55 m (180 ft) drop-in girders would also be fabricated on shore and lifted into position after the main girders were connected to the towers. This system would result in 275 m (902 ft) spans from tower to tower. This very stiff deck option was found to be close in cost to the haunched concrete box girder and was considered to be a viable second choice.

The major disadvantages found in all of the cable-stayed solutions that were investigated were scheduling, the costs associated with an extended construction schedule, and potential risk.

Substructure Systems

The design of the foundations would be dictated by the enormous horizontal loads and overturning moments due to

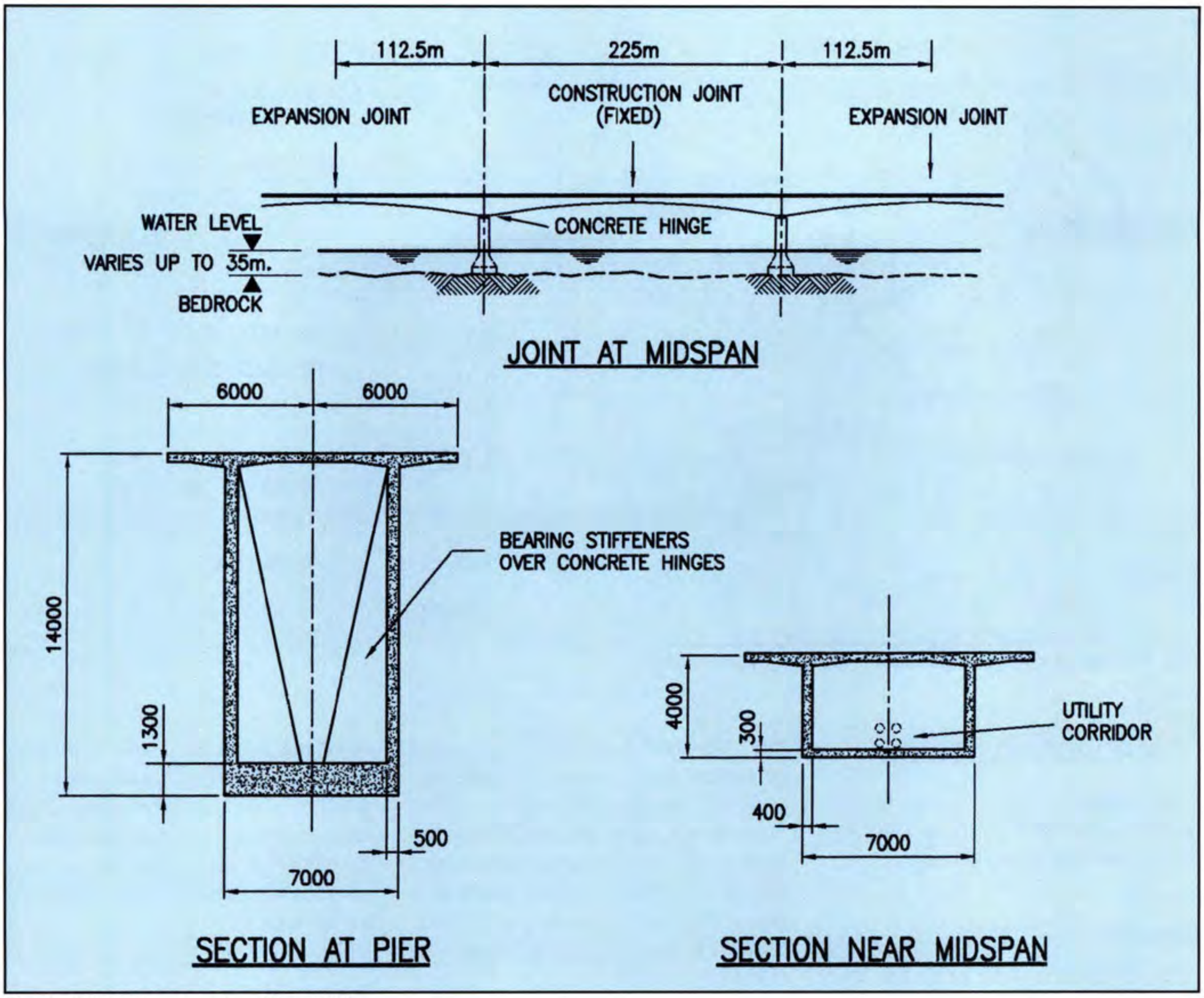

Fig. 9. Original proposal — May 1968.

ice and wind up to 3000 t (3308 tons) per pier applied near the waterline. While it was obvious that these forces could be resisted using pile foundations or rock anchors, these systems would require substantial construction operations to be carried out over extensive time periods in the inhospitable conditions of the Strait.

From the outset, a decision was made to use a gravity foundation system that would utilize large prefabricated footings bearing directly on the bedrock. The size of the footing was dictated by bearing pressures and overturning in the bedrock. Sliding failure of the soft mudstone was to be prevented by imposing sufficient vertical load, including ballast if necessary or internally installed rock anchors, to mobilize the internal friction of the mudstone.

One option was an inverted truncated cone supported by an annular ring around the perimeter; the other option was an octagonal raft footing using inclined ribs to support the pier. Either system was acceptable from a design viewpoint; the final choice would be dictated by the installation method to be determined later (see Fig. 8).

Construction Methods

The design of the bridge at every stage would be intimately related to the method of construction. Cast-in-place segmental construction, precast concrete segmental construction, incremental launching and floating/erection of completed sections were all reviewed. Cast-in-place segmental construction was quickly rejected for reasons of schedule and cost, largely as a result of the difficult climate conditions.

Precast concrete segmental construction, while given much more consideration, was also rejected due to the desire to carry out as much work as possible on shore in order to minimize the risk of construction. Incremental launching was considered obviously unsuitable for the main spans but was originally considered to be the most appropriate method for the shorter approach spans.

The floating and erection of completed components was determined to be the least risky and most likely to fit within the available weather windows for erection within two summer seasons. The choice of this system of construction would make the lifting capacity of the heavy marine erection equipment a key element in all future design developments.

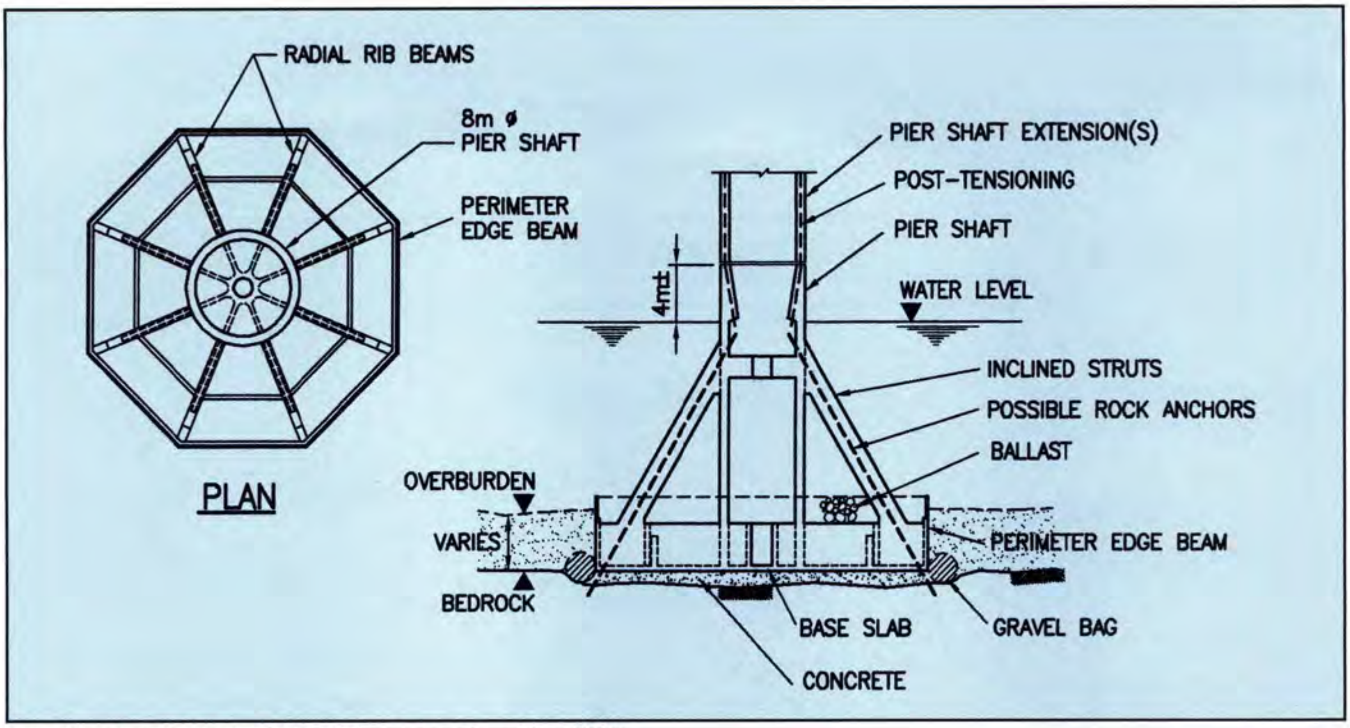

Fig. 10. Precast concrete foundation concept — May 1988.

PROPOSED DESIGN

Six proposals were submitted in confidence to PWC in May 1988 by the competing prequalified teams.

Concept

The Strait Crossing proposal was based on a main bridge design consisting of continuous, precast, prestressed concrete variable depth box girders with a span of 225 m (738 ft) (see Fig. 9). The depth of the girders varied from 4 m (13 ft) at midspan to 14 m (46 ft) at the pier.

The girders were pinned at the top of the piers using concrete hinges and expansion joints were provided in every alternate span. The resulting structure was essentially a series of frames consisting of two piers connected together via the concrete girder.

At the navigation span only, the typical span was increased to 250 m (820 ft) by the addition of a 4 m (13 ft) deep constant depth section 25 m (82 m) long. The typical footing/pier arrangement in the original conceptual design is shown in Fig. 10. Three different footing sizes ranging from 24 to 30 m (79 to 98 ft) were anticipated. The conceptual design of the substructure, however, was based solely on geotechnical information from previous PWC studies of the bedrock in the Strait that was neither specific to the final bridge location nor sufficiently accurate to allow confidence in the design. The footing design and sizes adopted at this stage were, therefore, obviously conservative.

It was anticipated that the foundations would be placed directly on the bedrock, exposed by dredging from a barge, with a variable length pier shaft such that the top of the pier would be 4 m (13 ft) above mean sea level. The footing would be temporarily supported on three concrete pads prior to the installation of tremie concrete to provide uniform bearing on the bedrock. Because the lateral load resisting capacity of the bedrock was not well known at this stage, provision was made for either ballasting or rock-anchoring the piers to increase the vertical loads.

The typical 225 m (738 ft) girders were to be cast segmentally in a stationary form on shore, floated into position, and erected in a single unit. Prefabricated concrete hinge elements were intended to permanently connect the girders to the piers with hydraulic jacks and prestressing tendons providing for temporary stability of the balanced double cantilever prior to connecting at midspan to the adjacent girder. A fixed moment and shear resisting joint was provided at the center of each frame with a moment resisting sliding joint in each alternate span.

Design Basis

The conceptual design was based on the Ontario Highway Bridge Design Code (1987) and the draft CSA CAN3-S6 "Design of Highway Bridges."

The design was the product of the core design team shown in Table 1, plus a large number of expert consultants. Special expertise in the areas of dynamic loading, time-dependent analysis, and thermal effects due to heat of hydration and solar radiation were included on the team.

Protection against progressive collapse was provided by the alternate span expansion joints, which would ensure that only a single frame would fail in the event of any catastrophic event. Also, although a calibration process was not carried out in this early stage, the team included Canada's leading experts in the field of load and resistance factor calibration.

From the outset, the design team included experts in the critical fields of

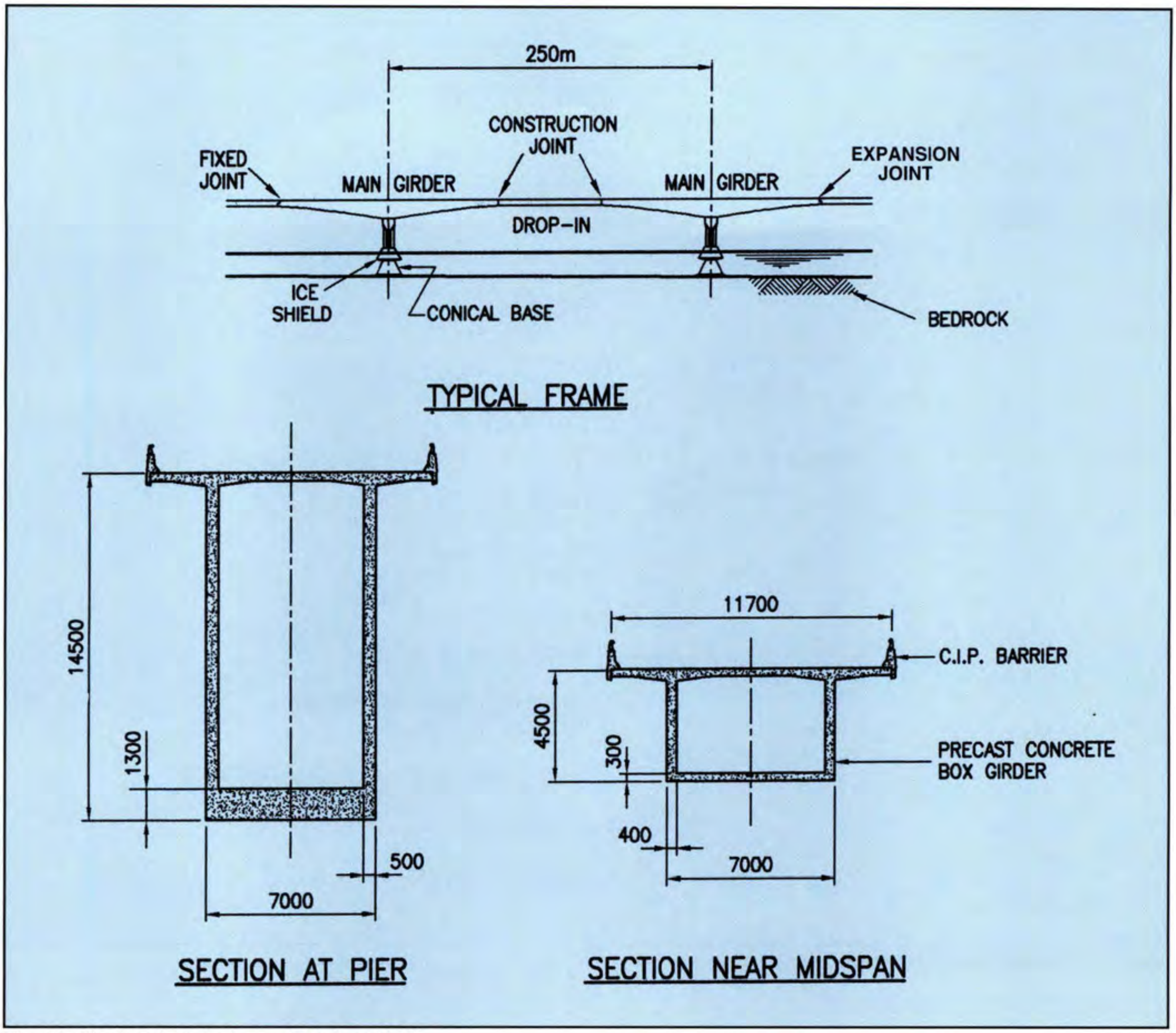

Fig. 11. Final project design — October 1993.

ice and wind loading and geotechnical engineering. Preliminary estimates of the ice and wind loads were prepared for the purpose of the conceptual design but were extensively studied again at the time of the final design.

Seismic forces were not considered to be significant in comparison to the extremely high horizontal ice loads; the conceptual design was based on a design ice load of 20 MN [2000 t (2205 tons)] per pier for the main spans. The capability of the bedrock to resist the horizontal ice forces was based predominantly on a 1968 report describing the stratigraphy and engineering properties of the bedrock. This, too, would be exhaustively reexamined prior to final design.

Durability

The Northumberland Strait is a very aggressive environment for reinforced and prestressed concrete. The major factors dictating the lifetime of concrete in marine environments are the quality of the raw materials, the density and permeability of the concrete, the extent of curing given to the concrete and the quality of the corrosion protection system for the reinforcing steel (including prestressing steel). When a dense homogeneous concrete with an impermeable concrete cover has been constructed, concrete structures in sea water have remained in good condition after many decades of operation.

Special attention was given to the concrete mix design. Fly ash and silica fume were added to the mix to reduce the temperature stresses in the fresh concrete and increase the long-term strength of the concrete in order to achieve high strength and high density. Added benefits are the increased workability of the fresh concrete and reduced permeability of the hardened concrete. At the same time, air entrainment would be provided to increase resistance against freeze-thaw cycles.

In the top deck and in the foundations in contact with water, epoxy coated reinforcement was originally intended to be used, a decision that was subsequently reversed at the final design stage.

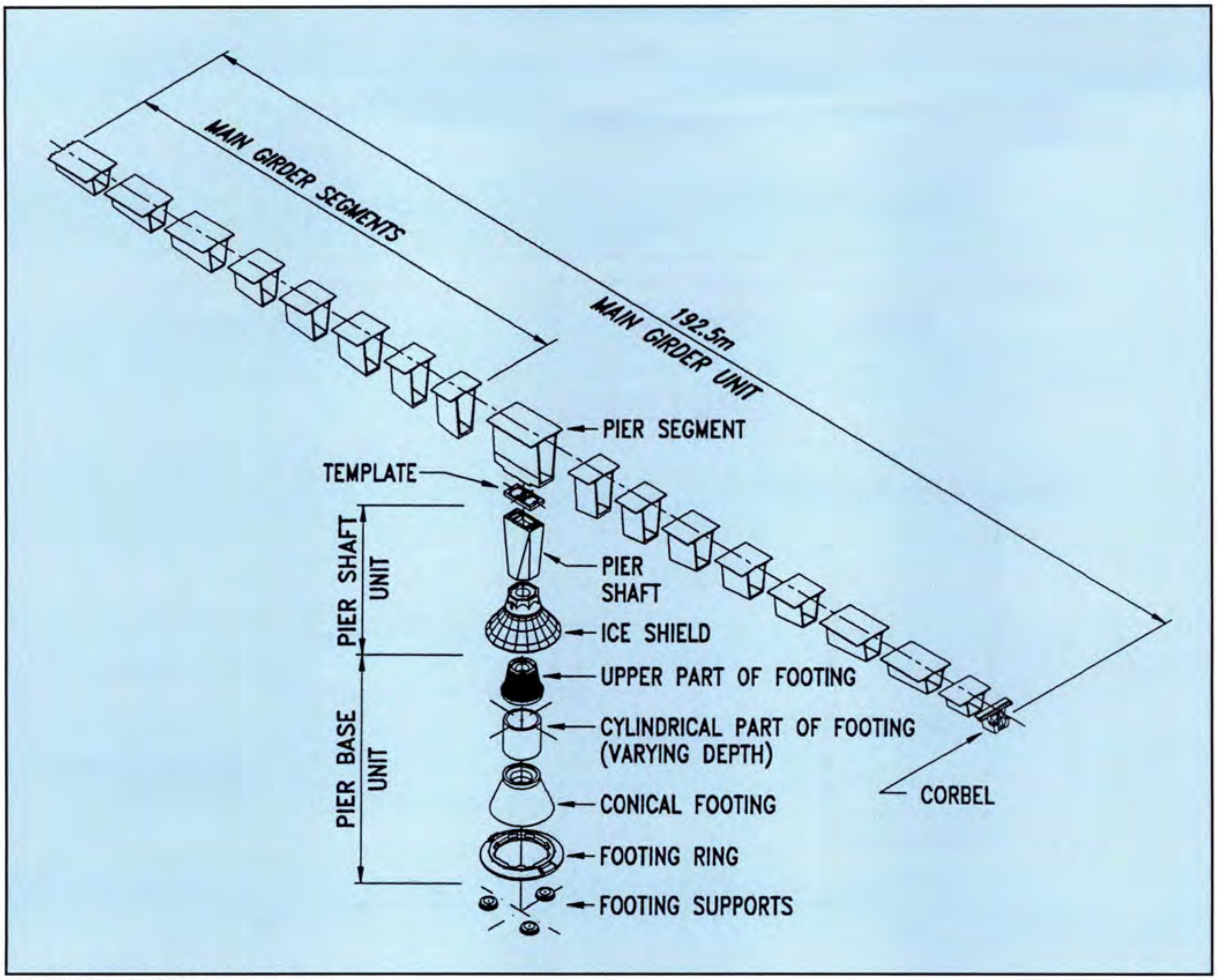

Fig. 12. Pier and girder components.

Aesthetic Suitability

The design of a bridge of the magnitude of the Northumberland Strait Crossing must be based not only on sound engineering criteria but also on other, more subjective factors. These include aesthetics, driver ergonomics and safety requirements.

A properly proportioned structural form is pleasing to the eye. There are certain techniques, however, that have been adopted for this project to enhance the appearance by emphasizing specific lines of the structure and softening others. The smoothly flowing curves of the soffit of the typical spans are a classical bridge form and need little improvement. A continuous fascia was added to the edge of the deck, however, to attract the eye of the viewer and to emphasize the slenderness of the structure. The girder itself is set back in the shadow behind this fascia in order to minimize its apparent depth.

From an aesthetic viewpoint, vertical and horizontal curves at each end of the bridge and at the navigation span create a more visually attractive crossing. More than 55 percent of the crossing from abutment to abutment is on either a vertical or a horizontal curve. This results in wide sweeping views of the structure from either shore and was recommended by an expert on driver psychology who was a member of the Strait Crossing team.

PROJECT TIMELINE

Of the six proposals submitted to PWC in May 1988, three were now qualified for the shortlist for the next stage of the proposal call.

Despite extensive levels of detail of these proposals and the numerous previous studies that had already been carried out, the project was now subjected to an extended period of delays and reviews prior to obtaining final approval to proceed. Through 1989, 1990 and into 1991, community meetings, review panel hearings, environmental studies and further ice studies were carried out to confirm the acceptability of the project.

Finally in May 1991, three years after the original design proposals were submitted, the three shortlisted teams were invited to resubmit their proposals to be evaluated against the revised environmental requirements and ice criteria detailed by this public process. All three submissions were re-qualified and in January 1992 financial bids were submitted.

At the opening of the bids in May 1992, the Strait Crossing team was the low bidder, but it would not be until October 1993, following further extensive negotiation, that a contract for the project was eventually signed. During the period from 1988 to 1993, the design did not remain static. In order to ensure the continuing competitiveness of the proposal, the Strait Crossing team repeatedly revisited the design on an ongoing basis and made numerous modifications to ensure that the financial bid, when and if it were called, would be optimized.

The 225 m (738 ft) span was increased to 250 m (820 ft) and a drop-in segment was added in order to minimize the number of piers and foundations in the Strait. The increase from 225 to 250 m (738 to 820 ft) is believed to be the maximum possible span for a concrete box girder bridge.

The round pier was changed to an octagonal pier and the concrete hinge replaced by a fixed connection in order to increase temporary stability and to simplify the girder-to-pier connection. Conical ice shields were added around the piers to cause the ice to ride up the piers and fail in a flexural mode rather than by crushing failure against the vertical pier face. This reduced the dynamic effects of the ice loading.

The pier base was modified from the octagonal raft to the truncated cone and annular ring originally considered in 1988 to reduce forming costs and simplify construction. Materials selection continually changed as new developments occurred: epoxy-coated reinforcement was deleted in favor of additional concrete cover and more impermeable concrete, and 55 MPa (8.0 ksi) concrete was substituted for the original 45 MPa (6.5 ksi), based on better knowledge of available materials.

FINAL PROJECT DESIGN

The contract between the Government of Canada and the Strait Crossing team was signed on October 7, 1993. By this time, the project design team had grown substantially since its inception in 1987, but the final project design, on which the contract was based, was still remarkably similar to the concept that had been originally proposed in 1988. The final project design for a typical frame is shown in Fig. 11.

The frame consists of a pair of 190 m (623 ft) double cantilever main girders fixed to 8 m (26 ft) octagonal piers supported on conical pier bases founded on bedrock. Drop-in girders 60 m (197 ft) in length complete the frame. A single expansion joint occurs in every second span.

The approach spans are designed using a precast segmental balanced cantilever system with typical spans of 93 m (305 ft).

Precast Components

All of the components for the main spans will be precast in a single casting yard located near the bridge site at Borden, Prince Edward Island, and will be floated out and erected using a large floating crane known as the Svanen.

The main girder will be cast segmentally using a balanced cantilever approach (see Fig. 12). Total weight for the 190 m (623 ft) finished girder is approximately 8000 t (8820 tons).

The drop-in girder will also be cast in segments and erected as a single 60 m (196 ft) long piece. The fixed joints between the double cantilever and the drop-in girder will be cast on site with the drop-in temporarily supported on erection frames. The expansion joints will consist of uni-directional bearings supported on prefabricated corbels cast separately and attached to the main girder and the drop-in girder in the casting yard.

The pier base will consist of an annular ring footing, conical base, lower pier shaft and ice shield cast segmentally to form a single unit. The pier shaft length varies so that the connection between the ice shield and the upper pier shaft will occur 4 m (13 ft) above mean sea level. The footing diameter varies from 20 to 28 m (66 to 92 ft) depending on the height of pier/depth of water and on the actual bedrock to be determined by detailed geotechnical investigation.

The pier shaft is a simple, hollow, octagonal section 8 m (26 ft) across at water level, changing to a 10 x 5 m (33 x 16 ft) rectangle at girder level.

Erection

The construction schedule is predicated on erecting one complete span per week over two summer seasons. Because this requires less than one piece per day to be floated out from the casting yard and erected, there is a substantial allowance for inclement weather even during the construction season.

The pier base is placed first, temporarily supported on three concrete "hard points" accurately positioned on the bedrock, which has been exposed by predredging. Uniform bearing on the bedrock is achieved by completely filling the space under the footing with tremie concrete pumped from a barge above.

The top of the base will be 4 m (13 ft) above sea level, allowing a simple cast-in-place joint for the pier shaft. The pier shaft will be post-tensioned to the pier base using post-tensioning cables accessible from the hollow center of the shaft.

A rectangular transition section at the top of the pier shaft is intended to provide space for temporary jacks to assist in positioning a match cast template for the main girder when it is lowered by the floating crane. Post-tensioning is provided through diaphragms at the main girder hammerhead to fix the girder to the pier.

The main girder and drop-in girder are post-tensioned for temporary construction loads and for permanent negative and positive moments, respectively, in the casting yard. In addition, after erection of the drop-in girders, additional post-tensioning will be provided in external ducts to create continuity through the fixed joints.

After erection, a continuous concrete guardrail will be cast-in-place, and a waterproofing membrane and wearing surface will be placed to protect the upper surface of the girder. Roadway lighting, an emergency telephone system, a closed circuit bridge television system, navigation lights and continuously monitored changeable message signs will maximize the safety of drivers using the bridge.

CONCLUDING REMARKS

Construction of the Northumberland Strait Crossing will be the realization of a 100-year-old dream in Canada. The bridge has been designed to the highest level of safety of any such structure in North America and has been designed for a useful life of over 100 years. The precast, prestressed concrete bridge will be built using state-of-the-art technology.

This paper has described the design development process from the outset of the project in 1987 to the signing of the construction contract in 1993. Subsequent to the signing of the contract, responsibility for completing the detailed design, preparing shop drawings and monitoring of construction was awarded to J. Muller International/Stanley Joint Venture Inc., a joint venture of J. Muller International of San Diego, California, and SLG Stanley Consultants Inc. (formerly Simpson Lester Goodrich Partnership and Stanley Associates Engineering Ltd.) of Calgary, Alberta, Canada. Further design refinements continue to be made to optimize the design-build process under which the project is being completed.

Construction activities commenced in October 1993 with construction of two precasting yards: the main span plant on Prince Edward Island and the approach span plant in New Brunswick. Construction of the permanent components of the bridge started in the summer of 1994, and erection of the approach spans is now underway. Erection of the 250 m (820 ft) main spans starts in September 1995, with overall project completion scheduled for the summer of 1997.

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