Northumberland Strait Crossing, Canada

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The Northumberland Strait Crossing is a bridge in Atlantic Canada; it is a prestressed, precast concrete structure that will provide a fixed link across the strait between Cape Tormentine, New Brunswick, and Borden, Prince Edward Island. It has been financed, designed, constructed, operated, and maintained for 35 years by the developer, a joint venture. The design service life of the structure is 100 years. The 13-km crossing comprises approaches with 93-m spans in shallow water near shores and a main bridge with 250-m spans in the strait. The scheduled completion date is the end of 1996. Because of the short construction time and the often adverse conditions for work at sea, precasting is used systematically on a large scale for the entire bridge. Precast pier bases are installed and grouted to bedrock at depths to 38 m below sea level. Precast shafts are erected on the bases. Typical cantilevers for marine spans weighing 78 MN are precast on shore and set in place with a floating heavy-lift crane, which is also used to place 52-m-long precast drop-in spans between cantilevers using a procedure that eliminates excessive erection moments in the piers. Innovative design features and the most advanced construction techniques and skills have been called on to match the challenge presented by such a major undertaking.

A fixed link between the provinces of New Brunswick and Prince Edward Island had been considered by Public Works Canada for a long time. It was not until 1988, however, that the idea materialized into a 13-km bridge, the Northumberland Strait Crossing. This bridge would be financed, built, and operated by a private developer for 35 years, then turned over to Public Works Canada (Figure 1). In 1992 three international joint ventures were on the final list for consideration. Strait Crossing Joint Venture (SCJV) the successful low bidder, is composed of SCI of Canada, Morrison Knudsen of the United States, GTM of France, and Ballast Nedam of the Netherlands. The prime consultant is J. Muller International•Stanley Joint Venture. Construction started in spring 1994 and will last until the end of 1996; the facility is scheduled to open in 1997. Considering the size of the project, the short construction time, and the adverse conditions generally encountered at sea in this region, the realization of this bridge is a monumental work (Figure 2).

DESCRIPTION OF PROJECT

General

Deep water in the strait calls for long spans, whereas shallow water near shores is more suited for shorter spans. The extremely short completion time calls for extensive use of precasting, large precast elements carried by heavy marine equipment for the long spans, and more conventional elements for the shorter spans. These requirements naturally divide the bridge into two different structures: the long marine spans in deep water, and the shorter approach spans in waters not accessible by deep draft vessels.

FIGURE 1 Northumberland Strait Crossing.

From Jourimain Island on the New Brunswick side to the village of Borden on the Prince Edward Island side, the bridge (Figure 3) comprises

- West approach, 1320 m long with 93-m spans;
- Main bridge across the strait, 10 990 m long with 250-m spans; and
- East approach, 600 m long with 93-m spans.

Main Bridge

Substructure

Foundations

The rock sequence across the strait consists of a series of interbedded sandstones, siltstones, and mudstones. These rocks are believed to have been deposited as sediments in a fluvial or estuarine environment, and a broad correlation can be made across the strait. However, at a small scale, the rock layers are not very consistent from pier to pier, and each pier location must be investigated fully and evaluated on its own. Thick layers of sandstone are interbedded with layers of relatively soft mudstone varying in thickness from 5 to 500 mm, most being 50 mm thick. Sandstone is competent rock, but mudstone layers underlying sandstone constitute weak planes for transmitting horizontal forces, such as those from ice and wind. Because of the uncertainty in assessment of the real geometry of these layers, it is assumed that they are present over 100 percent of the foundation areas.

The contractor chose to use spread footings for all the prefabricated piers. For the reasons explained earlier, the founding level must be on sandstone with the next layer of soft mudstone, if any, following at a depth not less than that determined by the geotechnical analysis on a pier-by-pier basis, but in no case less than 1.50 m. The dredging operations consist of first removing the overburden, which is up to 10 m thick, and excavating a trench to the competent sandstone level; a template is used to guide the dredging bucket in the circular pattern.

The prefabricated pier base ring footing is installed in the trench on three hard points about 0.5 m above the bottom. The three points determine a horizontal level on which to set the pier base and leave a space between the ring footing and the trench, which is then filled with a specially formulated tremie concrete, ensuring uniform bearing of the whole pier base on the rock (Figure 4).

Safety against sliding of the foundation is checked at the interface with the rock assuming a shear friction corresponding to 16 degrees/18 degrees for the undrained mudstone. The compressive stresses at ultimate limit state are in the range of 1.2 to 1.6 MPa; actual strength of the rock is twice that value or larger, depending on the pier location.

The modulus of subgrade reaction is in the magnitude of 110 MN/m^3; long-term settlements are minimal. At the ultimate limit state, the eccentricity of the resulting force applied to the footing is limited to 0.30 of its diameter.

Pier Bases and Pier Shafts

All pier bases and pier shafts are prefabricated in the casting yard at Borden. They are prefabricated separately because of height and capacity limitations of the catamaran-type floating heavy-lift equipment, called Svanen, which has been upgraded after previous use in Denmark on the Great Belt Project and will be used to transport and erect all the components of the main bridge.

There are two types of pier bases: Type B1 for depths down to −27.0 m, and Type B3 for depths of −27.0 to −38.2 m. B1 has a ring footing, 22.0 m in diameter and 4 m wide, that fits exactly between the two hulls of Svanen. B3 has a ring footing 28.0 m in diameter but with two flat surfaces spaced 22.0 m so that it also fits into Svanen. Above the ring footing, a conical shell transfers the loads from the barrel, which varies in height according to the depth of the foundation. The barrel ends at elevation −4.00 m by a male cone used to connect the pier shaft to the pier base (Figure 5). The maximum weights of the B1 and B3 bases are 35 and 52 MN, respectively. The maximum height of B3 is 42.0 m.

Each pier shaft comprises the shaft itself and the ice shield. It is one of the most critical components of the whole structure because it will be in direct contact with the most aggressive and corrosive environment, seawater in the tidal range, salt-laden spray and air, and abra-

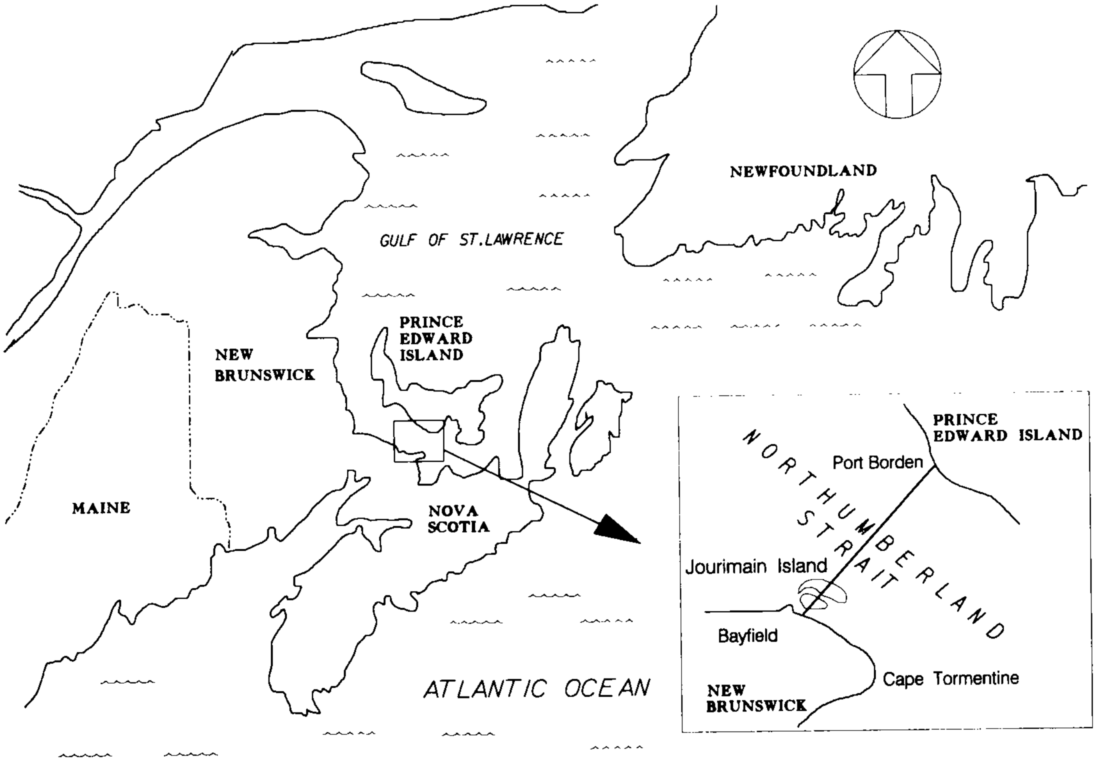

FIGURE 2 Project location.

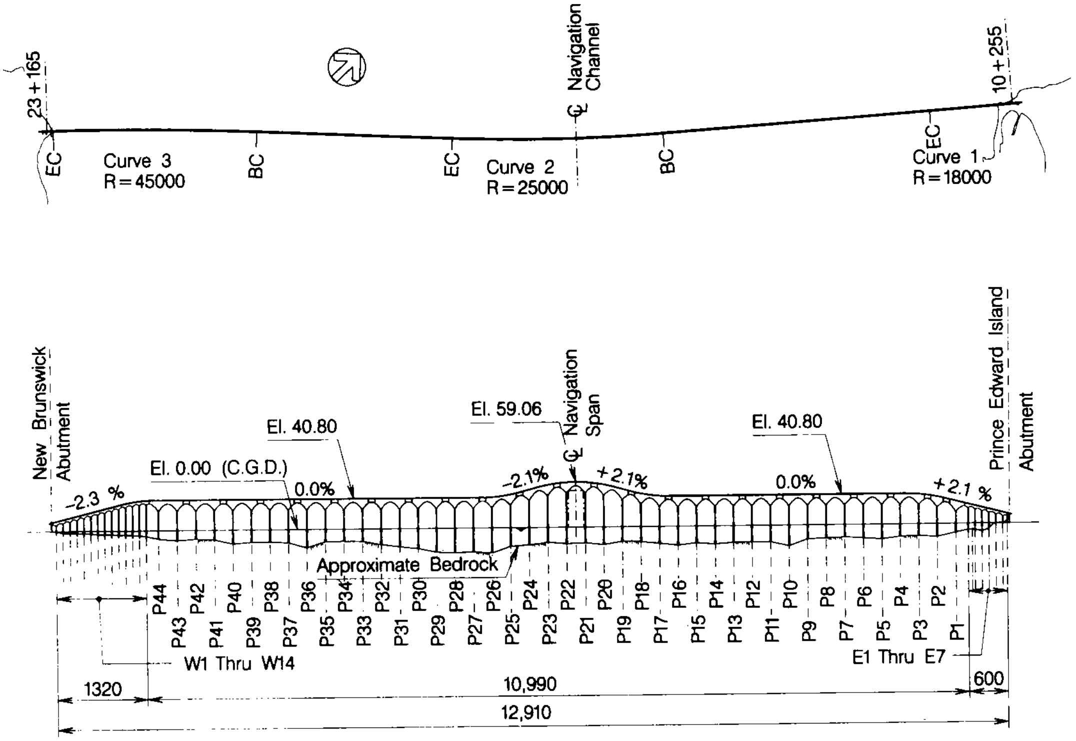

FIGURE 3 Bridge profile: *top*, plan; *bottom*, elevation.

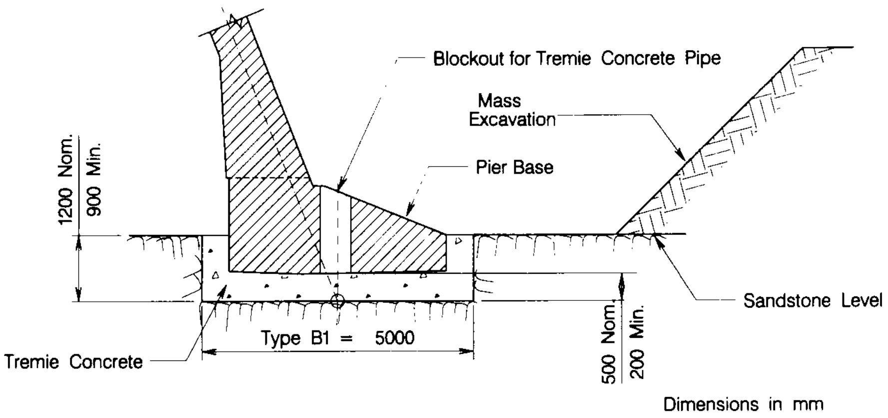

FIGURE 4 Trench and footing, main bridge.

sion from the ice; therefore, all exposed cast-in-place joints have been eliminated from this element, which is monolithic from the bottom of the ice shield to the top of the pier, with a maximum weight of 40 MN.

The ice shield is conical with a base diameter of 20.0 m, a height of 8.0 m, and a 52-degree angle on the horizontal. It is solid except for a central conical void that matches the top of the pier base. The ice shield itself extends between elevations −4.0 and +4.0 m; it is clad with a 10-mm mild steel sheet for abrasion protection.

The pier shaft has a box section, varying from an octagon at the top of the ice shield to a rectangle at the top of the shaft. The walls are 600 mm thick.

The pier shaft is assembled onto the pier base by being lowered until it rests on hydraulic jacks on top of the base; the position of the top of the pier shaft is adjusted by activating those jacks. The space left between the two cones is grouted, creating a continuous structure through the keyed joint, and vertical post-tensioning tendons crossing the joint are then stressed.

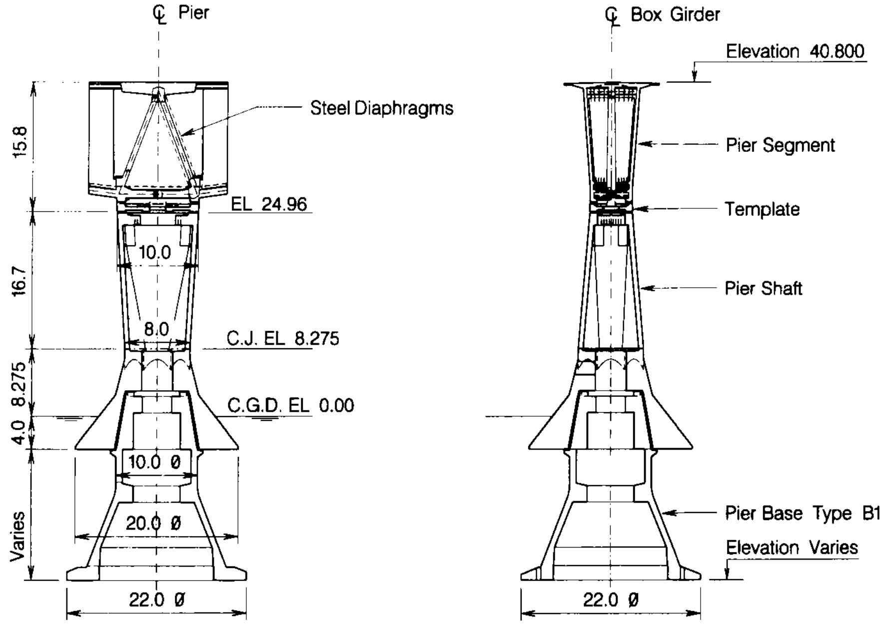

FIGURE 5 Typical pier, main bridge: *left*, longitudinal section; *right*, transverse section.

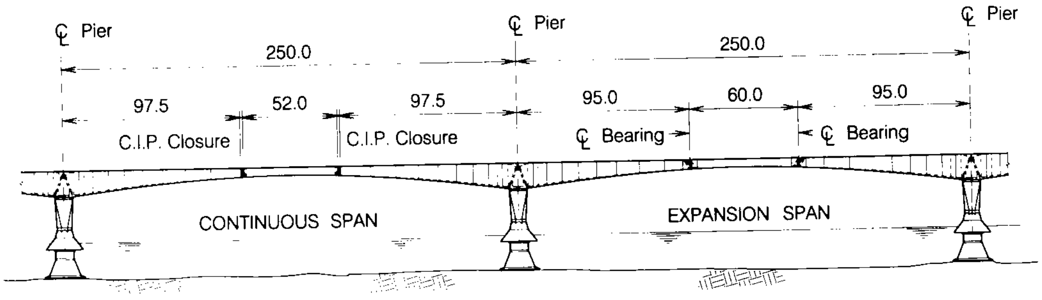

FIGURE 6 Typical superstructure, main bridge.

The top of the pier shaft is equipped with a template that is matchcast to the soffit of the pier segment. Once the pier shaft is in place, the template (1.0 MN) is grouted in position so that the future cantilever girder (78 MN) can be placed directly in its final position, thereby avoiding delicate and time-consuming adjustments of a heavy and unstable cantilever.

Superstructure

The superstructure forms a series of frames connected by 60.0-m-long drop-in expansion spans. A frame consists of two cantilevers, integral with the piers and made continuous by inserting a 52.0-m drop-in span between the cantilever tips, pouring closure joints, and stressing post-tensioning tendons to achieve a fully monolithic frame (Figure 6).

Cantilever Deck

The 44 cantilevers, 192.0 m long, are prefabricated in the casting yard. Each is made up of 17 segments, one 17.0-m-long pier segment with eight segments on either side, their lengths varying from 7.5 to 14.5 m. Segment depths vary from 14.0 m at the pier to 4.5 m at midspan. One end of the cantilever is equipped with a hinge to receive the simply supported drop-in span (Figure 7).

The pier segment has a composite post-tensioned inverted V diaphragm; its steel structure is used as form for casting of the segment and is supplied by the fab-

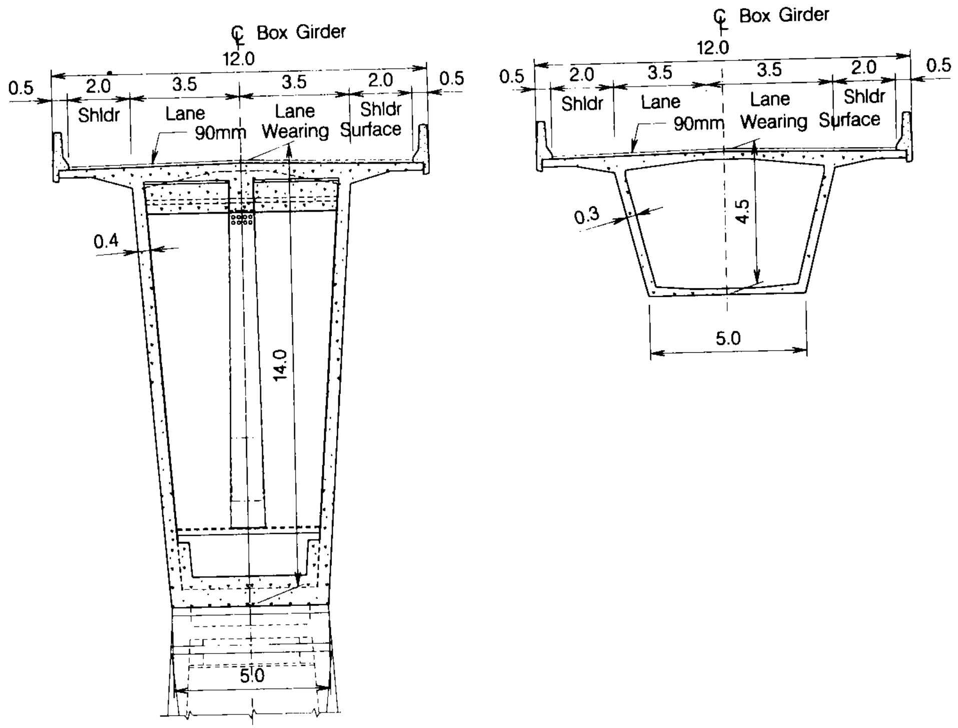

FIGURE 7 Typical cross section, main bridge: *left*, pier; *right*, midspan.

ricator with all the post-tensioning ducts installed to speed up fabrication. Steel diaphragms also help solve the congestion problem due to the large number of cantilever tendons needed for the long span that must be installed in a narrow cross section.

A moment-resisting connection between cantilever and pier is achieved through the matchcast template with vertical post-tensioning tendons, some of which are looped in the walls of the pier shaft and others that are external and replaceable, placed inside the pier shaft and anchored at the ice shield level.

In the precasting yard, the 16 cantilever segments are cast on 16 fixed beds, a pair at a time. The process starts with the pier segment, which is always cast at the same location; from there it is moved transversely until it aligns with the two first beds, where the first two cantilever segments are cast, one on each side, and post-tensioned. Then the assembly made of the pier segment and the two first segments is again moved transversely until it aligns with the next set of fixed beds, where another pair of segments is cast, and so on.

A system conceived to dampen the oscillations of the cantilever during load transfer from Svanen to the pier shaft is installed in the template (Figure 8).

Drop-In Span

A drop-in span is used to close the remaining gap between cantilever tips. A typical 52.0-m drop-in span is used either to connect two cantilevers rigidly to create a frame or to connect two frames. When used within a frame, the drop-in span is made continuous with the cantilever using the following sequence. The 52.0-m span is picked up in the center by Svanen at the casting yard, brought out to the pier, and guided into position between the tips of the facing cantilevers. The gap between either end of the span and the adjacent cantilever tip is closed by a shim-type device, whereafter the dead weight of the span is released by Svanen. If the cantilever tips were free to move longitudinally, toward each other, they would do so under the effect of the applied vertical loads, due to bending of the piers; such longitudinal movement is prevented, however, by the drop-in span acting as a strut; a compressive force is developed in the drop-in span counteracting the effect of its dead load, which otherwise would have induced adverse bending moments in the piers.

This horizontal force is such that no counterweights are needed. After the transfer of force, its magnitude is adjusted by means of hydraulic jacks to a design value, typically 18 MN, chosen to best compensate the long-term effects of creep and shrinkage. Then joints are cast and post-tensioning tendons stressed, whereby the continuity of the frame is achieved. When used to connect two frames, the basic 52.0-m span is fitted with hinge segments at either end to turn it into a 60.0-m simply supported span, which is always installed after the adjacent frames are completed.

Approaches

West and east approaches consist of thirteen and five 93.0-m spans, respectively, and shorter abutment spans. The rectangular prismatic box piers rest on footings, shaped as ice breakers similar to those of the main bridge, and cast in place within cofferdams directly on sandstone. Each footing is equipped with six to eight keys, cast in vertical shafts, 2 m in diameter, 5 m long, drilled into the sandstone to increase resistance against ice loads.

For the footings, casting in place was selected because the water depths of 0 to 8 m did not allow heavy floating equipment to access all locations. For shafts and superstructure, precasting was chosen to reduce construction time and improve quality.

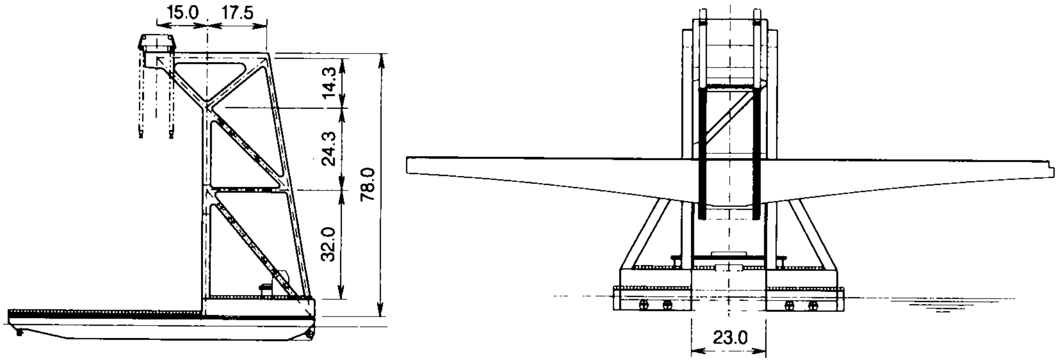

FIGURE 8 Floating heavy lift equipment, Svanen.

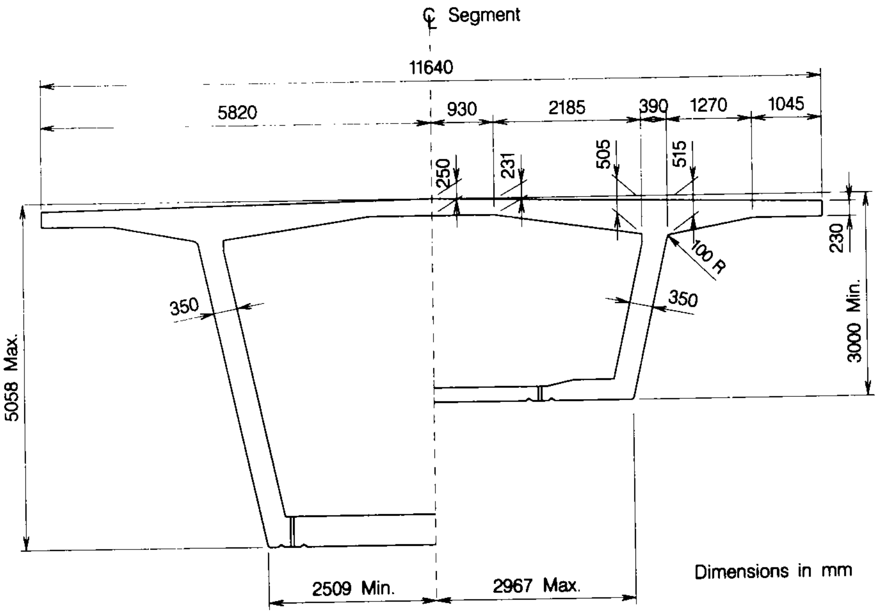

FIGURE 9 Typical cross section, approaches.

The 93.0-m spans with depths varying from 5.06 m at the pier to 3.0 m at midspan are made up of two pier segments and 14 pairs of symmetrical segments (Figures 9 and 10).

The approach spans are placed with launching equipment consisting of two parallel trusses supported on the pier segment and at the tip of the previously built cantilever. Segments are brought forward to the launching equipment over the deck already built, picked up by a trolley rolling on the trusses, and set symmetrically. Pier segments are also placed with this equipment during the launching operation.

Expansion joints are located at midspan for easier construction; they allow long-term displacements but are able to transfer continuity moments for deflection control. Long-term deflections can be compensated or adjusted, as required, by simply jacking the steel beams and shimming the bearings. The same type of expansion joint is used to connect the approaches with the marine spans (Figure 11).

Precasting Yards

Two precasting yards are installed—one on the New Brunswick side for the approaches, superstructure segments as well as pier shaft segments, and the other on Prince Edward Island side for all the marine spans (Figure 12). The anticipated production rate for a marine cantilever is 5 weeks for the pier segment and 2 weeks for each of the following segment pairs, which adds up to about 5½ months. Each pair of casting beds sees a cantilever passing every 2 weeks so that, theoretically, a full cantilever can be produced every 2 weeks. Twelve cantilevers can be stored at the staging area.

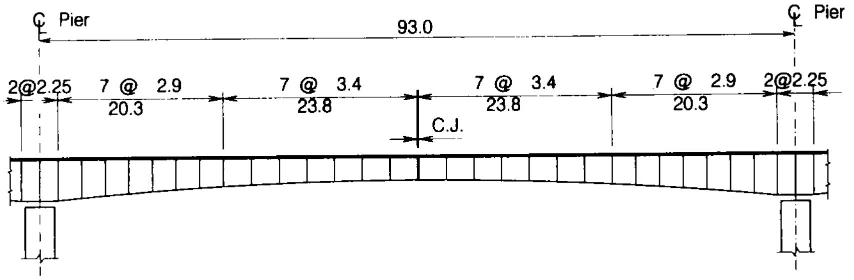

FIGURE 10 Typical segment layout, approaches.

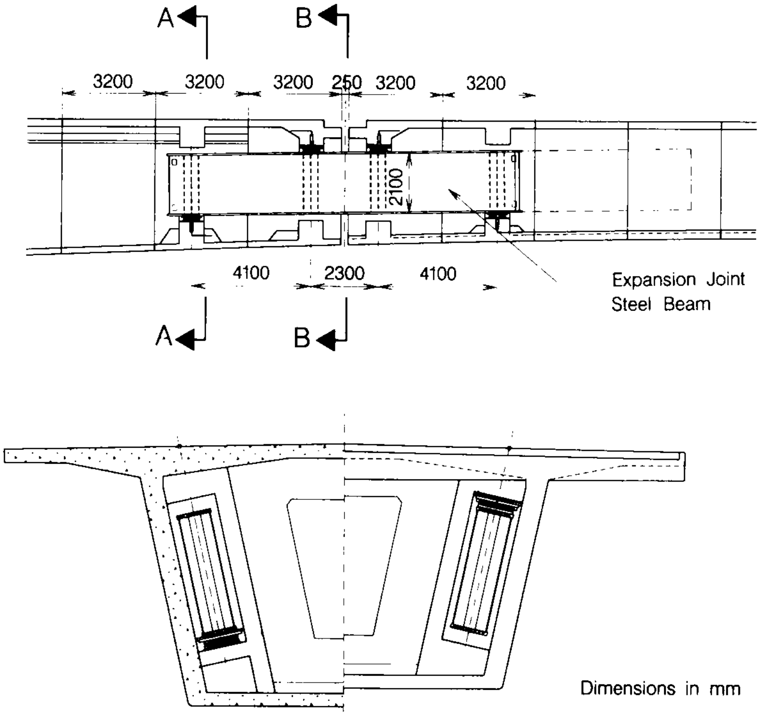

FIGURE 11 **Expansion joint, approaches: *top*, longitudinal section; *bottom*, Sections A-A (*left*) and B-B (*right*).**

Production time for a pier base is anticipated to be about 2 months, the same as for a pier shaft–ice shield. Twenty pier bases and 14 pier shafts can be stored.

Design Requirements

The design requirements issued by Public Works Canada, as part of the 1988 call for proposals, have had a direct impact on the chosen structural concept. The most important of these requirements are listed here:

- The design service life of the facility shall be 100 years, with high-quality performance, and must be achieved through excellence of concept, design, construction, maintenance, and operation procedures.
- Consideration shall be given to the fundamentals of aesthetics.
- The progressive collapse criterion, saying that the failure or collapse of any one span shall not lead to progressive failure or collapse of other spans, has had a large influence on the choice of the statical scheme of the bridge.
- Environmental loads, such as ice force and wind, in connection with the permanent loads are dictating the design of the substructures.
- Risk of ship impact in the vicinity of the navigation channel has led to either strengthened piers or protective islands.
- Roadway width is 11.0 m, providing a three-lane facility.
- The navigation channel has a 172-m horizontal clearance and 49.0-m vertical clearance, with a minimum depth of 13 m.

Load Combinations and Load Factors

Public Works Canada requires that load combinations and load and resistance factors for ultimate and ser-

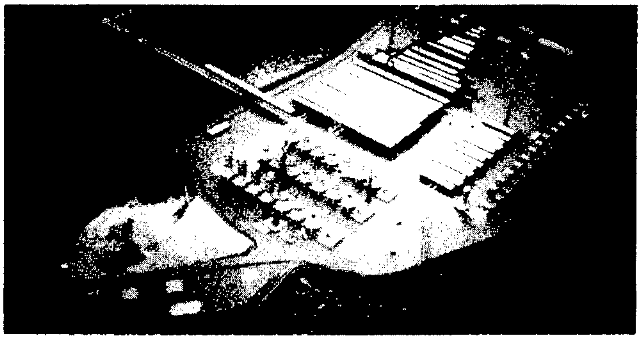

FIGURE 12 **Model of precasting yard.**

viceability limit states be derived specifically for the project through a full calibration process using probabilistic reliability techniques.

A target safety index $\beta = 4.0$, applies to each multi-load-path component of the bridge at ultimate limit states, for a 100-year design life. For single-load-path components, $\beta = 4.25$ is imposed. The target safety index is a measure of the accepted risk of failure of a structural member.

As a result of the analysis, load factors different from those usually recommended in codes were obtained. For serviceability limit states, crack widths are related to the change of stress level in the reinforcement or tendon for a given spacing.

Ice Loading

Generally, the ice season in the Northumberland Strait begins in December or early January, and conditions worsen until late March. The maximum thickness of ice floes (i.e., floating ice formed in large sheets af the surface of the sea) is about 0.30 m. Floe sizes occasionally reach 500 m, with a mean of 118 m.

Currents, waves, and wind induce ice movements, cause floes to break, and result in rafting and ridging; ice ridges consist of a consolidated core of refrozen ice at the waterline with loosely bonded blocks of ice forming a small sail on top of the ridge core and a much larger keel below it (Figure 13). Ridge dimensions are 50 to 75 m. The ridge keel depths can be evaluated from the number and location of scours seen on the bottom of the strait; the deepest is at 18 m, and the average is 8.5 m. The ridge core thickness may reach 2.5 m.

The critical case for the substructure of the bridge is the consolidated ridge core hitting the pier shaft. To minimize the horizontal force on the pier shaft, a conical ice shield has been designed with an angle of 52 degrees to break the ridge core in bending, the ice riding up the cone and collapsing under its own weight, rather than crushing directly on a vertical surface, producing a much higher force. The ice shield is clad with steel plate to minimize ice abrasion and reduce friction.

Numerical models are used to calculate ice loads, which are given as a function of their expected occurrence, such as once in 100 years, once in 1,000 years, and so on.

The direction of ice forces has been studied; it is related to the direction of the prevailing currents and, to a lesser degree, the wind. Rose diagrams for currents, winds, and ice forces were developed at several locations along the bridge. It was found that the maximum force was perpendicular to the bridge and a force of about 65 percent thereof may act in the longitudinal direction of the bridge.

It should be noted that all assessment of ice loads carries a degree of uncertainty as relevant on-site measurements of ice forces are scarce; besides those made at Lighthouse KEMI-1 in the Gulf of Bothnia in 1985–1986, practically none have been reported, and laboratory test results can be only a guide.

Another aspect of ice loading is its dynamics. The dynamic response of the bridge allows the assessment of the dynamic loading characteristics of the ice. An analysis was carried out, taking into account ice force versus time histories derived from the consideration of all contributing features:

- Ice failure frequencies;
- Ice speed;
- Ridge core characteristics, ridge keel dynamics; and
- Rubble surcharge.

Failure of the ridge core is estimated to be the most likely source of dynamic ice loads for frequencies of less

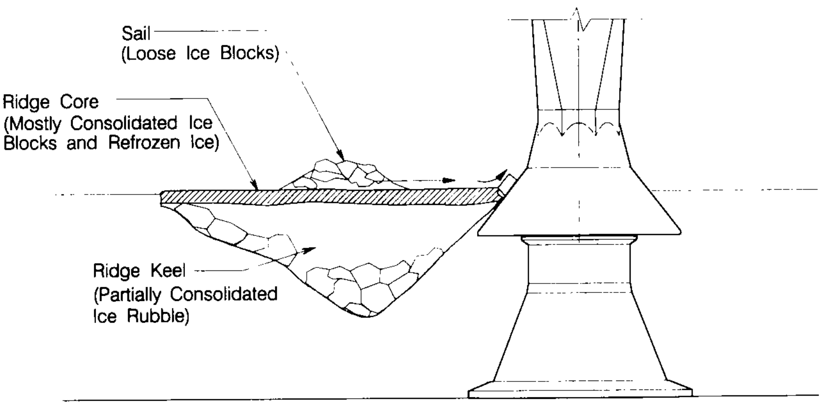

FIGURE 13 Ice ridge.

than 1.5 Hz; ridge keel dynamics activate frequencies below 1.0 Hz; the combination of ridge core and ridge keel effects is relevant only for frequencies less than 1.0 Hz. The lowest natural frequency to be considered for the completed bridge is 2.6 Hz, higher than the ice-induced frequencies.

Now, the design of the substructure is based on a transverse static ice force (perpendicular to the bridge) of 25 MN and a longitudinal static ice force (in the direction of the bridge) of 17.5 MN. For ultimate conditions a factor of 1.5 is applied to the loads, which are controlling the dimensions of the foundations.

Wind Loading

Because of the location of the structure in the windy Northumberland Strait, a complete study was done to investigate the safety of the bridge for aerodynamic stability and maximum wind speed loadings, in construction stages and in service. Wind effects on vehicular traffic and snow accumulation were also investigated.

Experimental wind tunnel testing, involving a 1:60-scale section model for aerodynamic parameters and a 1:250-scale full aeroelastic model, was undertaken; the latter was tested in three construction stages, namely, free-standing double cantilever, frame completed, and bridge completed.

Reference wind speed for a 100-year return period is 29.5 m/sec, with the maximum component transverse to the bridge being 26.4 m/sec, at 10 m above water. During construction, a wind speed of 22.5 m/sec corresponding to a 10-year return period is considered. In the casting yard, a wind speed of 15 m/sec is used. The wind load per unit length of bridge is given by

$$W(y) = q\ \mathrm{Ce}[C(y) \pm C_{\mathrm{dyn}}\ F(y)]\ B$$

where

q = reference wind pressure (q = 0.44 kPa for 26.4 m/sec),
Ce = exposure coefficient (varies with height),
$C(y)$ = static coefficients in x, y, z varying with longitudinal position (y),
C_{dyn} = dynamic coefficient,
$F(y)$ = modal load distribution factor, and
B = width of bridge deck.

The static part of the transverse wind load for a 250-m span is in the magnitude of 3.7 MN.

Wave and Current Loading

The location of the bridge is somewhat protected from the ocean and from the swells of the Gulf of St. Lawrence by the island itself. The wave environment in the strait is governed by waves generated within the strait. The peak period for the extreme waves ranges from 6 to 9 sec. The maximum wave height in the mid-

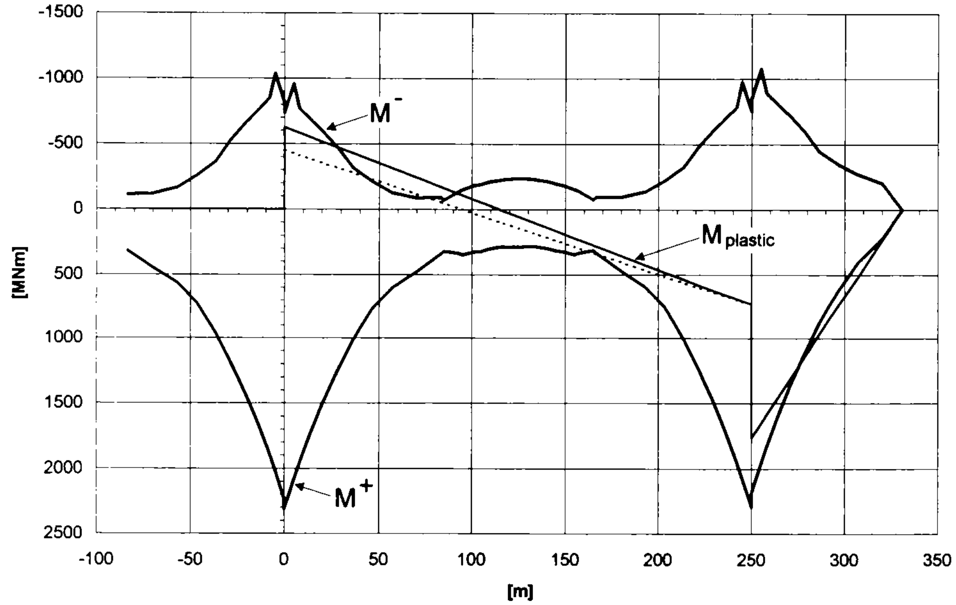

FIGURE 14 Progressive collapse, quasistatic analysis: bending moment after failure of hinge versus ultimate moment capacity, moment differences relative to dead load moment.

dle of the strait for a 100-year return period is 4.70 m. Tidal range is from +2.25 to −2.03 m. Maximum current velocity is 2 m/sec.

It was found that maximum forces develop at high tide and that a large part of the force is generated on the ice shield itself. Maximum horizontal and vertical forces are 8 and 4.3 MN, respectively.

Progressive Collapse

Collapse of one pier or one span or destruction of a hinge-expansion joint must not trigger the collapse of the following spans, as is actually the case in most continuous structures. A simple and still efficient scheme was chosen, consisting of two piers with the cantilevers rigidly connected by the drop-in span, the whole system forming a rigid frame. Frames are then linked with a drop-in span simply supported at the outer tips of the frames' cantilevers. Several analyses were carried out, including time-history analysis, and it was found that the quasistatic approach in which the weight of the missing drop-in span was replaced by an upward force equal to the reaction of the span yielded acceptable results. The graph in Figure 14 shows the result of such analysis where the "plastic moment" caused by the effect of the collapse must remain within the capacity of the span. The strengths of the pier-to-superstructure connection and of the superstructure were adjusted until this condition was satisfied. Progressive collapse criteria actually dictated the structural scheme of the bridge.