CHAPTER 173

Bridge Pier Scour Assessment for the Northumberland Strait Crossing

C.D. Anglin[1], Associate Member, R.B. Nairn[1],
A.M. Cornett[2], L. Dunaszegi[3] , J. Turnham[4], G.W. Annandale[5]

Abstract

In 1997, the Northumberland Strait Crossing will form a 13 km fixed link (bridge) between New Brunswick and Prince Edward Island in the Canadian Maritimes. This $800 million project has presented many engineering challenges, one of which has been the assessment of scour protection requirements for the 65 bridge piers. A multi-faceted coastal engineering investigation was undertaken by Baird & Associates to assess the potential for scour, and, where required, to design scour protection. Key activities included geotechnical investigations to define the seabed characteristics, numerical modelling to define the wave, current and water level conditions at the crossing site, physical modelling of wave-current interaction with the bridge piers, and the development of a new methodology to estimate the erosion potential of the seabed under extreme wave and current conditions.

The direct application of standard scour prediction techniques was not possible for this project due to the combination of complex flow conditions (waves and currents), complex pier geometry (conical base, with some piers located in dredged pits), and complex seabed conditions (highly weathered and fractured bedrock). A new methodology to estimate the potential for scour, considering these complex conditions, was developed using the empirical erodibility approach of Annandale (1995). Measurements of actual scour around one of the first four bridge piers installed early in the project were used to calibrate/verify the methodology. Using this new methodology, scour protection was recommended at approximately one-quarter of the bridge piers. The protection system consists of a 10 m wide band of either armour stone or tremie concrete placed around the base of the piers.

1 - Baird & Associates, 1145 Hunt Club Rd., Suite 1, Ottawa, ON, Canada K1V 0Y3
2 - Canadian Hydraulics Centre, National Research Council, Ottawa, ON, Canada K1A 0R6
3 - SLG Stanley Consultants Inc., Suite 400, 1122 - 4th St. SW, Calgary, AL, Canada T2R 1M1
4 - Strait Crossing JV, Trans Canada Hwy at Dickie Rd., Borden-Carleton, PEI, Canada C0B 1X0
5 - Golder Associates, 200 Union Blvd., Suite 500, Lakewood, CO, USA 80228

Overview of Project

The Northumberland Strait separates Prince Edward Island (PEI) from the mainland provinces of New Brunswick (NB) and Nova Scotia (NS), as shown in Figure 1.

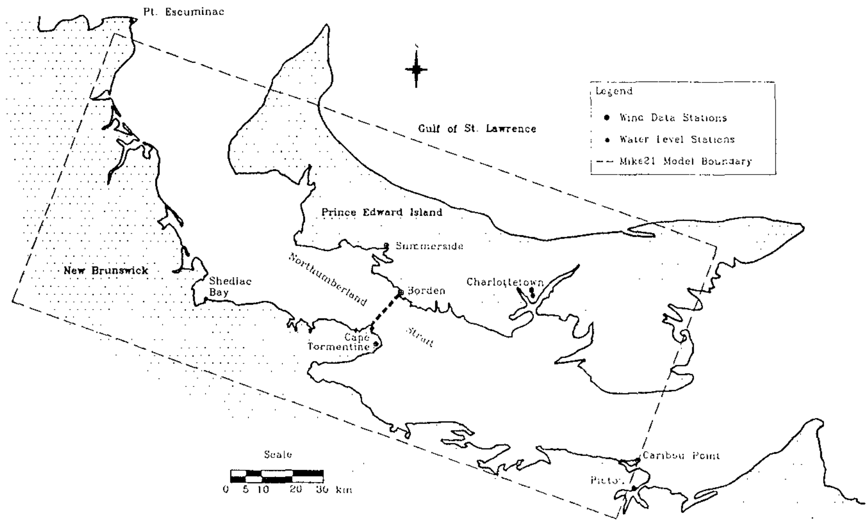

Figure 1 - The Northumberland Strait

At the crossing location, the Strait is approximately 13 km wide, with water depths ranging from 0 to 30 m (typically in the order of 15 m). Under extreme design conditions, this site (and the bridge) may be exposed to 120 kph winds, 4.5 m/9 s waves (Hs/Tp) and 2.5 m/s currents (the latter generated by the combined effects of tides, surges and wave-driven longshore currents). In addition, the Strait has a very dynamic ice environment, with ice present two to three months per year, level ice thicknesses of up to 1.2 m, and first year pressure ridges with keel depths of up to 15 m.

Ice forces on the bridge, and the effect of the bridge on ice breakup in the Strait, were the dominant design considerations for the bridge. The bridge structure consists of the east (PEI) and west (NB) approach bridges (93 m spans) and the main bridge (250 m spans). There are 7 approach piers on the PEI side and 14 on the NB side, and 44 main piers in between. Figure 2 provides a schematic illustration of one of the main piers, and shows the conical pier base, the conical ice shield and the pier shaft. For the approach piers, which are located in shallow water (depth < 8 m), the eonical pier base is also the ice shield.

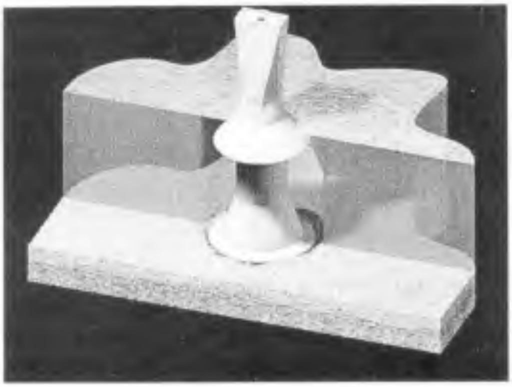

Figure 2 - Typical Main Bridge Pier

In order to meet the very tight project schedule, the primary bridge components (pier bases, ice shield/pier shaft, approach spans, main spans and drop-in spans) were all pre-cast in two production yards. Simultaneously, the pier foundations were prepared, including dredging/excavation to the founding elevation, and the placement of "hardpoints" to provide a level surface on which to place the pier bases. The main bridge components were then transported and placed using the heavy lift vessel (HLV) "Svanen" (see Figure 3), followed by connection of individual components. Construction began in the middle of 1994, and the final main bridge component was placed by the "Svanen" in November 1996. The bridge is scheduled to open in May 1997.

Figure 3 - Bridge Under Construction and HLV "Svanen" (view from PEI)

Overview of Development of Scour Assessment Methodology

Initially, an extensive literature survey was undertaken in an attempt to identify scour assessment techniques that could be applied to the Northumberland Strait Crossing Project (NSCP) (Baird, 1996). After reviewing all of the available information, including the HEC-18 manual of the U.S. Department of Transportation (1993), it was concluded that there was no acceptable technique to define scour potential for the NSCP bridge piers due to the following unique features/conditions associated with the project:

- combined waves and currents;
- conical shape of the pier bases;
- location of some pier bases in dredged pits (up to 7 m deep); and
- highly weathered/fractured and variable bedrock seabed.

An initial laboratory study was undertaken (Cornett et al, 1994) in an attempt to characterize and quantify the erosion potential of the various seabed materials at the crossing location. This investigation was completed in a tilting flume, and consisted of exposing intact samples (both slabs and cores) of various materials (glacial till, mudstone, siltstone and sandstone) to both open channel flows and submerged jet flows. The erosion process was found to be quite complex, and it was not possible to reliably quantify erosion of these materials as a function of either near bed velocity or shear stress.

Following these tests, the literature review was updated (Baird, 1996), leading to the identification of a promising new approach (Annandale, 1995) to estimate the erosion potential of "complex materials" (such as weathered and fractured bedrock). In general terms, Annandale's (1995) approach relates the driving force for scour, as defined by the "stream power" parameter, P (which provides a measure of the rate of energy dissipation in the near bed flow), to the resistance to scour, as defined by the "erodibility index" parameter, EI (which provides a measure of the in-situ strength of the material based on data derived from borehole logs). Annandale's (1995) database, and his relationship between stream power and erodibility index (which defines the threshold for scour) is based on observations of scour (or no scour) in spillways downstream of dams. In order to develop and apply this methodology to the NSCP, it was necessary to not only define the stream power (driving force for scour) and erodibility index (resistance to scour) for the unique conditions associated with the NSCP, but also to calibrate and verify the methodology for the assessment of scour potential around conical bridge piers exposed to combined waves and currents.

Driving Force for Scour

Two general issues must be addressed with respect to quantifying the driving force for scour for the NSCP bridge piers. First, the ambient flow conditions (waves and currents) at the crossing location must be defined, and second, the local influence of the bridge piers on these flow conditions must be defined.

Ambient Flow Conditions

Numerical modelling techniques were utilized to define the ambient flow conditions at the crossing location. A parametric wind-wave hindcast model was used to estimate the wave height, period and direction at four points along the crossing alignment on an hourly basis between 1960 and 1995. This 36 year period corresponded to the duration of available wind data in the vicinity of the Northumberland Strait. The hindcast model was calibrated (through modification of the overland wind data to represent overwater winds) against recorded wave data (five months) available in the immediate vicinity of the crossing, and excellent agreement was obtained for both wave height and period. Weekly composite ice charts were also reviewed, and wave conditions were set to zero during periods of significant ice cover on the Strait (typically two to three months per year).

The MIKE21 hydrodynamic model, developed by the Danish Hydraulic Institute, was used to estimate water levels and currents throughout the Strait on an hourly basis for the 23 year period between 1973 and 1995. The model utilized a 2.5 km grid spacing, and covered a total area of 95 by 208 km. The model boundary conditions were defined by recorded water level data at the model boundaries (Pictou, NS, and Pt. Escuminac, NB), thereby incorporating the effects of both tides and surges. The model was calibrated using recorded current data in the vicinity of the crossing location, and was verified against recorded water level data at locations on either side of the crossing (Charlottetown, PEI and Shediac Bay, NB). The model provided excellent agreement with the recorded current data, and also provided a good simulation of the very different tidal conditions at the two intermediate water level stations. The model results (hourly estimate of water level and current speed and direction) were extracted for the same four points as used in the wind-wave hindcast analyses. A sample output (vector plot of currents) for the hydrodynamic model is provided in Figure 4.

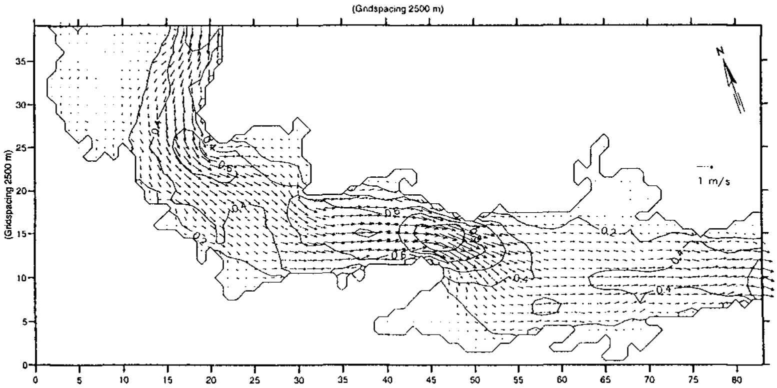

Figure 4 - Sample of Hydrodynamic Model Results (vector plot of currents)

A combined database (23 year hourly time series) was then developed for the four points along the crossing alignment, including wave height, period and direction, current speed and direction and water level. Shallow water processes, including refraction, shoaling, breaking and wave-driven longshore currents, were then estimated using the COSMOS model of coastal processes (Southgate and Nairn, 1993) in order to estimate the wave conditions at the shallow water approach piers (depth < 8 m). The stream power parameter, P, which defines the rate of energy dissipation in the flow, was then calculated as the product of the near bed shear stress and the near bed velocity, considering the combined effect of both waves and currents. The combined near bed shear stress was calculated using the method of Myrhaug and Slaatelid (1990), as presented in Soulsby et al (1993). The combined near bed velocity was calculated as the vector sum of the maximum wave orbital velocity and the depth-averaged tidal/surge current. Stokes second order wave theory was used in "deep" water (Ursell number < 26.3), while Cnoidal wave theory was used in "shallow" water (Ursell number > 26.3). Given the importance of water depth on wave orbital motions, these calculations were completed for a range in water depths representative of the 65 bridge pier locations.

Based on these calculations, a 23 year hourly time series of stream power was developed for a range in representative water depths. Severe stream power events were identified and extracted for each water depth, and extreme value analyses were completed to define the stream power parameter as a function of return period. The 100 year stream power event (considering the combined effect of waves and tidal/surge currents) was selected as the ambient design event for this project.

Local Influence of Bridge Piers

The presence of the piers in the Strait will result in accelerated flows and vortices in the immediate vicinity of the piers, leading to an increase in the driving force for scour around the base of the piers. The influence of the various pier shapes and dredged pit depths (0 to 7 m) on the local flow conditions around the base of the piers was investigated for a representative range of water depths using a 1:70 scale model in a test flume at the Canadian Hydraulics Centre (Cornett, 1996). Figure 5 shows a photograph of typical model approach and main piers.

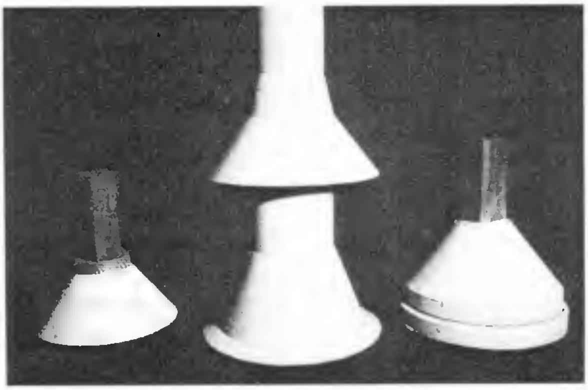

Figure 5 - 1:70 Scale Models of Bridge Piers
(L - West Approach Pier, C - Main Pier, R - East Approach Pier)

The test flume was connected to a 0.2 m^3/s pump and flow circulation system to generate unidirectional currents, and a wave generator at both ends of the flume cabable of generating both regular and irregular wave conditions. As such, it was possible to test waves with both following and opposing currents. The test section was located on a raised floor in the center of the flume. The flow patterns around the base of the pier were defined with the aid of a laser doppler velocimeter, acoustic velocity meters, flow visualization and tracer materials. Figure 6 presents a schematic diagram of the test flume.

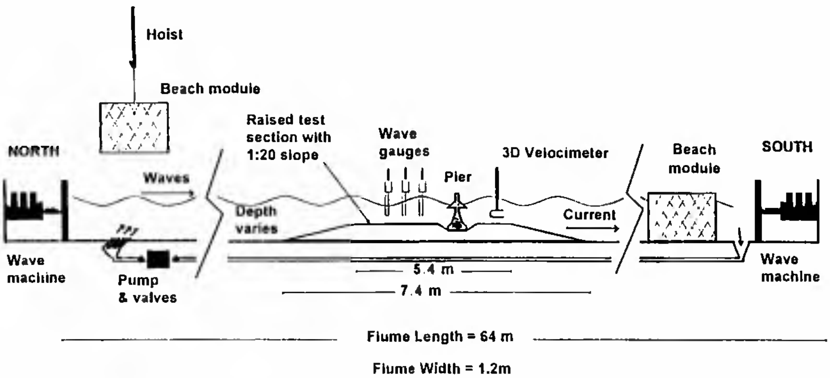

Figure 6 - Schematic Diagram of Test Flume

Stream power magnification factors were developed for the various water depths and pier geometries encountered at the 65 bridge piers through a comparison of the stream power required to initiate the scour of a tracer material (coarse sand or fine gravel) with and without the pier in place. The stream power magnification factors varied from 1.5, for a deepwater main pier founded in a 7 m dredged trench (Figure 7), to approximately 6, for a shallow water approach pier founded directly on the seabed (Figure 8). The product of the local 100 year ambient stream power and the local pier influence factor (stream power magnification factor) defined the design driving force for scour at each of the 65 bridge piers.

Figure 7 - Scour in Tracer Material for Main Pier Founded in a Dredged Pit

Figure 8 - Scour in Tracer Material for Approach Pier Founded on Seabed

Seabed Resistance to Scour

Estimating the erodibility of the various highly weathered bedrock materials was one of the most challenging aspects of this project. As noted earlier, the laboratory tests in the initial phase of the investigation revealed that the erosion process was very complex, and was not a direct function of either near bed shear stress or near bed velocity. Ulitmately, the empirical erodibility approach developed by Annandale (1995) was adopted. In this approach, the erosion resistance of the material is quantified by the "erodibility index", EI, which characterizes in-situ strength of the material, considering the mass strength of the material, the typical "particle" size, and the interparticle "friction". This parameter is calculated as the product of four dimensionless variables, all defined from information derived from standard geotechnical borehole logs, as summarized below:

$$EI = Km * Kb * Kd * Js$$

where EI = Erodibility Index
Km = Mass Strength Number
Kb = Block Size Number
Kd = Joint Roughness Number
Js = Joint Structure Number

As part of the geotechnical investigation undertaken to support the design of the NSCP bridge piers and foundations, between two and ten boreholes were drilled at each of the 65 bridge piers locations. For the scour assessment study, erodibility indices were calculated by the geotechnical engineer (Golder Associates) for each core run (approximately 0.3 m lengths) for each of these boreholes (approximately 300 in total). In general, the erodibility indices showed considerable variation (orders of magnitude) in both the horizontal and vertical dimensions. This variation reflected the highly variable nature of the materials on which the bridge piers are founded. In addition, it is noted that all of the boreholes were located under the pier bases, and not in the zone surrounding the pier bases where scour would initiate. This variability and uncertainty in the strength (erosion resistance) of the seabed materials was a primary consideration in the incorporation of a factor of safety in the assessment of scour potential for the bridge piers.

Calibration of Methodology

The NSCP represents the first application of Annandale's (1995) approach to bridge piers, waves and currents, or design of any kind. As such, calibration and verification of the methodology was a key component of the investigation.

Fortuitously, observations of actual scour experienced around one of the first four approach piers installed early in the project provided valuable information for calibration of the new methodology. More specifically, scour around one of these approach piers (Pier E7) was noted following a storm event (in November 1994) during construction of the piers. Figure 9 provides a schematic illustration of the observed scour, which extended up to 5 m out from the base of the pier, with undermining up to 1 m in and 1.5 m below the base. Scour was not observed around the other piers in place at the time of this event.

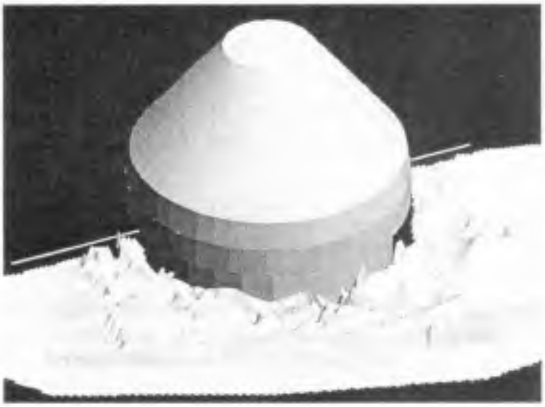

Figure 9 - Scour in Bedrock Observed Around and Under Pier E7

The wave and current conditions which caused the scour during this event were hindcast using the numerical models described earlier, and indicated that the event had a return period (based on the stream power parameter) of approximately five years. The flow patterns around the pier were modeled for this event in the 1:70 physical model investigation. Based on this information, along with the geotechnical data describing the seabed conditions in the vicinity of the four approach piers, an attempt was made to calibrate Annandale's (1995) methodology for this project. The key calibration parameters were the wave height (ie. Havg, Hs, H1/10, Hmax), the wave period (ie. Tavg, Tp, Tmax), the shear stress (ie. Tmean, Tmax) and the bottom roughness (ks). Ultimately, the best comparison between estimated and observed scour at Pier E7 was obtained using Hmax, Tmax, Tmax and a bottom roughness of 0.3 m. The use of the maximum wave height, period and shear stress values can be qualitatively justified by the hypothesis that the erosion of the highly weathered and fractured bedrock materials present at this site is a threshold process, and that once a rock fragment has been dislodged and removed from the matrix, the remaining material can be readily eroded. The lack of scour at the other three piers in place at the time of the November 1994 storm event can be explained by the presence of stronger materials (ie. higher EI values) on the seabed at these pier locations.

A qualitative confirmation of the scour assessment methodology was also made through consideration of the morphological development of the sea bed across the Strait. Through the application of the erodibility index approach, it was possible to explain the existence of a glacial till (soft clay/silt/sand) over the underlying bedrock for areas with depths greater than about 13 m. More specifically, in these areas, the 100 year stream power was less than the stream power required to erode the till material according to Annandale's (1995) approach. Together, the quantitative and qualitative observations of scour substantiated the methodology for the assessment of scour potential for the Northumberland Strait conditions.

A detailed review of Annandale's (1995) database, in particular the critical data points which describe the threshold condition for scour for erodibility indices similar to those encountered at the pier bases for the NSCP, was also undertaken in order to assess the compatibility of Annandale's database to the hydrodynamic and geotechnical conditions associated with the NSCP. In general, it was found that the critical data points which define the threshold condition for rock and complex earth materials represent similar rock conditions to those encountered in this project. Further, the hydrodynamic conditions for these data points, although not generated by wind-waves and tidal/surge currents, were associated with high velocities and turbulent flow conditions. As such, it was concluded that Annandale's (1995) scour threshold relationship could be applied to the NSCP.

Requirement for Scour Protection

A pier by pier assessment was undertaken in order to assess the requirement for scour protection at each of the 65 bridge piers. In general, this assessment consisted of the following steps:

- define the "critical depth zone" beneath the foundation of each pier (considering the allowable scour, which varies from 0 to 0.5 m the various approach and main pier foundation designs);
- define erodibility indices (based on available borehole data) within the critical depth zone, and estimate the corresponding threshold stream power for scour;
- compare local design stream power (100 year ambient value times pier magnification factor) to local threshold stream power;
- recommend protection if factor of safety is less than two to four.

The factor of safety was incorporated to address uncertainties associated with the driving forces, resisting forces and scour threshold relationship. The key uncertainty was the highly variable seabed conditions. A higher factor of safety was applied at piers with greater variation in seabed conditions, and/or where the tolerance for scour was lower. Ultimately, scour protection was recommended for approximately one quarter of the 65 bridge piers.

Design of Scour Protection

The design of the scour protection system around the base of the piers was developed and optimized using a physical model investigation. The test facilities and setup were very similar to that described earlier for the tracer tests undertaken to quantify the pier magnification factors. In general, these tests indicated that the influence of the piers on flow conditions extended approximately 7 to 9 m out from the toe of the conical pier bases. As such, a 10 m wide band of scour protection was adopted. Scour protection designs were initially developed using either one or two layers of armour stone. For the shallow water approach piers, these armour stones were in the order of 2 to 7 tonnes. Smaller armour materials were adequate for deep water piers. Figure 10 shows a picture of a scour protection test in progress.

Figure 10 - Scour Protection Test at Shallow Water Approach Pier

Subsequently, construction considerations led to the development of a scour protection system using tremie concrete. Again, this system extended out 10 m from the base of the pier. The key design details associated with the tremie concrete solution were careful cleaning of the seabed prior to concrete placement, and construction and monitoring operations adequate to provide a minimum 0.5 m thick mat of concrete over the seabed.

Monitoring Program

An extensive monitoring program has been recommended in order to quantify potential scour events over the design life of the Northumberland Strait Crossing Project, and to document scour which may occur around the base of the bridge piers. This monitoring program has been recommended for several reasons, as noted below:

- the scour assessment methodology utilized for this project is new, and has never been applied to bridge piers, waves and currents, or design of any kind;
- there are uncertainties associated with the estimation of both the driving forces for scour and the seabed resistance to scour;
- there is a desire to minimize seabed survey requirements around the base of the bridge piers associated with the monitoring program.

The monitoring program will consist of a near real-time wave and tide prediction system installed at the site. The prediction system will utilize numerical models similar to those used to develop the design database for this project. This system will run continuously, and will quantify the magnitude of potential scour (ie. stream power) events to which the bridge is exposed. Over time, a data base will be developed for each pier documenting the conditions to which the pier has been previously exposed (based on the prediction system) and the response of the seabed to these conditions (ie. scour or no scour, based on detailed surveys of the seabed). The database will be updated on a regular basis, and the system will identify any requirement for action by the bridge operation and maintenance staff. For example, additional surveys of the seabed around any particular pier will be required if the pier has been exposed to an event greater than any prior event, or if a certain period of time has elapsed since the last survey.

Conclusions

A multi-faceted coastal engineering investigation has been completed to support the assessment of scour around bridge piers for the Northumberland Strait Crossing Project. The application of conventional scour design techniques to this project was precluded by the unique conditions associated with this project, including complex flow conditions (combined waves and currents), complex pier base geometry (conical pier bases, with some located in dredged pits), and complex foundation materials (highly weathered and fractured bedrock).

The investigation has led to the development of a new methodology to assess scour potential around bridge piers which can address the unique conditions noted above, but can also be applied to more conventional/less complicated scour design problems. The new methodology is based on the empirical erodibility approach of Annandale (1995), and has been developed, calibrated and verified, to the extent possible, for this project. A detailed, long-term monitoring program will be implemented upon completion of the project in 1997, and will be used to verify this new scour design methodology.

Photograph of Bridge Nearing Completion

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