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Confederation Bridge – New Scour Design Methodology for Complex Materials

R.B. Nairn¹ and C.D. Anglin²

ABSTRACT

The \$800 million Confederation Bridge, spanning 13 km across the Northumberland Strait in Eastern Canada, presented many engineering challenges, one of which was the assessment of scour potential and protection requirements for the 65 bridge piers. The direct application of standard scour assessment/design techniques was not possible for this project due to the combination of complex flow conditions (waves and currents), complex pier geometries (conical pier bases, with some piers located in dredged pits), and complex seabed conditions (highly weathered and fractured bedrock). A multi-faceted coastal engineering investigation was undertaken by Baird & Associates to assess scour potential, define scour protection requirements and design scour protection. Key activities included geotechnical investigations to define the seabed characteristics, numerical modeling to define the wave, current and water level conditions at the crossing site, physical modeling of wave-current interaction with the bridge piers, the development of a new methodology to estimate the scour potential of the seabed around the bridge piers under extreme wave and current conditions, and post-construction scour monitoring. This paper provides an overview of the investigations completed, including a description of the new scour design methodology and the results of the scour monitoring program over the five year period since the bridge was completed.

INTRODUCTION

The 13 km long, \$800 million Confederation Bridge crosses the Northumberland Strait and joins the provinces of New Brunswick and Prince Edward Island in Eastern Canada (refer to Figure 1). The bridge, developed under a finance-design-build-operate agreement between Strait Crossing Bridge Limited (SCBL) and the Canadian Government, was constructed in 1994-97, and opened to traffic on June 1, 1997.

Figure 1 – The Confederation Bridge



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One of the engineering challenges associated with this \$800 million project was the assessment of scour potential and scour protection requirements for the 65 bridge piers. The direct application of standard scour design techniques (such as those documented in TAC, 1973 and HEC-18/FHWA 1993, available at the time of the original design investigations) was not possible due to the unique combination of complex flow conditions, complex pier base geometries and complex seabed conditions. This paper provides an overview of the multi-faceted coastal engineering investigation undertaken to assess the scour potential and scour protection requirements for the Confederation Bridge, and presents a new methodology to assess the potential for scour around bridge piers.

RELEVANT SITE AND PROJECT CHARACTERISTICS

At the crossing location, the Northumberland 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, the bridge may be exposed to winds up to 120 km/h, waves of significant height (H_s) up to 4.5 m and peak period (T_p) up to 9 s, and currents up to 2.5 m/s (the latter generated by the combined effects of tides, surges and wave-driven longshore currents). Seabed conditions are highly variable, and consist of highly weathered mudstone, siltstone and sandstone, which are sometimes overlain by glacial till.

The crossing consists of the main bridge (forty four 250 m long spans), the East approach (seven 93 m long spans) and the West approach (fourteen 93 m long spans). The main bridge piers (P1 to P44) consist of an 8 m wide octagonal shaft cast integral with a conical ice shield (20 m base diameter) and supported by a conical pier base (22 m base diameter). The pier base may rest directly on the seabed or in dredged pits up to 14 m deep. Figure 2a provides a schematic illustration of a typical main pier. For the approach piers (E1 to E7 and W1 to W14), which are located in water depths less than 8 m, the conical pier base is also the ice shield, as shown in Figure 2b.

Figure 2a – Schematic of Main Pier

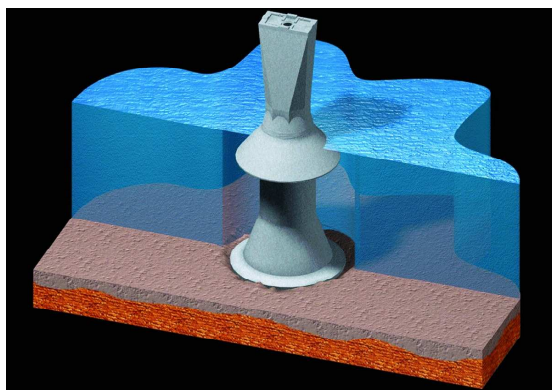


Figure 2b – Model of Approach Pier



The individual bridge components, weighing up to 8,000 t, were pre-cast on land and placed in the Strait using a heavy lift vessel (HLV Svanen) guided by a differential global positioning system (refer to Figure 3).

Figure 3 – HLV Svanen Placing a Main Bridge Span



KEY SCOUR DESIGN ISSUES

An extensive literature review was undertaken in an attempt to identify scour assessment techniques that could be applied to the Confederation Bridge. This included review of numerous technical papers and several design manuals related to scour around bridge piers, as well as numerous papers related to scour around coastal structures. In general, the bridge papers focused on the scour of cohesionless sediments (i.e. sands and gravels) around rectangular or cylindrical piers in unidirectional flows, while the coastal structures papers focused on wave-induced scour of cohesionless sediments along breakwaters, revetments and seawalls (i.e. long, linear structures, without three-dimensional flow effects). In addition, a few papers were reviewed that dealt with erosion/scour of cohesive materials and weak rock by unidirectional flows. However, it was concluded that there were no acceptable techniques to define scour potential for the Confederation Bridge project because of the following unique features and complex conditions:

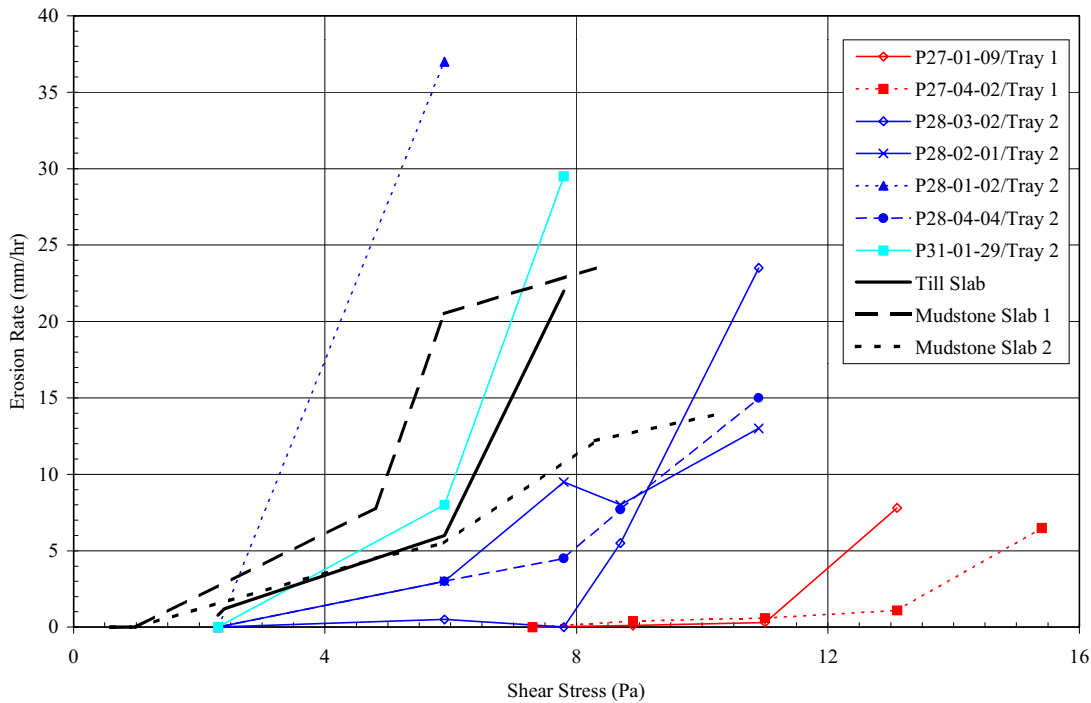
- combined waves and currents;
- conical pier bases, some located in dredged pits; and
- highly weathered and fractured bedrock seabed.

As such, it was necessary to develop a new methodology to assess scour potential for this project.

DEVELOPMENT OF NEW SCOUR ASSESSMENT METHODOLOGY

Initial laboratory studies (Cornett et al., 1994) were undertaken to characterize and quantify the erosion potential of the various seabed materials at the crossing location. This included flume tests to assess the erodibility of both core and slab samples of till, mudstone, siltstone and sandstone. These test results showed considerable variability, as illustrated in Figure 4 for the weakest (till and mudstone) samples.

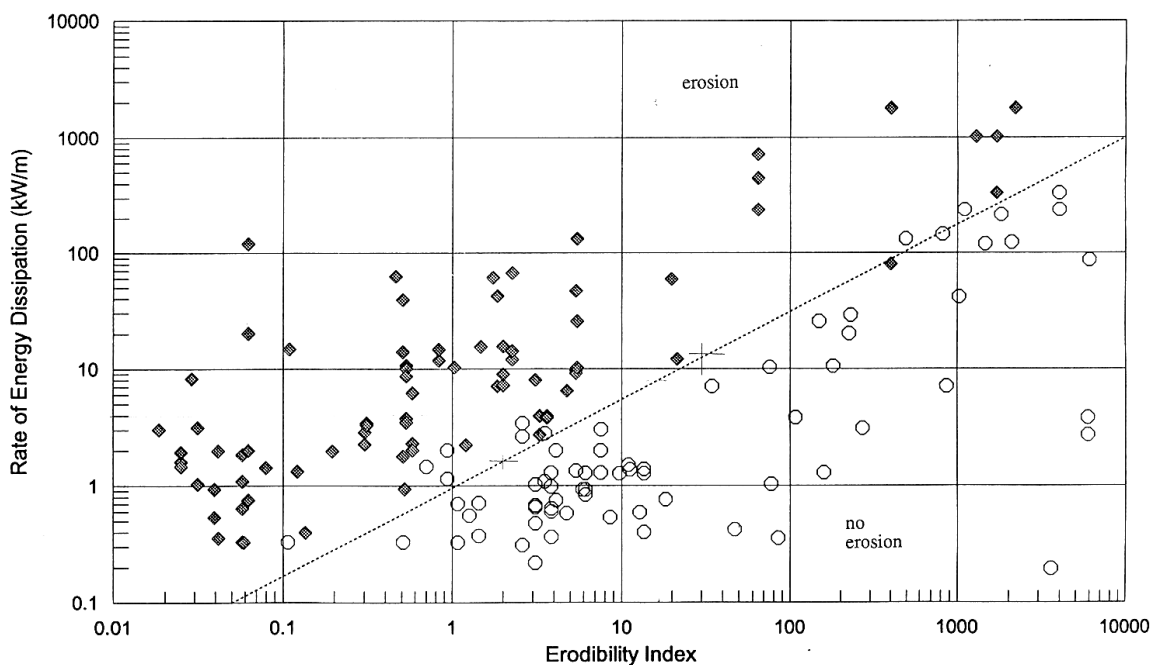
Figure 4 – Erodibility Test Results for Till and Mudstone from Northumberland Strait



Considering the rock materials (mudstone, siltstone and sandstone), it was noted that the sample sizes were not sufficient to incorporate the highly variable bedding/fracture/joint patterns within the insitu rock mass, clearly an important parameter in the overall erosion process for these materials. Given the complex nature of the erosion process, and the associated variability in the test results, it was not possible to develop a reliable method to quantify the erosion process as a function of either shear stress or near bed velocity.

Subsequently, a promising new approach (Annandale, 1995) to estimate the erosion potential of “complex materials” was identified. 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”, EI (which provides a measure of the in-situ strength of the material). Annandale’s (1995) database, and his relationship between stream power and erodibility index (which defines the threshold for scour) is based on observations of erosion (or no erosion) in spillways downstream of dams. A subset of the Annandale database (for “rock and complex earth materials”) is presented in Figure 5. This figure shows a log-log plot of stream power versus erodibility index for approximately 150 field observations in materials ranging from cohesive sediments to hard, massive rock. The closed symbols represent events where erosion did occur, while the open symbols represent events where erosion did not occur. The sloping line is the estimated “erosion threshold” relationship between stream power and erodibility index.

Figure 5 - Erodibility of Rock and Complex Earth Materials
(after Annandale, 1995)



Annandale materials:
 [cohesive sediment] [weathered shale] [sandstone] [dolerite] [hard rock]

Northumberland Strait seabed materials:
 [till] [mudstone, siltstone, sandstone]

As shown above, the estimated erodibility indices for the seabed materials encountered along the Confederation Bridge crossing alignment fall within the range of Annandale's database (the available geotechnical data and EI calculations are summarized later in this paper). However, in order to develop and apply this methodology to the Confederation Bridge project, it was necessary not only to evaluate the stream power (driving force for scour) and erodibility index (resistance to scour) for this project, but also to calibrate and verify the methodology for the assessment of scour potential around conical bridge piers exposed to combined waves and currents. These aspects of the investigation are described below.

Driving Force for Scour

Two general issues must be addressed with respect to quantifying the driving force for scour around the Confederation 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.

Numerical modeling techniques were utilized to define the ambient flow conditions at the crossing location. Tidal and surge induced currents and water levels in the Strait were

estimated on an hourly basis over a 23 year period (1973-95) using the MIKE21 hydrodynamic model of the Danish Hydraulic Institute. The model was driven by recorded water levels at either end of the Strait and the model predictions were successfully verified against available recorded current data (approximately three months) at the crossing location. The mean and large tidal ranges at the crossing location are approximately 1.5 m and 2.25 m respectively, with peak tidal currents (depth-averaged) in the order of 0.9 m/s (during large tides). Water level fluctuations and currents associated with storm surges can be similar in magnitude to the tidal effects.

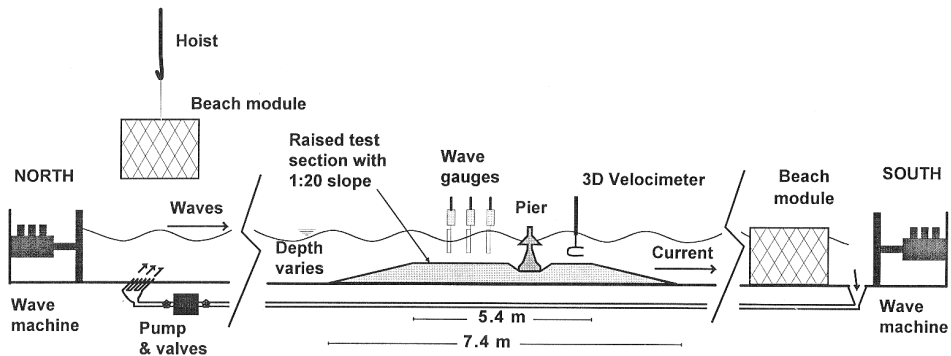
A parametric wind-wave hindcast model was used to estimate hourly wave conditions at four locations along the crossing alignment for the same 23 year period. The wave predictions were validated against available recorded wave data (approximately five months) at the crossing location. Extreme wave heights were estimated using a peak over threshold (POT) extreme value model. For example, the 2-year and 100-year significant wave heights (H_s , the average the highest one third of the waves; the maximum wave height, H_{max} , is typically 1.6 to 2 times H_s) near the middle of the crossing are in the order of 3 m and 4 m respectively. Shallow water processes, including refraction, shoaling, breaking and wave-driven longshore currents, were estimated using the COSMOS coastal processes model (Southgate and Nairn, 1993).

The hindcast water level, current and wave data were used to estimate the near bed velocity, shear stress and stream power, considering the combined effect of both waves and currents, on an hourly basis over the 23 year period of the environmental database. The combined shear stress was calculated using the method of Myrhaug and Slaatelid (1990), as presented in Soulsby et al. (1993), while the combined velocity was calculated as the vector sum of the maximum wave orbital velocity and the depth-averaged tidal/surge current. Stream power was calculated as the product of the combined shear stress and the combined velocity. Given the importance of water depth on wave orbital motions, the calculations were repeated for a range in water depths representative of the 65 bridge pier locations.

Severe stream power events were extracted from the time series data base and input to a POT extreme value model to estimate extreme events as a function of return period. The 100-year event was selected as the design condition to evaluate the requirement for, and the design of, scour protection.

The influence of the various pier shapes and dredged pit depths on the local flow conditions around the base of the piers were investigated for a range in water depths using a 1/70 scale model in a 1.2 m wide flume at the Canadian Hydraulics Centre in Ottawa, Canada (Cornett, 1996). Figure 6 presents a schematic diagram of the test configuration in the flume. The flume setup allowed the simulation of unidirectional currents with either “following” or “opposing” irregular wave conditions at a range in water depths.

Figure 6 – Schematic Diagram of Test Configuration in Flume



The flow patterns around the base of the piers were defined with the aid of a laser doppler velocimeter, acoustic velocity meters, flow visualization and tracer materials. Stream power magnification factors were developed for the various conditions encountered at the 65 bridge piers through a comparison of the stream power required to initiate the “scour” of tracer materials with and without the pier in place. Well-sorted coarse sands and fine gravels were used for the tracer materials, with median grain sizes (D_{50}) ranging from 1 to 5 mm. The tracer mat was placed to a thickness of two to three grains, and “scour” was defined as the complete removal of grains from any area resulting in an exposed patch on the flume floor. This was found to be a more repeatable “threshold condition” than the “initiation of motion” of individual grains for the irregular wave conditions in these tests.

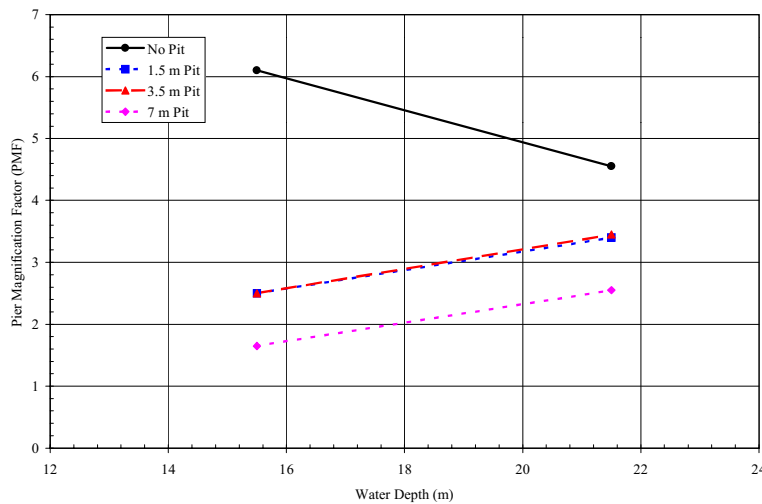
Figure 7 shows photographs of the tracer mat around a model approach pier before and after a test. In general, scour of the tracer mat initiated on either side of the piers as a result of acceleration of flows in these areas. Flow visualization techniques confirmed that a strong horseshoe vortex did not develop on the upstream/upwave side of the piers, probably as a result of the conical shape of the pier base.

Figure 7 – Tracer Mat Around Model Approach Pier Before and After Test



The resulting estimates of the stream power magnification factor (PMF) varied from approximately 1.6 for a deep water main pier placed in a deep pit, to approximately 6 for moderate depth main piers and shallow water approach piers placed directly on the seabed. The tracer test results for the main piers are summarized in Figure 8.

Figure 8 – Main Pier Magnification Factors Estimated from Tracer Test Results



The PMF is proportional to the cube of velocity; hence, PMF’s of 1.6 to 6 correspond to velocity magnification factors of approximately 1.2 to 1.8. The upper limit, for a conical pier base placed directly on the seabed, is somewhat larger than the values recommended in HEC-23 (FHWA, 2001c) for the application of the Isbash equation to design scour protection around round nose and rectangular piers (1.5 and 1.7 respectively). The reduction in PMF with deeper pits infers the existence of an “equilibrium” scour depth that could be estimated using such tracer tests (i.e. no further scour when PMF = 1.0).

Seabed Resistance to Scour

Estimating the erodibility of the highly weathered and variable seabed materials was one of the most challenging aspects of the project. As noted earlier, considerable variation was noted in the results of the erodibility flume tests. Further, the size of the test samples (both cores and slabs) was insufficient to incorporate the highly variable bedding/fracture/joint patterns within the insitu rock mass. As such, it was not possible to describe or quantify the erosion process using only these test results. Ultimately, the empirical erodibility approach developed by Annandale (1995) for scour in spillways was adopted. In this approach, the erosion resistance of the material is quantified by the “erodibility index”, EI, which accounts for the mass strength of the material, the typical block size, the interparticle shear stress, and the orientation of the layers of rock. The erodibility index is calculated as the product of four dimensionless variables, all defined from standard borehole records, as summarized below:

$$EI = K_m K_b K_d J_s$$

- where EI = erodibility index
- K_m = mass strength number
- K_b = block size number
- K_d = joint roughness number, and
- J_s = joint structure number

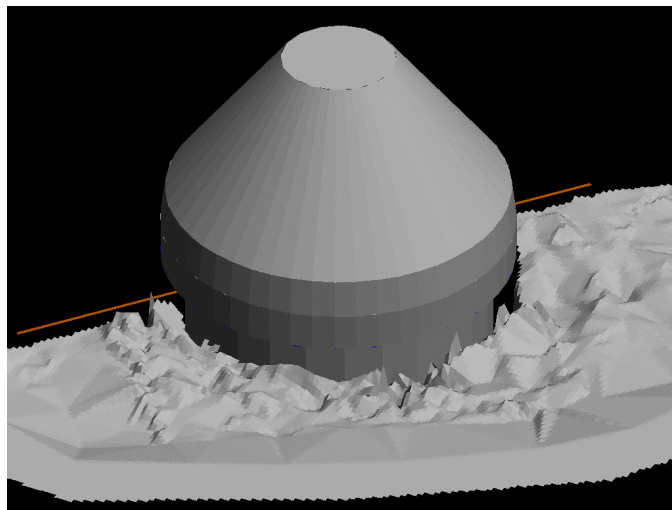
As part of the geotechnical investigation undertaken to support the design of the bridge piers and foundations, between two and ten boreholes were drilled at each of the 65 bridge pier locations. A total of approximately 300 boreholes were drilled. Erodibility indices were calculated by a geologist/geotechnical engineer for each core run (approximately 0.3 m lengths) for each borehole. The erodibility indices showed considerable variability in both the horizontal and vertical dimensions, reflecting the highly variable nature of the materials on which the bridge piers are founded. This variability was a primary consideration in the incorporation of a factor of safety in the scour design methodology.

Calibration of Methodology

The Confederation Bridge represents the first known application of Annandale's (1995) methodology 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 piers installed early in the project provided valuable information for calibration of the new methodology. Figure 9 provides an illustration of the measured scour around Pier E7. The scour extended up to 5 m out from the base of the pier, with undermining of up to 1 m in and 1.5 m below the pier base. This scour was caused by a moderate storm event (return period of approximately five years) that occurred in November 1994. No significant scour was noted around several other East approach piers in place at that time.

Figure 9 - Scour in Bedrock Observed at Approach Pier E7 (Nov. 1994)



The wave and current conditions during this event were hindcast using the numerical models, and the corresponding flow patterns around the piers were simulated in the physical model. Based on this information, along with the geotechnical data describing the seabed conditions in the vicinity of the East approach piers, comparisons of measured and predicted scour were used to calibrate the methodology. The key calibration parameters were the wave height (ie. H_{avg} , H_s , $H_{1/10}$, H_{max}), the wave period (ie. T_{avg} , T_p ,

T_{\max}), the combined shear stress (ie. τ_{mean} , τ_{\max}) and the bottom roughness (k_s). The best comparison between estimated and observed scour at the single pier was obtained using H_{\max} , T_{\max} , τ_{\max} and a bottom roughness of 0.3 m. The use of the maximum wave height, wave period and shear stress can be qualitatively justified by the hypothesis that the erosion process for the weathered bedrock is a threshold process, and that once a rock fragment has been dislodged and removed from the surrounding matrix, the remaining material will be more susceptible to erosion. The lack of scour at the adjacent piers can be explained by the presence of stronger materials at these locations.

A qualitative confirmation of the methodology was also made through consideration of the morphological development of the seabed across the Strait. Through the application of the erodibility index approach, it was possible to explain the existence of glacial till over the underlying bedrock for areas with depths greater than about 13 m (i.e. in these areas the 100-year stream power event was less than the stream power required to erode the till material according to Annandale's (1995) relationship).

REQUIREMENT FOR SCOUR PROTECTION

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

- for each borehole at each pier, define the maximum EI value in the “buffer zone” between the seabed (or the mass excavation level for piers placed in a dredged pit) and the pier founding elevation; these “local EI values” represent the strength of the most erosion resistant material above the pier founding elevation (note that scour is allowed in the buffer zone, but not below the pier founding elevation);
- estimate the “design threshold EI value” at each pier based on the local design stream power (100-year ambient stream power value times pier magnification factor) and Annandale's (1995) scour threshold relationship;
- compare the “local EI values” at each pier to the “design threshold EI value”, and recommend scour protection if the factor of safety (local EI value/design threshold EI value) is less than two to four (a higher factor of safety was used at piers with greater variability in seabed conditions, and/or where the tolerance for scour was lower).

Based on the results of this assessment, scour protection was recommended at 14 of the 65 bridge piers.

MODELING AND DESIGN OF SCOUR PROTECTION

The design of the scour protection system was developed and optimized using a physical model investigation. These model tests were completed in the same wave flume as the tracer tests described earlier, again at a scale of 1:70. The scour protection tests were used to define the size of armour stone required to remain stable during the 100 year design wave and current conditions. The extent of the scour protection was defined based

on the results of the tracer tests, which defined the “zone of influence” of the piers where ambient flow conditions were significantly affected by the presence of the pier. The recommended protection design consists of one or two layers of armour stone placed in a 10 m wide band around the base of the piers. The size of the armour stone is dependent on the water depth, with larger stones being required in shallower depths. Additional information on the modeling and design of the armour stone scour protection is provided in a companion paper in these proceedings (Anglin et al, 2002).

CONSTRUCTION

SCBL chose to install scour protection at five of the 14 piers where Baird recommended protection. This decision was based on careful consideration of the cost of scour protection (approximately \$0.5 million per pier) versus the risk of scour, recognizing the significant uncertainties and (likely) conservative approach to the assessment of scour potential. Armour stone scour pads were installed at three approach piers (refer to Figure 12), while construction logistics led to the design and implementation of tremie concrete scour pads at two other approach piers (refer to companion paper by Anglin et al (2002) in these proceedings for additional information).

Figure 12 – Armour Stone Scour Pad at Shallow Water Approach Pier (photo by Boily)



In response to SCBL’s decision, Baird recommended a detailed and systematic scour monitoring program. This recommendation was accepted by SCBL; the resulting monitoring program is discussed further below.

SCOUR MONITORING PROGRAM

An extensive long-term monitoring program was designed and implemented by Baird in order to assist SCBL in identifying any scour that might occur around the base of the bridge piers such that appropriate action can be taken before scour compromises the integrity of the structure (ie. before scour extends beneath the founding elevation of any pier). The scour monitoring program is a critical component of the overall scour investigation for the following reasons:

- the Confederation Bridge represents the first known application of the new scour assessment methodology to bridge piers, waves and currents, or design of any kind;

The output from the system is digitally archived to provide a historical database for each pier documenting the conditions (stream power) to which each pier has been exposed since the bridge opened in June, 1997.

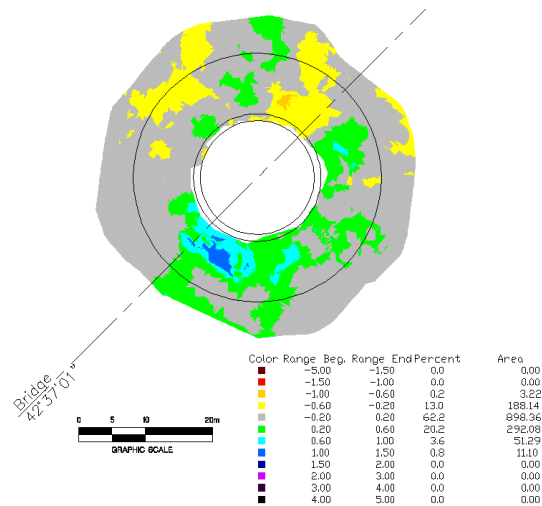
SCBL has followed this monitoring program since the bridge opened in 1997, and has undertaken at least one diver inspection around every pier, and numerous diver inspections around the high priority AA piers. Scour was detected during a diver inspection around one of the AA piers (P41) in 1998 (despite the fact that the scour hole was partially infilled with loose granular material). The scour reached a maximum depth of 1.6 m below the original seabed (approximately 1 m below the pier base elevation), and extended 12 to 15 m out from the pier base over a +/-100 degree sector. This pier was subsequently protected with an armour stone scour pad.

No significant scour has been observed around any of the other piers during diver inspections, despite the fact that the bridge has been exposed to several moderate storm events (the most severe of which had an estimated return period in the order of five years) for which the original scour assessment predicted scour at some of the AA piers. These results suggest that the original scour assessment may be conservative, as intended.

However, it is noted that diver inspections are qualitative, and can only identify significant changes or specific problems in localized areas (i.e. scour below the pier base). The diver inspections might not identify widespread, ongoing scour around a pier base. Further, it is interesting to note that P41 was not the most critical AA pier, and that scour was predicted to occur at other piers before it actually occurred at P41 (i.e. other AA piers had lower estimated factors of safety against scour). This information highlights the limitations and uncertainties in the original scour assessment methodologies, principally as a result of the large variation in (and limited characterization of) seabed material characteristics, but also the application of a new methodology for scour potential in complex materials subject to complex flow conditions.

In response to these issues, and to SCBL's interest in reducing their monitoring requirements/costs, Baird again recommended that a systematic reassessment of the scour assessment and design methodologies be undertaken. SCBL has initiated this process, with detailed multi-beam sonar (MBS) seabed surveys being undertaken around 14 piers (including all nine AA piers) in the summer of 2001. The remaining piers are to be surveyed using MBS in the summer of 2002. The MBS survey data provide an accurate description of the existing seabed surface, and have be overlain on the pre-construction/as-built seabed surveys to allow an estimate of changes in the seabed elevation between the two surveys. A sample result, showing the change in seabed elevation around a West approach pier between 1997 (as-built) and 2001 (four years later), is presented in Figure 14.

Figure 14 – Sample Contour Map of Change in Seabed Elevation, 1997-2001



This information, along with the archived wave/current information and the results of diver inspections undertaken between 1997 and 2002, will be used to review/verify/refine the scour assessment and design methodologies, and, if possible/appropriate, to support a reduction in the scour monitoring requirements.

CONCLUSIONS

A multi-faceted coastal engineering investigation was completed to support the assessment of scour and design of scour protection around the Confederation Bridge piers. This investigation led to the development of a new methodology to assess scour potential around bridge piers which can address complex flow conditions, pier geometries and foundation materials, but can also be applied to less complicated scour design problems. This methodology, derived from the empirical erodibility approach of Annandale (1995), has been calibrated for the Confederation Bridge project on the basis of the seabed response (scour or no scour) measured around four approach piers in place during a moderate storm event which occurred early in the construction period.

An extensive long-term monitoring program has been implemented to quantify the exposure of the bridge piers to potential scour events, to identify and address any scour that does occur, and to provide the information necessary to verify and improve the new scour assessment methodology. Preliminary results of the monitoring program, including diver inspections around all piers and multi-beam sonar seabed surveys around selected piers, suggest that the original scour assessment methodology may be conservative, as intended. A detailed reassessment study has been proposed, but has not yet been undertaken.

It is noted that the Annandale (1995) approach is referenced in the most recent version of HEC-18 (FHWA, 2001) in Appendix M – Scour Competence of Rock. The Confederation Bridge project represents the first known application of this method to bridge scour assessment and design.

ACKNOWLEDGEMENTS

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