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Riprap as a Permanent Scour Protection Around Bridge Piers

D. Anglin[1], F. Itamunoala[2], G. Millen[3]

ABSTRACT

Scour design guidance in the United States (FWHA, 2001a, b, c) allows the use of riprap as a countermeasure to reduce the risk/implications of scour for existing bridges, but does not allow its use for new bridges. Rather, the foundation of new bridges must be placed "at such a depth that the structural stability will not be at risk with maximum scour". This approach may have significant implications with respect to the design and cost of the bridge structure. In contrast, riprap is generally accepted as a permanent countermeasure against scour for bridges in Europe (TRB, 1999) and in Canada (TAC, 2001). In addition, thousands of "rubblemound" structures have been designed and implemented in the field of coastal engineering over the past 150 years, including breakwaters (to protect harbour and other marine facilities), revetments, embankments and dams (to prevent erosion) and scour protection (for coastal structures, marine pipelines, etc.). Some of this experience can be applied to the design of scour protection for bridges.

Baird has recently undertaken scour assessments for two large bridges in Eastern Canada, including the St. John River Bridge on the Trans-Canada Highway in New Brunswick and the Confederation Bridge across the Northumberland Strait between New Brunswick and Prince Edward Island. Extensive analyses were undertaken for both projects in order to estimate potential scour depths, assess alternative scour countermeasures, and design effective scour protection systems. Physical modeling was undertaken in order to design riprap scour pads to prevent scour around the piers while also remaining stable under the extreme design conditions.

This paper provides an overview of these two projects and scour-related issues, focusing on the investigations undertaken to develop designs for riprap scour pads to provide permanent protection against scour. In particular, it is concluded that a carefully designed physical model investigation provides an accurate and cost-effective tool to assess/quantify the performance of riprap scour protection systems under extreme flow conditions, thereby allowing the design of permanent scour protection systems that may result in significant cost savings for many bridge projects.

THE ST. JOHN RIVER BRIDGE

Overview of Project

The Province of New Brunswick has recently upgraded the Trans-Canada Highway (TCH) between Fredericton and Moncton to a four lane freeway. This $585 million

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project includes 195 km of freeway, 58 interchanges and six river crossings, and opened in 2001 (see http://www.gnb.ca/dot/fred-mon.htm).

Baird, under contract to the Maritime Road Development Corporation (MRDC), was responsible for the scour assessment and design for the St. John River Bridge (refer to Anglin et al, 2001). This is a 1 km long high level structure supported by thirteen pile-supported piers (eleven standard piers and two larger main piers), with earth fill approach embankments and concrete abutments at either end of the structure (refer to Figure 1).

Figure 1 – The St. John River Bridge

The 100 year design conditions at the crossing location were defined by others using hydrodynamic model simulations. The peak water level was estimated to be +6.4 m GD, while the peak velocity was estimated to be 2.2 m/s in the navigation channel (near the main piers), with reduced velocities towards either riverbank.

Five of the piers are located on the flood plain (existing land elevation = +2 to +4 m GD), while eight are located within the main river channel (riverbed elevation = -3 to -5 m GD). The riverbed consists of loose, fine silty sand, with the potential for significant scour. Scour depth calculations undertaken using several methodologies, including those recommended in HEC-18 (FHWA, 2001a), suggested local scour depths of 6 to 12 m around the various piers and abutments. Contraction scour was estimated to be 1 m.

Preliminary Design of Scour Protection – Empirical Procedures

Given the potential for significant scour around the piers and abutments, preliminary designs were developed for riprap scour pads based on available published procedures. In general, these procedures are based on theoretical considerations and/or empirical analyses of physical model test results. A list of the more common methodologies is provided below, along with the design manuals in which they are referenced:

- Canadian “compromise” curve (TAC, 1973; TAC, 2001);
- Isbash equation (ASCE, 1975; USACE, 1984; FHWA, 1989; FHWA, 2001c); and
- Maynord equation (USACE, 1994; TAC, 2001, USACE, 2001).

Numerous other scour protection design methodologies have been published in the technical literature, but have not yet received widespread application or been incorporated in design manuals. Each approach requires the definition of various input parameters, the most important of which are listed below:

- Density of riprap (ρ_r) and water (ρ_w);
- Ambient flow velocity (V) - including adjustments for pier location considering river alignment (i.e. straight or curved), cross-sectional variations, etc.;
- Velocity magnification factor (K) - to account for local influence of the bridge pier on flow conditions (the TAC, Isbash and Maynord approaches require specification of this parameter; the other methods inherently incorporate the local influence of the bridge pier on flow conditions, but require specification of a pier shape coefficient);
- Water depth (d);
- Factor of safety (FS); and
- Bed slope (θ)

Riprap design calculations were undertaken using various methods for the eleven standard piers and two main piers along the St. John River Bridge. The piers consist of a number of 0.7 m diameter vertical and battered piles (typically spaced at 1.7 m center to center) extending down from the pile cap into the riverbed. The overall width of the standard piers (based on the area encompassed by the pile caps and piles) ranges from 7.5 to 10 m between the water surface and the riverbed, with a “flow blockage ratio” in the order of 50 to 70% depending on the water level (debris blockage could increase this to 100%). The main piers are similar, but larger, with their overall width ranging from 12 to 15 m.

The riprap design calculations were undertaken for the 100 year design velocity of 2.2 m/s. A velocity magnification factor (K) of 1.7 was assumed for the TAC, Isbash and Maynord approaches in the absence of any relevant guidance for pile-supported piers. “Effective” pier widths of 7.5 and 12 m were assumed for the standard and main piers respectively. The results of the main pier calculations (design water depth = 10.4 m) are presented in Table 1.

Table 1
Empirical Estimates of Riprap Scour Protection Requirements
St. John River Bridge, Main Piers

Methodology/Reference	Stone Size D_{50} (m)	Min. No. of Layers	Min. Layer Thickness, t (m)
TAC (1973, 2001)[1]	0.45	2	0.9
Isbash/FHWA (1993)[1]	0.33	3	1.0
Maynord/USACE (1994)[1, 2]	0.23	1.5	0.5
Parola (1993)	0.41	n/a	n/a
Chiew (1995)[3]	0.10 to 0.37	n/a	n/a
Fotherby & Ruff (1996)	0.55	2	1.1
Lauchlan & Melville (2001)	0.50	2	1.0

Notes:

1. TAC, Isbash and Maynord calculations assume K = 1.7.
2. Maynord approach gives D_{30}; result has been converted to D_{50} assuming $D_{50} = 1.25*D_{30}$, based on assumed riprap gradation with $D_{85}/D_{15} = 2$.
3. Chiew results presented with and without "flow depth effect".

These results show considerable variation in the estimated size of riprap required to provide a stable scour pad. This variation may be due to numerous factors, including different testing facilities/methodologies, different observation/measurement procedures (such as damage criteria) and different test conditions (such as stone shape/gradation, flow depth, etc.). Further, this variation does not include the uncertainty associated with defining the velocity magnification factor for the pile-supported pier configuration.

Physical Modeling of Scour Protection

Given the variation in the empirical estimates of scour protection requirements, and the uncertainty in the selection of an appropriate velocity magnification factor for the pile-supported pier configuration, a site-specific physical model investigation was undertaken to refine and optimize the design of scour protection for the St. John River Bridge. The tests were undertaken in a 2 m wide tilting flume at the Canada Centre for Inland Waters (CCIW) in Burlington, ON at a geometric scale of 1:37.5. The focus of the model tests was the areal extent and thickness of the scour pads, and the requirement for a filter layer between the scour pad and river bed. Tests were undertaken with flow conditions up to and exceeding the 100 year flood event for two design concepts, as follows:

- a 1.0 m thick layer of riprap (D_{50} = 0.3 m) over a 0.3 m thick filter layer; and
- a 1.3 m thick layer of 0.45 m minus quarry run (D_{50} = 0.2 m).

The horizontal extent of both scour pads was 1.5 times the "effective" pier width, which represents the lower limit of published design guidance (1.5 to 2.0). Figure 2 presents a photograph of the model test setup for a standard pier.

Figure 2 – Standard Pier and Scour Pad in Test Flume

The test results showed acceptable performance of both designs under flow conditions up to and exceeding the 100 year design event, with no instability of either scour pad noted in the tests. Additional desktop analyses were undertaken in order to assess the quarry run design concept, specifically the potential to use smaller stone (D_{50}) with a greater layer thickness (t). The model test results were found to be generally consistent with empirical relationships for D_{50} versus t presented in USACE (1994) and Chiew (1995).

The physical model results led to a reduction in the areal extent of the scour pad relative to that recommended by HEC-23 (FHWA, 2001c), and confirmed the acceptable performance of a wide gradation quarry run material without a filter layer. Final designs were developed for both riprap and quarry run scour pads. The riprap design utilizes a relatively narrow stone gradation ($D_{50} = 0.4$ m) with a layer thickness of $2*D_{50}$ placed over a filter layer (granular or geotextile). The quarry run design, which does not require a filter layer, utilized a wider gradation of smaller stone (D_{50} approximately 60% of that of the riprap) and a layer thickness of $5*D_{50}$.

Construction

The project schedule evolved such that scour protection had to be placed after the piles and pile caps had been installed. As such, considerable difficulty was anticipated with respect to placing stone materials amongst the piles underneath the pile caps. This concern led to consideration of several alternative scour protection design concepts, including concrete filled Fabriform bags and tremie concrete. The tremie concrete option was selected by the successful contractor for the area under the pile caps, while the quarry run option was retained for the area outside the pile caps.

Construction of the St. John River Bridge, including its scour protection system, was completed in 2001. A scour monitoring program was developed by Baird and recommended to MRDC, including a visual/diver inspection of the scour protection around each pier and abutment following the spring flood each year, with the frequency of these inspections to be reduced in the future if appropriate. No scour monitoring data were available at the time this paper was prepared.

THE CONFEDERATION BRIDGE

Overview of Project

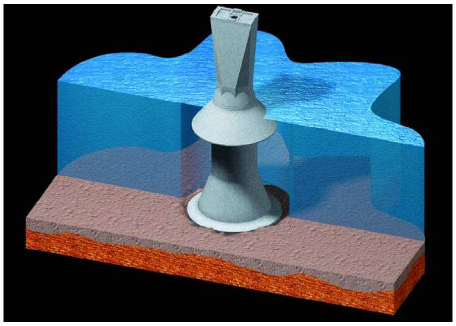
The 13 km long, $800 million Confederation Bridge crosses the Northumberland Strait and joins the provinces of New Brunswick and Prince Edward Island in Eastern Canada (refer to Figure 3). The bridge, developed under a finance-design-build-operate agreement between Strait Crossing Bridge Limited (SCBL) and the Canadian Government, was constructed in 1994-97, and opened to traffic on June 1, 1997.

Figure 3 – The Confederation Bridge (photo by Boily)

At the crossing location, the Strait is approximately 13 km wide, with water depths ranging up to 30 m, but typically in the order of 15 m. The seabed generally consists of weak, fractured bedrock (mudstone, siltstone and sandstone), with highly variable material characteristics. The bedrock is overlain by glacial till in some areas. Under extreme design conditions, this site 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.

The 65 bridge piers are large gravity structures with conical bases (16 to 22 m base diameter) and conical ice shields at the water level (refer to Figure 4). For the shallow water approach piers (21 piers in water depths less than 8 m), the pier base and ice shield are a single unit.

Figure 4 – Schematic of Main Bridge Pier with Conical Base and Ice Shield



Overview of Scour Assessment and Design Investigations

Baird, under contract to SCBL, was responsible for the scour assessment and design for this project. This aspect of the project was complicated by several factors, including:

- Exposure to severe waves and currents;
- Conical pier bases, some founded in dredged pits;
- Complex and variable foundation conditions (weak, fractured bedrock).

These factors precluded the application of "standard" scour assessment and design methodologies (such as those in HEC-18, HEC-20 and HEC-23). Extensive investigations were undertaken to estimate the potential for scour around the pier bases, resulting in the development of a new methodology to assess scour potential in complex materials (based on the erodibility approach of Annandale, 1995), as discussed in a companion paper in these proceedings (Nairn and Anglin, 2002; refer also to Anglin et al, 1996).

There was considerable uncertainty in the scour assessment, principally due to the complex nature and highly variable characteristics of the foundation materials, but also due to the application of a new methodology to estimate scour potential. As such, a conservative approach was adopted in defining the requirement for scour protection, with scour protection recommended at any pier where the estimated factor of safety (FS) against scour during the 100 year design event was less than four. This approach led to the recommendation for scour protection around 14 of the 65 bridge piers, with the majority of these being shallow water approach piers (water depth less than 8 m), where wave action is the dominant mechanism with respect to scour and scour protection.

The design of scour protection was supported by the following investigations:

- numerical modeling to define long-term wave and current conditions at the site;
- literature review to identify the most relevant hydrodynamic parameter to define the combined effects of waves and currents ("stream power", P, was selected);
- extreme value analyses to define stream power as a function of return period at representative locations and depths along the crossing alignment;
- literature review and application of published procedures to estimate riprap scour pad design details (riprap size, horizontal extent, layer thickness and filter requirements);
- physical modeling of wave-current interaction with the bridge piers to establish pier magnification factors, and to optimize the design of the riprap scour pads;
- final designs, plans and specifications for bridge pier scour protection.

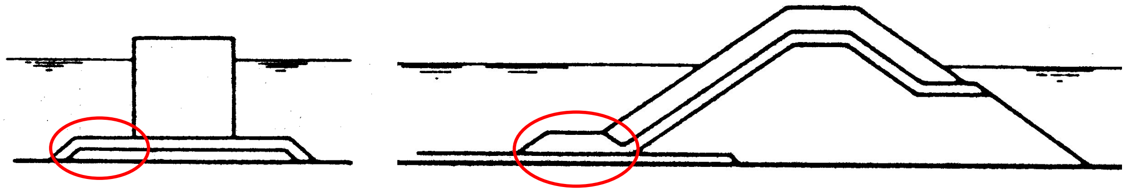
These investigations are discussed in more detail below.

Design of Scour Protection

Most scour assessment and design methodologies are applicable to river crossings, where the flow conditions are "unidirectional" and there is no significant wave action. Wave action results in "orbital motions" in the water column, and horizontal oscillating flow conditions at the seabed. A literature review undertaken for this project highlighted the absence of relevant scour design methodologies for bridge piers exposed to significant wave action. There is considerable information available on the design of toe/scour protection for coastal structures (such as revetments and breakwaters) exposed to wave action (for example, refer to USACE, 2001). However, these structures tend to be two-dimensional (2D) in nature (i.e. long and straight), and the associated toe/scour protection design methodologies cannot be applied with any confidence to the more complex three-dimensional (3D) flow conditions around bridge piers.

In the absence of more relevant procedures, preliminary scour protection designs for the shallow water approach piers were estimated using the toe/scour protection approaches of Tanimoto et al (1982) for "composite" breakwaters and CIRIA/CUR (1991) for "rubblemound" breakwaters. Figure 5 illustrates these breakwater design concepts, while Table 2 summarizes the results of the toe/scour protection calculations.

Figure 5 – Schematic Cross-Sections of Breakwater Design Concepts



Vertical/Composite

Sloping/Rubblemound

Table 2
Estimated Scour Protection Requirements for Approach Piers
Breakwater Toe/Scour Protection Design Methods

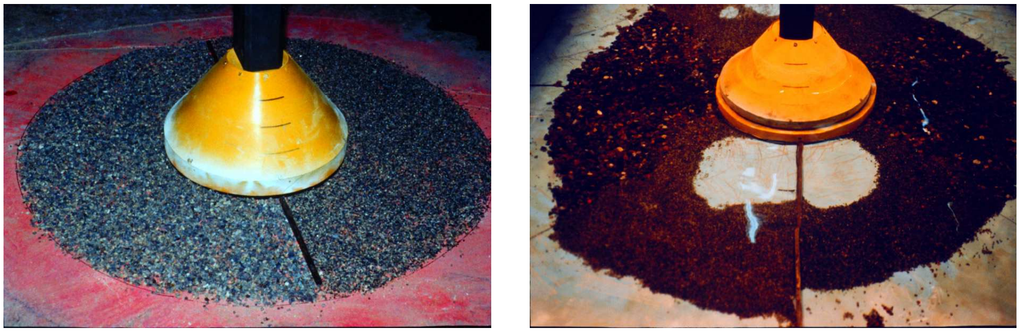
Breakwater Design Concept	Reference	D_{50} (m)
Vertical/Composite	Tanimoto et al (1982)	1.5
Sloping/Rubblemound	CIRIA/CUR (1991)	0.5

Clearly, there is a significant difference in these two estimates, and neither can be applied with any confidence to the complex, 3D flow conditions caused by the interaction of waves and currents with conical bridge piers. In addition, there is no relevant design guidance for the horizontal extent of scour pads around conical piers. "Conventional" design guidance suggests scour pad widths in the order of 1.5 to 2 times the pier diameter. Considering the variation in approach pier diameter from 10 m at the water line to 18 m at the base, this suggests scour pad widths in the order of 15 to 36 m.

Given these uncertainties, and the high cost of the preliminary scour protection designs, a physical model investigation was undertaken to assess scour protection alternatives and to refine and optimize the scour protection design. Two sets of model tests were undertaken in a 1.2 m wide wave-current flume at the Canadian Hydraulics Centre in Ottawa, ON. All tests were undertaken at a geometric scale of 1:70.

The first test series was completed to assess the influence of various pier shapes and dredged pit depths on flow conditions around the piers, specifically the characteristics and extent of accelerated flows and vortices. The flow patterns around the base of the model piers were defined with the aid of a laser doppler velocimeter, acoustic velocity meters, flow visualization and tracer materials. Pier magnification factors (PMF) were developed for the various water depths and pier geometries through a comparison of the flow conditions required to initiate the scour of a tracer material (coarse sand or fine gravel) placed on the model "seabed" with and without the pier in place (refer to Figure 6).

Figure 6 – Granular Tracer Mat around Model Pier Before and After Test



These tests were completed using various combinations of waves and currents, including each in the absence of the other. In general, the influence of the piers on flow conditions was limited to an area within 7 to 9 m from the toe of the conical pier bases (as noted earlier, the pier base diameters range from 16 to 22 m). The test flow conditions were quantified by the "stream power" parameter (P), which is the product of the nearbed shear stress (τ) and velocity (V). The stream power pier magnification factors (PMF's) varied from approximately 1.6 (deep water main pier placed in a deep pit) to 6.0 (moderate depth main piers and shallow water approach piers placed directly on the seabed). These PMF's correspond to velocity magnification factors of approximately 1.2 to 1.8 (stream power is proportional to the cube of velocity). 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). Additional information on the tracer tests and PMF's is provided in a companion paper in these proceedings (Nairn and Anglin, 2002).

The second test series was undertaken to investigate and optimize the design of scour protection around the pier bases. These tests were completed in the same wave flume as the tracer tests described above, again at a scale of 1:70. The horizontal extent of the scour protection pads was defined based on the results of the tracer tests, which demonstrated that the "zone of influence" of the piers extended approximately 7 to 9 m out from the toe of the conical pier bases. Hence, 10 m wide scour pads were tested in the model. This width is similar to the pier diameter at the waterline, and approximately one-half of the pier diameter at the seabed. Scour protection tests were undertaken with one or two layers of armour stone placed around the model pier bases, in water depths ranging from 5 to 10 m. In general, the various designs were tested under progressively increasing combinations of waves and currents, with the onset of stone motion and progressive damage documented using visual observations and photographic records. Figure 7 shows photographs documenting the construction an armour stone scour pad around one of the model approach piers, while Figure 8 presents photographs of damage observed to a model armour stone scour pad following extreme flow conditions.

Figure 7
Construction of Model Scour Pad

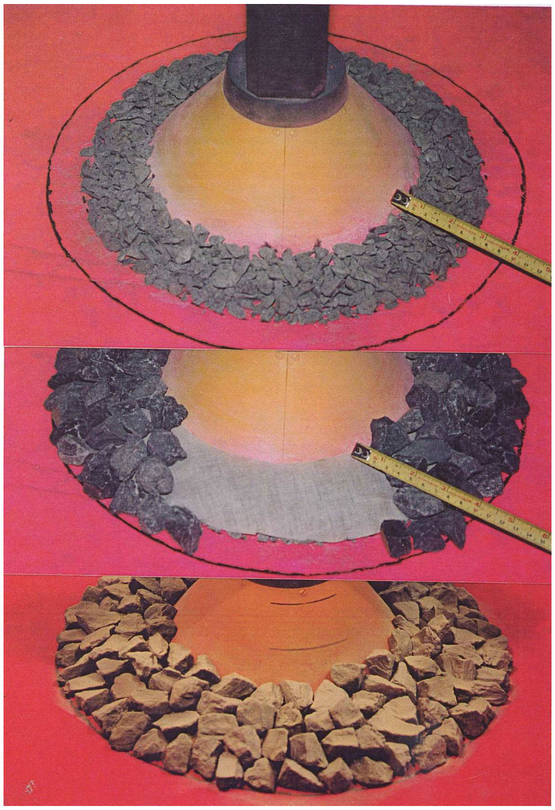
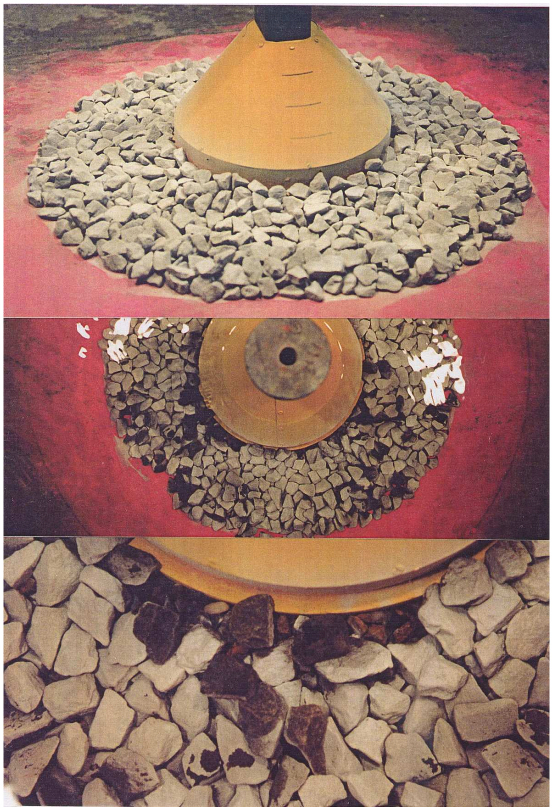


Figure 8
Damage to Model Scour Pad



The recommended scour protection design consists of two layers of armour stone placed in a 10 m wide band around the base of the piers. The 10 m width is significantly less than the "conventional" estimate of 1.5 to 2 times the pier diameter. For the shallow water approach piers, the test results indicated that two layers of 2 to 4 tonne armour stone (D_{50} = 1.2 m, assuming angular stone) was required to provide a stable scour pad under the extreme design conditions. This result falls in between the stone sizes estimated for vertical/composite and sloping/rubblemound breakwater structures presented earlier (refer to Table 2). An alternative design was also developed using a single layer of 5 to 7 tonne armour stone (D_{50} = 1.5 m, assuming angular stone). Smaller stone sizes were found to be stable for deeper piers, where the influence of wave action on the seabed (i.e. wave orbital velocities) is less.

For comparison purposes, additional calculations were undertaken using "conventional" riprap design equations for bridge pier scour protection by considering the combined design velocity associated with the wave orbital motion at the seabed and the unidirectional tidal/surge current. These calculations are summarized in Table 3.

Table 3
Estimated Scour Protection Requirements for Approach Piers
"Conventional" Riprap Design Equations with Combined Wave-Current Velocity

Methodology/Reference	D_{50} (m)
TAC (1973, 2001)[1]	1.3
Isbash/FHWA (1993)[1]	0.8
Maynord/USACE (1994)[1, 2]	1.1
Parola (1993)	0.9
Chiew (1995)[3]	0.2 to 2.8
Fotherby & Ruff (1996)	1.1
Lauchlan & Melville (2001)	0.7

Notes:

1. TAC, Isbash and Maynord calculations assume a velocity magnification factor (K) of 1.8 as per the physical model test results.
2. Maynord approach assumes $D_{50} = 1.2*D_{30}$ based on armour stone gradation with $D_{85}/D_{15} = 1.8$.
3. Chiew results presented with and without "flow depth effect"

These methods (excluding Chiew, 1995) suggest stone sizes (D_{50}) in the order of 0.7 to 1.3 m, as compared to the model study result of 1.2 m for the two layer design. The variation in the empirical estimates is significant, and none of the methods is considered to provide a reliable approach that can be applied with confidence to bridge piers exposed to wave action. Further, it is noted that the TAC, Isbash and Maynord calculations include a velocity magnification factor that was estimated from the model test results.

As such, the physical model was a critical component of the scour protection design. The model supported the development of designs that meet specific performance criteria (i.e. tolerable damage) under the extreme 100 year design flow conditions (waves and currents). In addition, the areal extent of the scour pads is significantly less than that suggested by "conventional" scour design guidance, with an associated reduction in cost.

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 of these piers (see Figure 9), while construction logistics led to the development of a tremie concrete design concept at the other two piers. In the absence of a systematic design methodology, the tremie concrete design concept was based on experience and judgement. A minimum tremie thickness of 0.5 m was specified based on consideration of hydrodynamic lift forces, and "airlifting" of loose material from the seabed was required prior to tremie placement.

Figure 9 – Armour Stone Scour Pad at Shallow Water Approach Pier (photo by Boily)

Given SCBL's decision not to protect a number of "scour susceptible" piers, as well as the uncertainties in the overall assessment of scour potential, Baird recommended a detailed and systematic scour monitoring program. This recommendation was accepted by SCBL. The resulting monitoring program is discussed briefly below.

Scour Monitoring Program

As noted above, Baird assisted SCBL in the development and implementation of a systematic scour monitoring program for this project. This included dividing the piers into priority classes based on the estimated risk of scour, with the highest priority class (nine AA piers) being those at which scour protection was recommended by Baird (FS < 4) but not implemented by SCBL. In addition, Baird developed and installed a near real-time wave/current monitoring system for this project. This system quantifies the magnitude of storm events (considering the combined occurrence of waves and currents) to which the bridge is exposed and relates these to the design conditions, thereby providing a systematic method to define the requirement for monitoring of the seabed or scour protection around the base of each pier.

SCBL has followed this monitoring program since the bridge opened in 1997. Scour was detected around one of the AA piers in 1998; it was subsequently protected with an armour stone scour pad. No scour of any significance has been observed around any of the other piers, 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.

The archived wave/current information, along with the results of diver inspections undertaken between 1997 and 2002 and detailed multibeam sonar seabed surveys undertaken in 2001 and 2002, will be used to verify and improve the scour assessment and design methodologies, and, if appropriate, to reduce the scour monitoring requirements. Additional information on the monitoring program and the proposed scour reassessment study is provided in a companion paper in these proceedings (Nairn and Anglin, 2002).

DISCUSSION AND CONCLUSIONS

Extensive investigations undertaken for the St. John River Bridge and Confederation Bridge in Eastern Canada have highlighted limitations in existing scour protection design methodologies, and have clearly demonstrated the benefits of undertaking project specific physical model studies.

For example, riprap design calculations undertaken using published design methodologies give a wide range in stone sizes for unidirectional flow conditions. This variation, also reported by Lauchlan and Melville (2001), leaves the design engineer with the difficult task of selecting the most appropriate design methodology and/or specifying a design based on experience and judgement. Further, there is no methodology presently available to design scour protection for bridge piers exposed to significant wave action.

These uncertainties and limitations can be overcome by undertaking a site-specific physical model investigation. A physical model provides the best tool currently available to investigate the complex interaction of flows with structures, and can be used to develop, refine and optimize designs to meet specific performance objectives under extreme design conditions. For example, physical models have been used for decades in the field of coastal engineering to design cost-effective rubblemound breakwaters to provide permanent protection from extreme wave action for large, multi-million dollar marine/waterfront facilities (such as ports and harbours), and represent the accepted "standard of care" in the design of such structures (refer to USACE, 2001). In addition, physical models have been used extensively to assess the stability of riprap under unidirectional flow conditions, including the protection of stream beds/banks from flood flows (for example, Maynord, 1988; USACE, 1994), and the protection of embankments, dams etc. from overtopping flows (for example, CIRIA, 1987; Abt et al, 1998).

Similarly, a bridge scour design investigation can benefit significantly from a site-specific physical model study. The physical model investigation undertaken for the St. John River Bridge led to the development of a scour protection design using widely graded riprap without a filter layer. The stone size was significantly smaller than that estimated using empirical design approaches. In addition, the model confirmed the acceptable performance of a scour pad with an areal extent at the lower limit of published design guidance. These features resulted in significant cost savings as compared to the preliminary designs developed using published design guidance.

For the Confederation Bridge, the physical model investigation was an essential step in the scour investigation due to the complex flow conditions (waves and currents), seabed characteristics (weak, fractured bedrock) and pier geometry (conical pier bases, some founded in dredged pits). These conditions precluded the application of "conventional" bridge scour methodologies. The physical model provided a wealth of information related to the complex flow conditions around the piers, and allowed the development and optimization of scour protection designs to resist the 100 year design flow conditions.

In general, and certainly for large, complex and/or unique bridge projects, experience indicates that the cost of a physical model investigation will be more than offset by the construction cost savings realized through design optimization of the scour protection. Further, a physical model allows demonstration/verification of the performance of the scour protection system under extreme flow conditions (design and "overload"), and can provide extremely useful information on damage/failure mechanisms and likely maintenance/repair requirements. This approach, in combination with a systematic monitoring program, allows the development of "permanent" scour protection designs that may result in significant cost savings for some bridges as compared to a foundation design that accommodates the maximum anticipated scour depth.

In addition, tracer tests allow accurate quantification of the "pier magnification factor". It is suggested this parameter should be quantified in any physical model investigation of bridge pier scour/scour protection in order to support the development of a comprehensive database for various pier geometries and flow conditions.

In closing, it must be emphasized that a physical model is only one aspect in a comprehensive bridge scour investigation. Clearly, the engineer must have a detailed and complete understanding of the site conditions (in particular, surface/subsurface conditions and bank and bed stability), extreme flow conditions, bridge foundation design, etc. prior to undertaking the physical model investigation. The interested reader is referred to HEC-18, 20 and 23 (FHWA, 2001a, b and c) for further information on these topics. In addition, the successful performance of any scour protection system is critically dependent on good quality materials and construction. Hence, an effective QA/QC program during construction is essential. Finally, a systematic post-construction monitoring program is strongly recommended for any bridge scour protection system.

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