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SCOUR IN COMPLEX BRIDGE PIERS: FRASER AND PADMA RIVERS

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ABSTRACT

The construction of complex bridge piers in large sand-bed rivers has become increasingly common. These piers are made by driving or boring a group of piles deep into the riverbed and then connecting them by a pile cap on top, over which the stem of the pier supporting the deck is located. In contrast with conventional footings, the pile cap is located high above the riverbed and close to the water surface, functioning also as protection against ship collision. The combination of several piles, pile cap and stem above the riverbed gives the pier a complex geometry, which does not easily fit with the simple geometry commonly assumed by most scour prediction equations; hence the need for mobile-bed physical modelling in order to determine scour depths for design purposes. We report the results of several complex piers scour experiments carried out at Northwest Hydraulic Consultants' laboratory including the Golden Ears Bridge, Port Mann Bridge and Pattullo Bridge in the Fraser River, British Columbia and the Padma River Bridge in Bangladesh. These pier tests encompass a wide range of conditions such as vertical and inclined piles (diameters from 1.8 to 3.0 m), rectangular, octagonal and dumbbell-shaped pile caps (pile cap lengths between 18 and 60 m), and flow discharges ranging from 2-year to 100-year floods. Maximum observed local scour depths varied between 14 and 22 m.

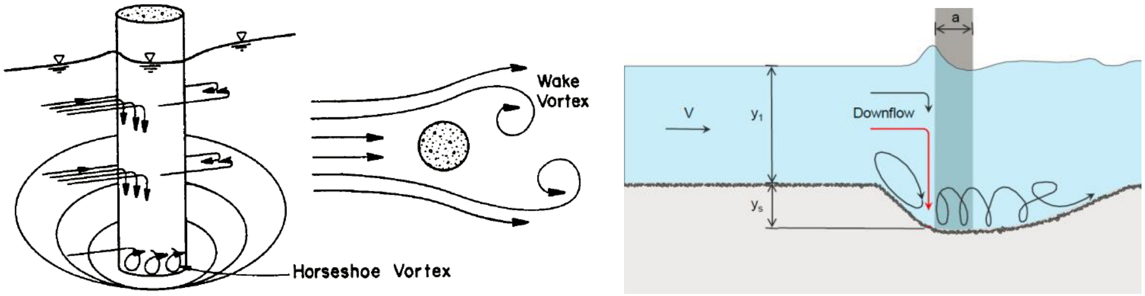
Keywords: Bridge; pier scour; complex pier; physical modelling; Fraser River.

1. INTRODUCTION

It is well-known that the most common cause of bridge failure is due to the erosion of riverbed material surrounding the foundations of piers and abutments (Arneson et al. 2012). The local erosion or scour of solid piers, like the cylindrical pier shown in Figure 1.a has been thoroughly studied and is well understood. In the horizontal plane, water flowing around the cylindrical pier typically detaches and creates wake vortices behind it, while in the vertical plane a downflow current generated at the upstream nose of the pier directs water towards the bed. The combination of downflow current and flow around the pier creates a complex three-dimensional horseshoe vortex, which removes bed sediment and generates a scour hole around the pier (Figure 1.a). The Transportation Association of Canada (TAC 2004) provides empirical equations to estimate scour depths in solid piers of different shapes. However, in large sand bed rivers bridge piers typically have complex shapes consisting of several clearly definable components (Figure 1.b), for which TAC (2004) only provides some interim guidance.

Complex piers (Figure 1.b) are typically built by driving or boring a group of piles deep into the riverbed and then connecting them by a pile cap on top, over which the stem or column of the pier supporting the deck is located (Figure 2). In the United States, the Federal Highway Administration (Arneson et al. 2012) and the Florida Department of Transportation (FDOT 2005) provide empirical methods to estimate scour in complex piers. The basic simplifiying assumption in these methods is that scour of each individual component (column/stem, pile cap and pile group) can be computed independently and then summed together to find the total local scour in the complex pier, in some way neglecting the possible interaction of the flow structure between the components, especially the downflow current (Moreno et al. 2014).

a) Solid pier



b) Complex pier

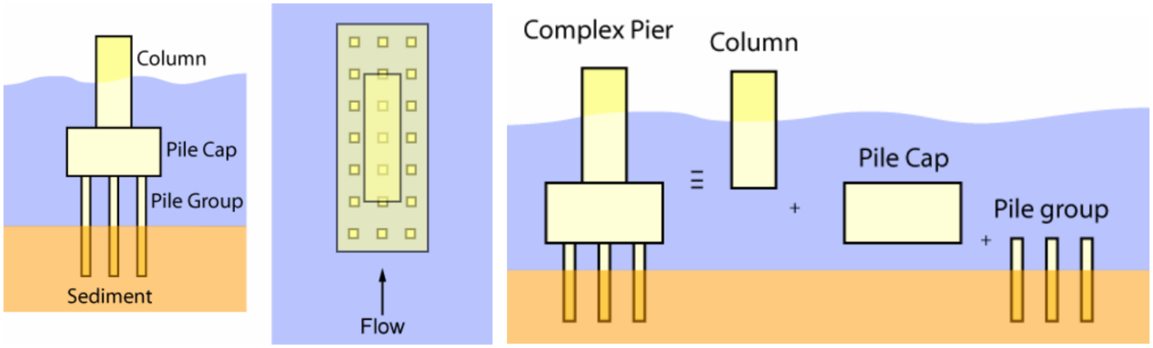


Figure 1. (a) Scour in single solid cylindrical pier (Arneson et al. 2012); and (b) scour-producing components of complex pier (FDOT 2005).

Although complex piers are sensible and cost effective from a structural standpoint, their shape can present a challenge for hydrotechnical engineers responsible for estimating design scour depths at these structures (FDOT 2005). Figure 2.a illustrates the contrast between the old solid pier of the Port Mann Bridge in the Fraser River and its complex pier replacement built downstream. The old solid pier had a hydrodynamic shape in the form of an elongated ellipse aligned with the main flow direction. The complex pier replacement is rectangular in shape and aligned with the bridge deck, not the flow, which further complicates the application of empirical scour equations.

a) Port Mann Bridge **b) Pitt River Bridge**

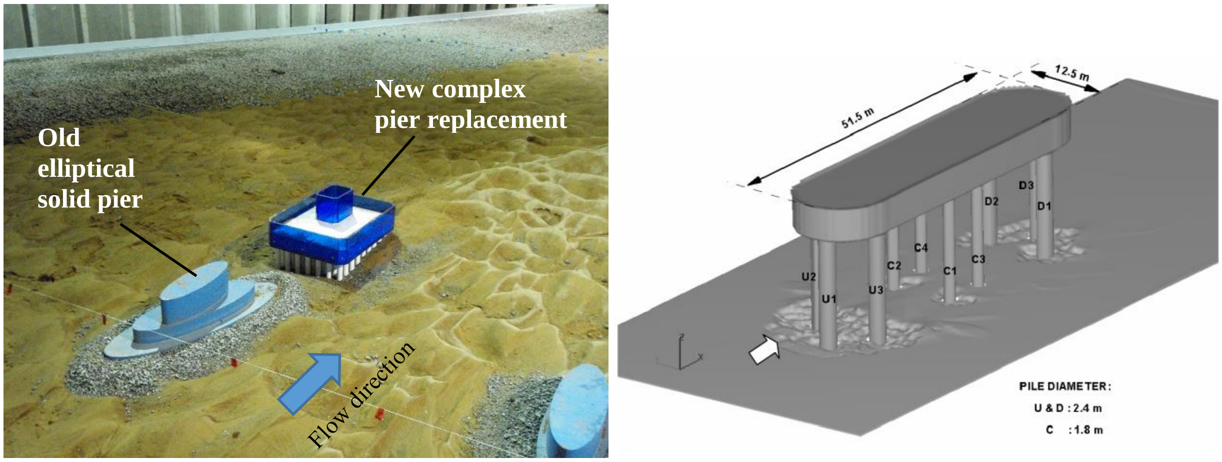


Figure 2. (a) Physical model showing old solid pier and new complex pier of Port Mann Bridge in the Fraser River (NHC 2009a); and (b) initial scour around the complex pier of Pitt River Bridge computed using Flow-3D (Vasquez and Walsh 2009).

As shown in Table 1, complex piers are becoming the norm in recent bridge crossings built during the past decade in the Fraser River and the Pitt River in Metro Vancouver, BC (Figure 3). The same is true in other large sand-bed rivers, such as the Padma River in Bangladesh, where the largest river crossing in the world is currently under construction. The apparent popularity of complex piers in large rivers is not due to any particular hydrotechnical advantage, but it is probably more related to advances in pile driving technology and the risk of soil liquefaction during seismic events (Hannigan et al. 2016). In the navigable Fraser and Padma Rivers, the pile cap is located at the water surface to provide protection against ship collision. Therefore, the column or pier stem above the pile cap remains dry and can be disregarded as a scour-producing component.

Table 1. Examples of complex pier dimensions in the Fraser, Pitt and Padma Rivers (NHC 2006, 2009a,b; Vasquez 2007; Vasquez and Walsh 2009)

Bridge	Completed	Pile cap length (m)	Pile cap width (m)	Pile diameter (m)	Number of piles (-)	Figure
Golden Ears Bridge	2009	44.2	18.8	2.4	12	Figure 4
Pitt River Bridge	2009	51.5	12.5	2.4/1.8	6/4	Figure 2.b
Port Mann Bridge	2012	41.4	32.4	1.8	63	Figure 2.a
Padma River Bridge	Construction	16.1	16.1	3.0	6	Figure 6
New Pattullo Bridge	Proposed	26.5	17.5	1.8	24	-

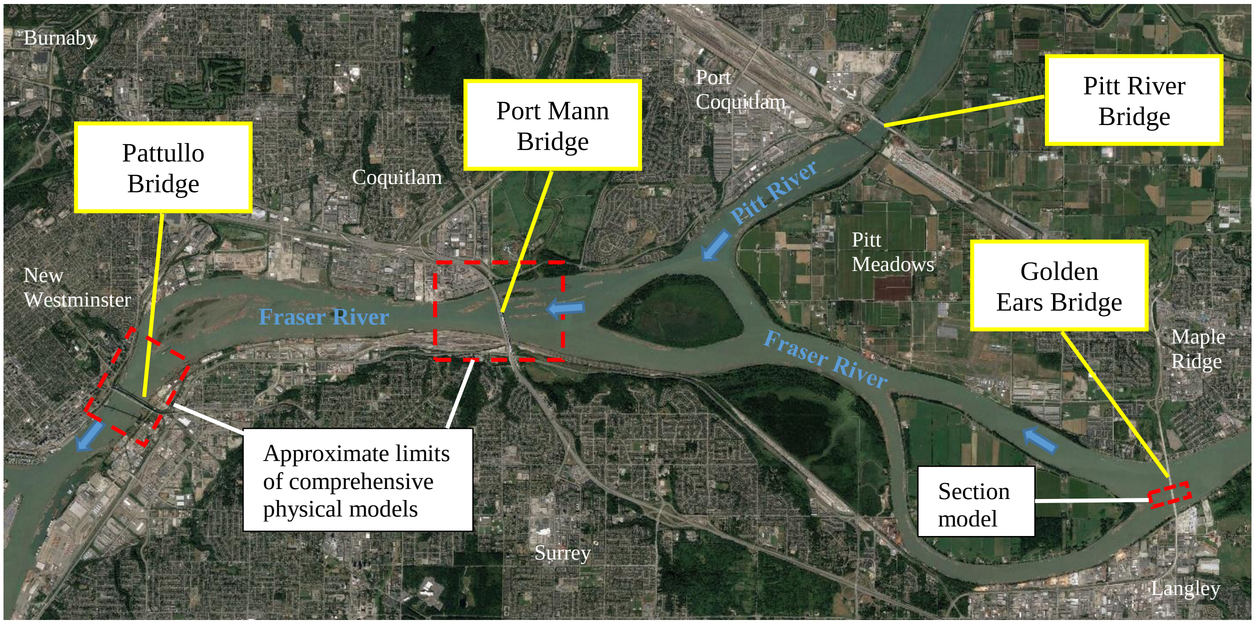


Figure 3. Google Earth image of Fraser River showing location of bridge crossings mentioned in Table 1 and approximate limits of movable-bed physical models used to study local pier scour.

The purpose of this paper is to describe some observations made in physical mobile-bed models of local scour in complex piers in the Fraser River and Padma River.

2. SCOUR MODELLING FOR COMPLEX PIERS

Although numerical models have been successfully applied to compute scour in solid cylindrical piers since the 1990s (Olsen and Melaaen 1993); the same is not true for complex piers due to their shape and size. Figure 2.b shows an early attempt by Vasquez and Walsh (2009) to simulate scour in the complex pier of the Pitt River Bridge using the computational fluid dynamics (CFD) code Flow-3D version 9. Flow-3D correctly predicted the flow interaction between the pile groups and the initial scour development, but the computational time needed to compute the maximum equilibrium scour was excessive. Also, in tests with a simpler 3-pile group under tidal conditions (Vasquez and Walsh 2009) the CFD model showed a tendency to under-predict the maximum scour depth. At present, CFD models are still not capable of accurately and efficiently predicting local scour in complex piers, leaving physical modelling as the only viable option. However, numerical models still play an important role in providing boundary conditions to physical models, such that the size of the physical model can be reduced.

Physical models intended to study local pier scour can be classified as comprehensive models if they include the entire bridge crossing and piers, or section (flume) models if they only include a single pier. Comprehensive models are needed in complex crossings such as when more than one bridge is present, which was the case for the Port Mann and Pattullo Bridge replacements (NHC 2009a; Figure 2.a and Figure 3). The main disadvantage of mobile-bed comprehensive models is their large size and complex operation. Section models are simpler to operate, less expensive and are appropriate when the pier is not influenced by other nearby structures. Water depth and velocity in a section model can be changed to represent local flow conditions at individual piers. Similarly, the pier orientation can be rotated to simulate various angles of attack. This approach was used to model complex piers of the Golden Ears Bridge (NHC 2006; Vasquez et al. 2007; Figure 3; Figure 4) and Padma River Bridge (Figure 7); in both cases the local boundary conditions to the section model were provided by a two-dimensional flow model.

One important challenge when modelling sand-bed rivers using reduced-scale physical models is the impossibility of scaling sand grain sizes geometrically. For example, the 0.35 mm sand grain in the Fraser River, if scaled geometrically in a 1 to 100 reduced-scale physical model will require 0.0035 mm silt in the model, which is cohesive and hence behaves differently from sand. For that reason, using sand in a physical model may be preferred although it may be more representative of a gravel-bed river. Fortunately, local scour is mostly dependent on the pier geometry and not so much on the grain size. However, the general bed mobility and sediment transport in the model becomes very low and bed features such as dunes do not fully develop. One option is to use light-weight material in the model to represent sand in the prototype, but this is complicated and requires considerable experience (Shen 1990, Vollmers 1990). The hydraulics laboratories in Northwest Hydraulic Consultants (NHC) have been using crushed walnut shell over the years, an industrial abrasive with relative submerged density of 0.3 (compared to 1.65 for natural sand) to model sand bed rivers. Crushed walnut shell allows the formation of realistic dune patterns (Figure 2.a), which is particularly important when studying the stability of riprap in the riverbed used as scour protection in piers and pipeline crossings (Vasquez et al. 2007). All the results presented here come from mobile bed models that used crushed walnut shell to model sand.

3. FRASER RIVER

3.1 Setting

The Fraser River is the longest river in British Columbia, draining a 250,000 km^2 watershed and flowing for 1,375 km into the Strait of Georgia at the city of Vancouver. The Fraser's mean annual discharge at its mouth is 3,550 m^3/s and it discharges 20 million tons of sediment into the Pacific Ocean. Near the town of Mission, about 85 km from the ocean the river transitions from gravel to sand. The sand-bed reach continues for 50 km down to the head of the alluvial delta at New Westminster, below Port Mann Bridge (Figure 3). From there the Fraser delta flows for 35 km to the ocean (McLean et al. 1999). The median sand grain size in the riverbed is 0.35 mm, and dunes typically range from 3 m to 5 m high in the lower reaches.

The flood of record in the Fraser occurred in 1894 and was estimated to reach 17,200 m^3/s at Mission (McLean et al. 1999) and 21,150 m^3/s at Pattulo Bridge (Figure 3). This flood of record is commonly used for testing local pier scour in physical models. Because the Fraser River below Mission is tidally influenced and the river planform morphology exhibits several bends, islands, bars, contractions and expansions (Figure 3), defining boundary conditions for physical models would be challenging if not for the use of large-scale numerical models. A one-dimensional (1D) unsteady flow model of the entire Fraser River below Mission is used to provide boundary conditions to local two-dimensional (2D) models. The 2D model, which is typically at least 10 km long and includes the entire extent of the physical model, is then used to provide the velocity distribution across the entrance section of the physical model (headbox) and water levels at the downstream section; in this way reducing the size and cost of the physical model. In some instances and when available, ADCP field velocity data can also be used to provide inflow boundary conditions.

3.2 Golden Ears Bridge

Golden Ears Bridge, which is located 54 km upstream from the sea, was completed in 2009 to link the municipalities of Surrey and Langley on the south side of the Fraser River with Maple Ridge and Pitt Meadows on the north side (Figure 3). The 6-lane bridge is a 968 m long cable-stayed structure supported by 4 towers, spaced 242 m apart. The towers are H-shaped with two legs; each leg transfers load to a hexagonal pile cap and from there to the ground through 6 cylindrical piles. The two hexagonal pile caps are connected by a rectangular element, making a single dumbbell-shaped structure at each tower (Table 1, Figure 4).

An 11-km long reach of the Fraser River around the bridge crossing was modelled with the 2D flow model River2D to compute the local flow conditions (depth, velocity and angle of attack) at each pier (Vasquez et al. 2007), which was used as a boundary condition for a 1:100 scaled section model of an individual pier. The most adverse flow conditions that led to the maximum scour depth of 14 m (Figure 4), were for a flow depth of 13 m, flow velocity of 2.5 m/s and angle of attack of 6 degrees. Due to the skewed alignment (angle of attack), maximum scour depth occurred at a downstream pile directly attacked by the flow.

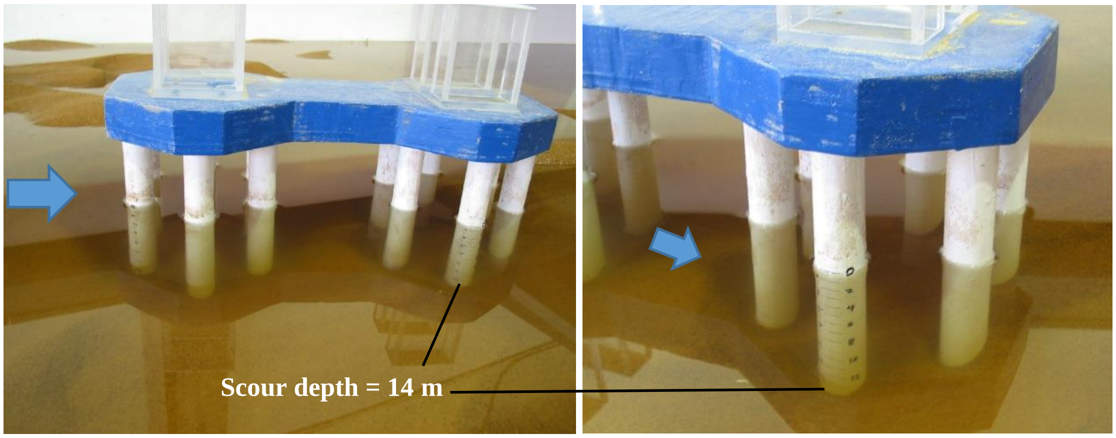


Figure 4. Physical model of Golden Ears Pier showing maximum scour depth of 14 m at downstream pile (drained model with water surface matching initial bed level elevation)

3.3 Port Mann Bridge

The Port Mann Bridge is a 10-lane cable-stayed bridge in the Trans-Canada Highway that opened to traffic in 2012, connecting Coquitlam to Surrey over the Fraser River (Figure 3). It is currently the second longest cable-stayed bridge in North America, handling a traffic volume in excess of 100,000 trips per day. The main free span between towers is 470 m long. The new bridge replaced a steel arch bridge that was located upstream until fully removed in 2015. Pier N1 is the main in-channel pier and initially located downstream from an existing pier of the old bridge (Table 1, Figure 2.a). Pre-construction bed levels around pier N1 were around El. -11 m.

A 1:75 scale comprehensive physical model of Port Mann Bridge plus a 2 km long reach of the Fraser River (Figure 3) was built to study local pier scour during the construction phase, when the old and new bridge structures were present, and during normal operation with the old bridge removed (NHC 2009a). The riprap scour protection was also studied in the physical model. Boundary conditions were provided by a 12-km long River2D model. Approximate local flow conditions at Pier N1 were 14 m water depth and 2.4 m/s flow velocity. Results from the physical model showed that if left unprotected (i.e. without riprap), local scour will cause bed levels at Pier N1 to reach El. -28 m (Figure 5), equivalent to 17 m of scour depth.

Figure 5. Comprehensive physical model of Port Mann showing scour at Pier N1 (NHC 2009a)

3.4 Pattullo Bridge Replacement

The existing Pattullo Bridge opened to traffic in 1937 to link New Westminster and Surrey over the Fraser River (Figure 3). It is located right downstream from the New Westminster Rail Bridge. A new bridge replacement has been proposed for Pattullo Bridge, to be located upstream of the Rail Bridge and is currently being studied in a 1:80 comprehensive physical model. Preliminary testing of two bridge concepts that include a complex bridge pier design has resulted in maximum local scour of 18 m for an unprotected pier (NHC 2017).

4. PADMA RIVER BRIDGE

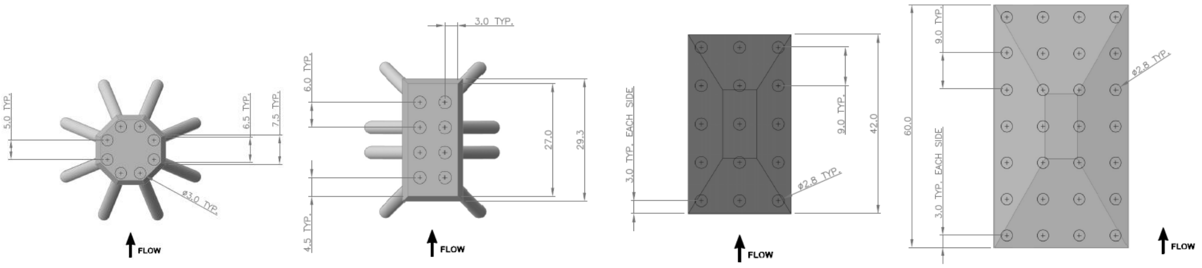
4.1 The Padma River

The Padma River forms by the confluence of the Brahmaputra (Jamuna) and Ganges Rivers in Bangladesh, both originating in the Himalayas. The Padma River flows for 100 km until its confluence with the Lower Meghna River, which discharges 90 km downstream into the Bay of Bengal in the Indian Ocean. The mean annual flow of the Padma River, around 30,000 m^3/s, is the third largest in the world. Bankfull discharges vary between 60,000 and 90,000 m^3/s with an approximate mean value of 76,000 m^3/s. Considering the effects of climate change, the 100-year and 500-year floods have been estimated at 148,000 m^3/s and 160,000 m^3/s respectively (McLean et al. 2012).

The Padma River is one of the most morphodynamically active rivers in the world; over the years its planform geometry changes almost cyclically between straight, meandering and braided morphologies. Channel widths have been observed to vary between 1.5 and 10 km. Annual sediment loads have been estimated to be around 1 billion tonne/year; bed material is fine 0.11 mm sand (McLean et al. 2012).

4.2 The Padma River Bridge

At present, a 6.15 km long bridge is under construction over the Padma River, 35 km southwest of Dhaka. The bridge is made of 41 spans, 150 m long between piers. The complex pier has 6 inclined piles each of 3 m diameter, raked at 1 horizontal to 6 vertical in circular arrangement (Table 1). Natural scour depths in the area near the bridge section have been observed to reach El. -50 m. Three mobile-bed physical models were used to study different scour aspects (Vasquez et al. 2012). A comprehensive physical model was used to study scour around the river training works (RTW); a section model was built to study scour along the south RTW; while another section model was used to study local pier scour, which is reported here. Four pier options, shown in Figure 6 and summarized in Table 2, were tested in the 1:80 scale section model under various flow conditions and angles of attack. Bed levels in the section model were read using a laser scanner, examples are shown in Figure 7.



S8 **R8** **B15** **B28**

Figure 6. Plan views of four pier options for Padma Bridge tested in physical model (NHC 2009b)

4.3 Pier scour section model

In order to take into account the effects of general bed scour in the Padma River during floods, bed levels in the section models were set to El. -21 m for the 2-year general scour and El. -50 m for the 100-year general scour, corresponding water levels were El. 5.7 m and El. 7.3 m, respectively. The scour around individual piles varied considerably, but was always deepest in the vicinity of the farthest downstream piles (Figure 7). The location of the maximum scour consistently occurred in the same piles regardless of the bed at either El. -21 m or El. -50 m.

Table 2. Maximum scour depths for single pile and four pier options of the Padma Bridge measured in physical section model (NHC 2009b)

Pier	Pile group layout	Pile cap width (m)	Pile cap length (m)	Pile diameter (m)	Scour depth (m)
S1*	1 single pile without pile cap	-	-		7
R8	8 inclined piles in 2 × 4 grid	14.3	29.3	3.0	17
B15	15 vertical piles in 3 × 5 grid	24.0	42.0	2.8	21
B28	28 vertical piles in 4 × 7 grid	33.0	60.0	2.8	22
S8	8 inclined piles in circular pattern	18.1	18.1	3.0	16

*Used for reference

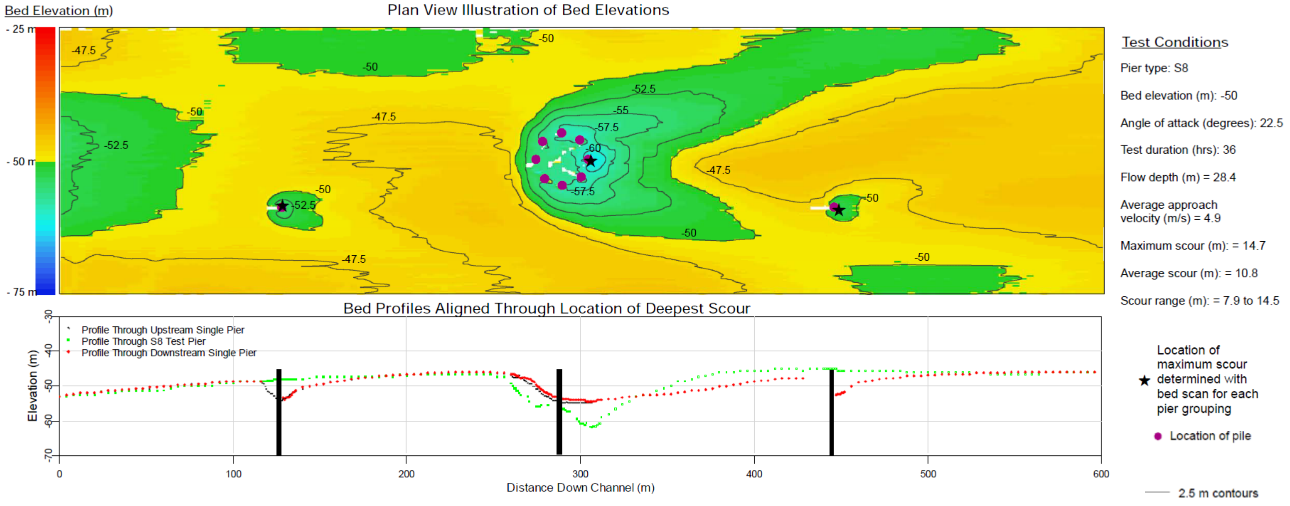
4.3.1 Pier options

For the **S8 pier** design, the physical model results indicate 14 to 16 m of local scour in the vicinity of the farthest downstream piles, and 11 to 13 m as an average depth among all 8 piles. Whether the starting bed elevation was at El. -21 m or El. -50 m had no significant effect. Also attack angles of 0, 11.25 and 22.5 degrees produced closely similar local scour depths.

For the **R8 pier** design with attack angles of 0 and 22.5 degrees, local scour depths of 13 m and 17 m, respectively were observed in the vicinity of the farthest downstream pile, while the average depths among all piles were 11 m and 12 m respectively. Scour was clearly deeper at the 22.5 degrees attack angle.

In comparison with the S8 and R8 raked-pile arrangements, the **B15 and B28** vertical-pile arrangements generated significantly more scour. The maximum local scour depth at an individual pile ranged between 18 and 21 m for the B15 design and exceeded 22 m for the B28 design. The average scour depth was between 16 to 17 m for the B15 design and about 20 m for the B28 design. With the B15 design, an attack angle of 11.25 degrees produced about 2 m more scour than angles of 0 or 22.5 degrees. With the B28 design, attack angles of 0 and 22.5 degrees produced the same depth of scour.

Based on these observations, it seems that piles arranged in circular or ring arrangements such as S8, given their symmetrical layout are rather insensitive to the angle of attack compared to piles in rectangular arrangements.



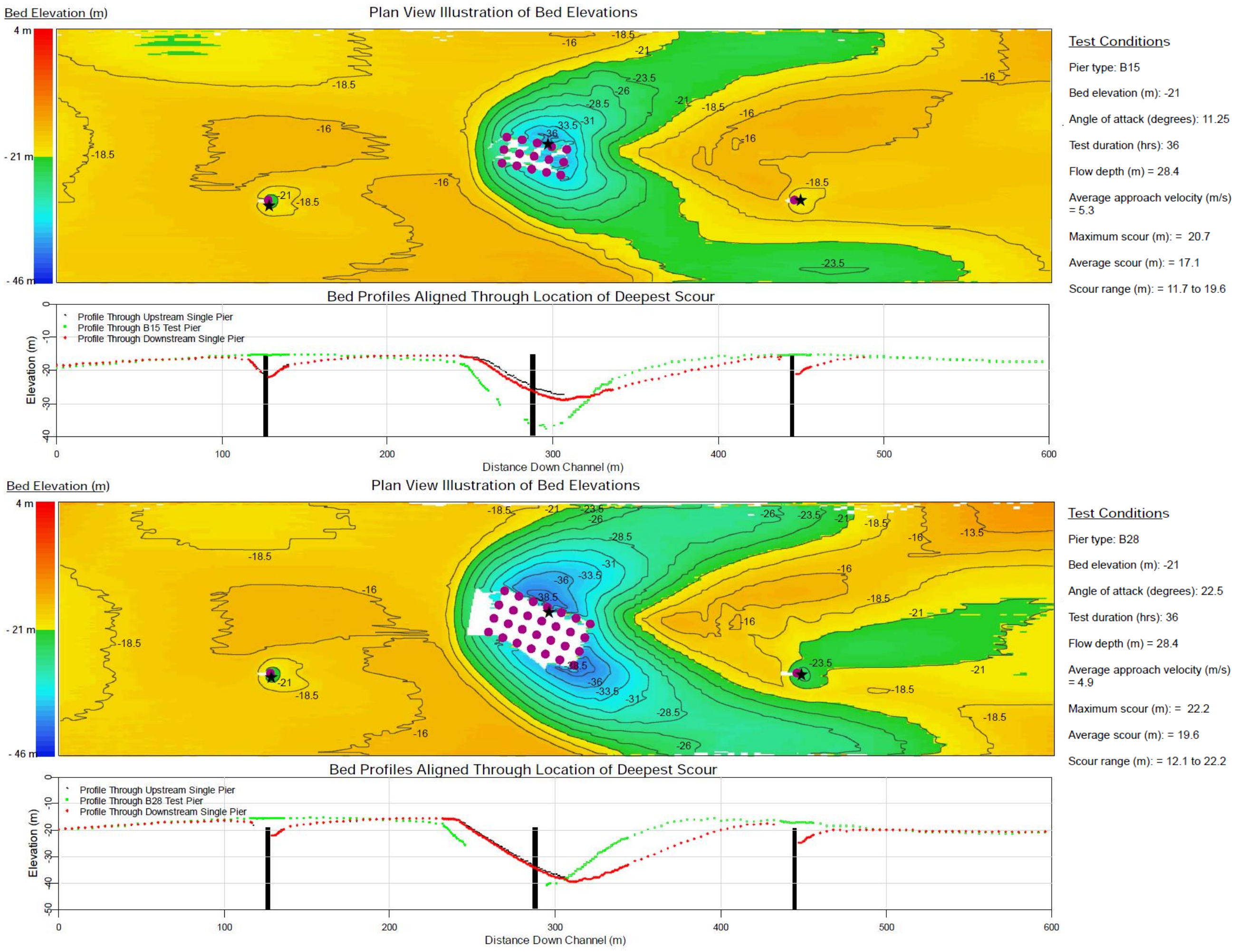


Figure 7. Examples of bed level measurements made by laser scanner for pier options S8, B15 and B28.

4.3.2 Raked piles in Pier S8

Raked piles driven on an inclination from vertical are used when large static loads are expected (Hannigan et al. 2016). However, the effect of raked piles on complex pier scour has not been investigated in great detail, and the available empirical equations assume vertical piles. During the S8 physical model tests, it became evident that the rake on the downstream piles could increase local scour. Scour reached 16 m at the downstream piles compared with 9 m at the most upstream pile (Figure 8.a).

It can be hypothesised that the vertical angle of the pile affects how the downflow current dives into the bed, increasing or decreasing scour. Figure 8.b shows this effects in solid pier, which seems to agree with the observations for Pier S8.

The real pier geometry currently under construction in the Padma River was not tested in the physical model, but it is a 6-pile arrangement somewhat similar in shape to pier S8 and it is expected that scour depths would be similar.

a) Pier S8 scour **b) Effect of pier inclination on scour depth (TAC 2004)**

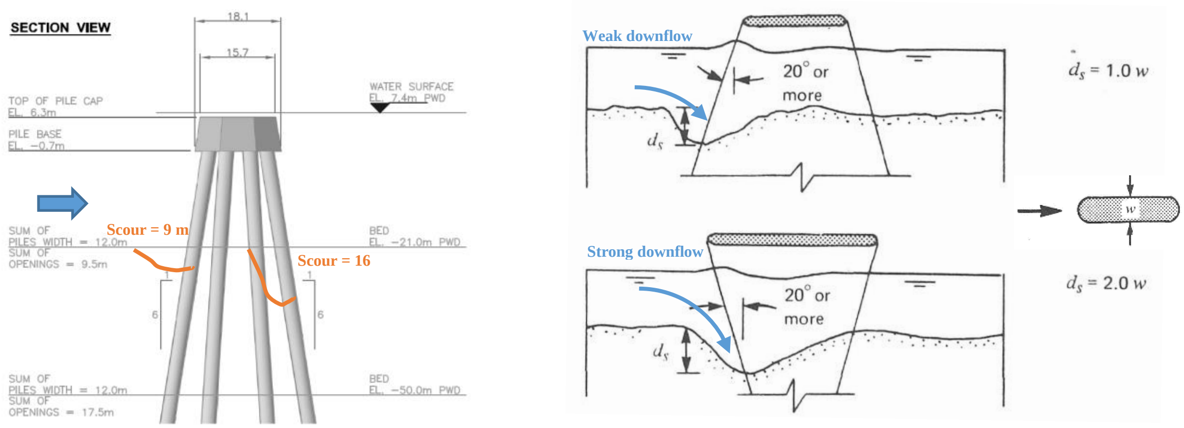


Figure 8. Influence of pier face inclination on downflow current and scour depth that could explain scour observed in complex pier S8 with raked piles.

5. SUMMARY AND CONCLUSIONS

The construction of complex piers in bridge structures has become increasingly common, as demonstrated by the recent bridge projects in the Fraser and Pitt rivers in BC, and Padma River in Bangladesh (Table 1). In contrast with conventional solid piers, complex piers are made of several piles connected on top by a pile cap over which the pier column is located (Figure 1). Given their complex geometry, empirical equations are less reliable to estimate maximum scour depth and physical modelling is required to model local scour in important crossings.

Because complex piers are seldom aligned with the flow, maximum scour depths typically tend to occur in downstream piles. Maximum scour depths in the various complex piers that were modelled ranged between 14 and 22 m. In relative terms, maximum scour depths varied between 4.3 and 10.0 times the pile diameter, which is much larger than the typical range of 1.5 to 2.7 times observed in a single solid cylindrical pile (Figure 1a). This increased pile scour in complex piers can be attributed to the grouping effect of several surrounding piles plus the pressurized flow effect under the pile cap.

Scour in complex piers with rectangular pile arrangements seem to be more sensitive to the angle of attack than piers where piles are arranged in more symmetrical circular (ring) arrangements.

Scour at the downstream piles of raked piles groups can be considerably deeper, which may be attributable to the vertical angle of the piles affecting downflow currents.

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