# SCOURING AROUND A CYLINDRICAL BRIDGE PIER UNDER ICE-COVERED FLOW CONDITION – EXPERIMENTAL ANALYSIS

by

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**Abstract**

Sediment transport processes represent a significant parameter in any work that involves management of water flow. Moreover, all river structures are affected and prone to various types of these processes, which are also known as the erosion/deposition phenomenon. Another aspect which has become extremely important in recent decades is the effect of ice-cover on rivers. The presence of ice-cover in an open channel dramatically alters many features of the flow as well as bed mobility. Laboratory experiments were conducted under clear-water conditions in order to determine features of scouring around a cylindrical bridge pier under partially ice-covered and free-surface flow. The results showed an increase in scour depth up to 55% for the ice-cover configuration when compared to the free-surface case.

*Keywords*: scouring around bridge pier, ice-covered flow, numerical model

## INTRODUCTION

Increasing developments in Northern regions in the last half-century have opened a new area of research: hydraulics of ice-covered flow. The presence of ice-cover in an open channel approximately doubles the wetted perimeter, and thereby produces a redistribution of flow velocities and bed shear stresses. As a result, the water flow changes to a higher depth and/or sharper flow slope, which are expected to cause changes on the sediment transport characteristics of the stream.

Scouring is another important phenomenon, which occurs where an obstacle is placed in the way of the flow. Experience has shown that scouring can gradually undermine the foundation of a structure regardless of the water flow depth. In extreme cases of unsteady flows, or under changes in channel conditions, scouring becomes exponentially powerful, potentially leading to the failure of water structures.

Studies conducted by Lau and Krishnappan (1985), Wuebben (1988), Smith and Ettema (1995), Zabilansky (1996), and Ettema et al. (1999), confirm that sediment transport in ice-covered channels decreases compared to the open-water situation; whereas, studies performed by Bacuta and Dargahi (1986), Yankielun and Zabilansky (1998), Olsson (2000), and Zabilansky (2002) confirm that the scouring around bridge piers in ice-cover conditions increases compared to the free-surface scouring.

Most of the studies regarding the sediment transport in ice-covered and free-surface flow situations were conducted in a flow depth adjustment condition, maintaining the energy slope for both cases constant. This is a valid hypothesis when an appropriate length scale is considered (i.e. long river reaches), but numerous other phenomena must be analyzed at a much shorter length scale: i.e. river reaches that contain abutments, bridge piers, cross-section alterations, etc. According to Zabilansky (2002), for these cases, it is common in nature for the ice-covered flow to adjust the flow slope faster than the flow depth, thus leading to drastic changes in the sediment transport and scouring behaviour.

Rough theoretical computation of a shallow-water case for ice-covered (subscript "$_{IC}$") and free-surface (subscript "$_{FS}$") flow shows that the bed shear stress ratio $\tau_{IC}/\tau_{FS}=2^{-3/5}<1$ when only the flow depth varies, and $\tau_{IC}/\tau_{FS}=2^{1/3}>1$ when only the energy slope changes (Munteanu, 2004). This computation considers the roughness of both boundaries (bed and ice-cover) to be identical and the ice cover to stretch over the entire channel width.

From a scouring point of view, when the flow depth has minor variations compared to the energy slope changes, the presence of ice-cover significantly increases the flow velocities in the bottom half of the flow depth. As a result, a larger part of the flow energy is directed to the scouring process compared to the free-surface case.

The objectives of this experimental analysis are to uncover features of scouring around bridge piers taking into account the effects of ice-cover and to examine the difference between scouring in free-surface and different ice-cover configurations. The analysis is carried out for the clear-water case when the flow regime is approaching critical sediment transport conditions.

## EXPERIMENTAL SET-UP

All the experiments performed this study were conducted at the Civil Engineering Department's Hydraulics Laboratory of the University of Ottawa.

The tests were performed in a 29.2m long by 1.49m width by 0.77m high rectangular flume made of concrete blocks. In these tests, the flume is divided into three sections along its length: Upstream false bed, Basin sand bed and Downstream false bed (**Figure 1**).

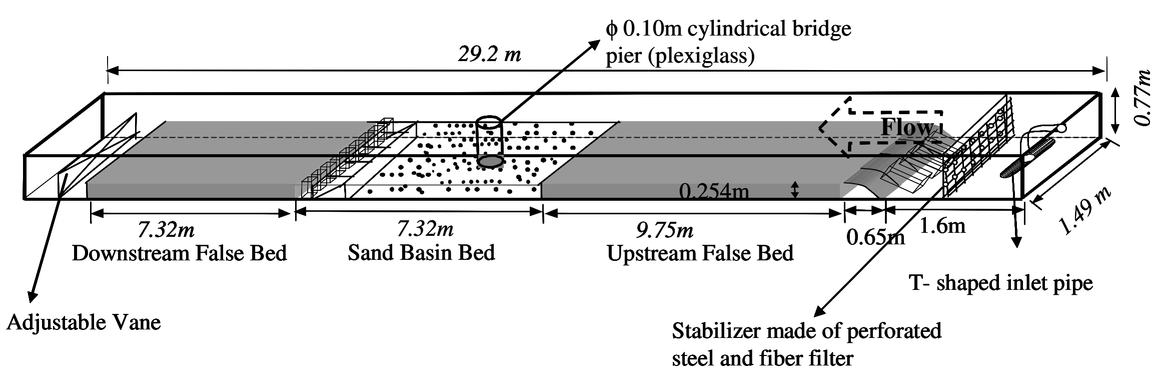


**Figure 1** Isometric View of the Rectangular Flume

Both false bed sections are made of aluminium sheets covering the entire width of the channel. The sand basin section is filled with relatively uniform medium sand of $d_{50}$=0.646mm and geometric standard deviation of $\sigma_g$=1.465. In order to provide similar flow regime for the upstream and the sand basin sections, the same sand material used to fill the sand basin was glued on the upstream false bed surface.

Velocity measurements were taken over ≈800mm spaced out cross-sections of the sand basin using an Electromagnetic velocity meter (EV) from Alec Electronics LTD, Japan. Laterally these cross-sections contain 9 measurement points located ≈150mm apart over the channel width. Vertically, velocity readings were taken at 15, 20, 50, 80 and 85% of the flow depth.

In this study, a 102mm diameter Plexiglas cylinder was used as a bridge pier, and was positioned in the centre-line of the channel (aligned to measurement point 5), at 1.83m downstream the beginning of the sand basin section. The simulated ice made of painted plywood and Styrofoam covered the Upstream false bed and the Basin sand sections of the flume. The roughness of the simulated ice was considered to reproduce a smooth ice-cover.

The experiments are performed with and without the simulated bridge pier in place at sediment critical conditions. Tests without the pier are meant to determine the worst case scenario between different configurations such as: total ice-cover case (TIC), when the ice is covering the entire width of the channel, two-side partial ice-cover case (2PIC) when the channel is covered with ice only on the sides, having the centre in open-water, and free-surface configuration (FS). In the 2PIC configuration the measurement points 4, 5 and 6 of every lateral cross-section are located in the open-water region. The tests with the bridge pier in place focused on the scouring features for the worse ice-cover configuration and the FS case.

## RESULTS AND DISCUSSION

### Hydraulic features

Results of the first tests session defined the 2PIC configuration as the extreme case of the sediment transport in the centre open-water region of the flow. Since the bridge pier is to be installed in this region, the 2PIC case is also considered the worst scenario of the scouring around a bridge pier. The experiments were conducted approaching the sediment critical conditions of the 2PIC configuration, $U/U_{cr} \approx 0.9$.

The first observation refers to significant changes in energy slope, recorded between different ice-covered flow configurations: 36% higher value in the TIC case when compared to the 2PIC case, and up to 3.7 times higher when compared both ice-cover configurations to the FS flow test. In contrast, flow depth changes were considered negligible (less than 1%).

**Figure 2** presents a comparison of the vertical velocity distribution in the central region of the channel width points 4, 5 and 6. The readings were taken in a cross-section approximately 4.3m downstream the beginning of the sand basin part of the channel. For these experiments the discharge was set to $0.043m^3/s$ and the flow depth to 0.133m.

For the TIC case, the maximum velocity measured at 50% of the flow depth was approximately 30.7cm/s. For the 2PIC case, the maximum velocity (≈ 32.8cm/s) was recorded in point 5 (centerline) at 80% of the flow depth while for the other lateral points, the maximum values of velocity were located at 50% of the depth and were between 23.9 and 32.6cm/s. In the FS test, the maximum velocity measured at 80% of flow depth varied from 25.3 to 28.9cm/s. In all three configurations, velocity readings at points 1 and 9 presented the same strong influence of the sidewall vicinity.

Analyzing the lower part of the flow ($y < 1/2\ h$), the 2PIC case shows approximately 6 to 8% increased velocity compared to the TIC case, and between 16 to 24% when both ice-cover cases are compared to the FS configuration (**Figure 2**). Comparing velocity gradients, dramatic acceleration characterize the ice-cover configurations in contrast to the free-surface scenario. In the bottom region of the flow depth (20 to 50%), the 2PIC configuration shows more than 3 times increase in velocity gradients when compared to the TIC case. Hence, a higher discharge (higher flow velocities) is directed through this open water region of the 2PIC configuration, that is anticipated to boost significantly the scouring process around the bridge pier. When compared to the FS configuration, the velocity gradients are about 35 to 50% higher in the 2PIC case in the same bottom region of the flow depth.

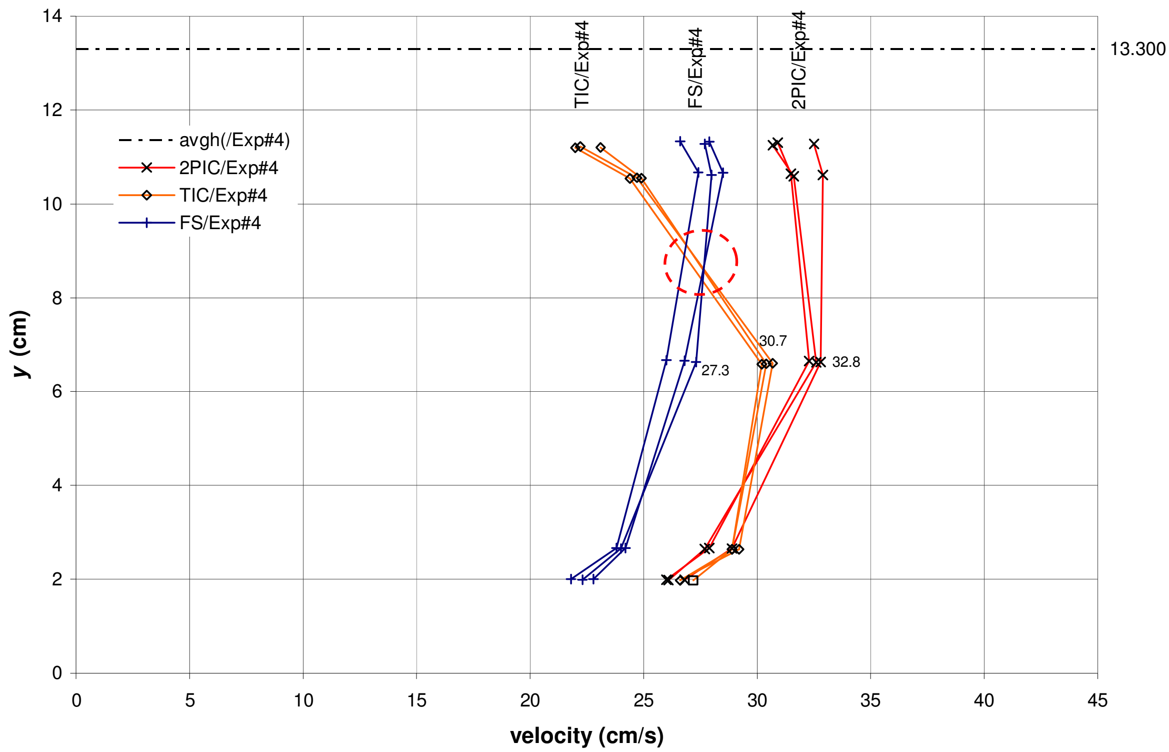


**Figure 2:** Exp#4/Vertical velocity profiles, c/s BB points 4, 5 & 6 (TIC, 2PIC & FS configurations).

## Scour depths and sediment erosion/deposition features

Results of the second session of tests show the maximum scour depth to be recorded in all tests at the bridge pier nose. The scour hole presented a conic shape, disrupted at the pier toe due to small amounts of deposited sand and easily elongated behind the pier. The erosion/deposition features behind the pier were considerably different when the 2PIC case is compared to the FS conditions. The tests of this session were performed in the same conditions of discharge and flow depth as in the first session.

As predicted in the previous analysis, for the 2PIC configuration, scouring around the bridge pier presented deeper and wider shape compared to the FS case, both at the same 2PIC critical conditions. Measurements recorded 50 to 55% deeper scour hole and 50% wider scouring circumference around the cylindrical pier for the 2PIC tests than for the FS test (**Figure 3**).

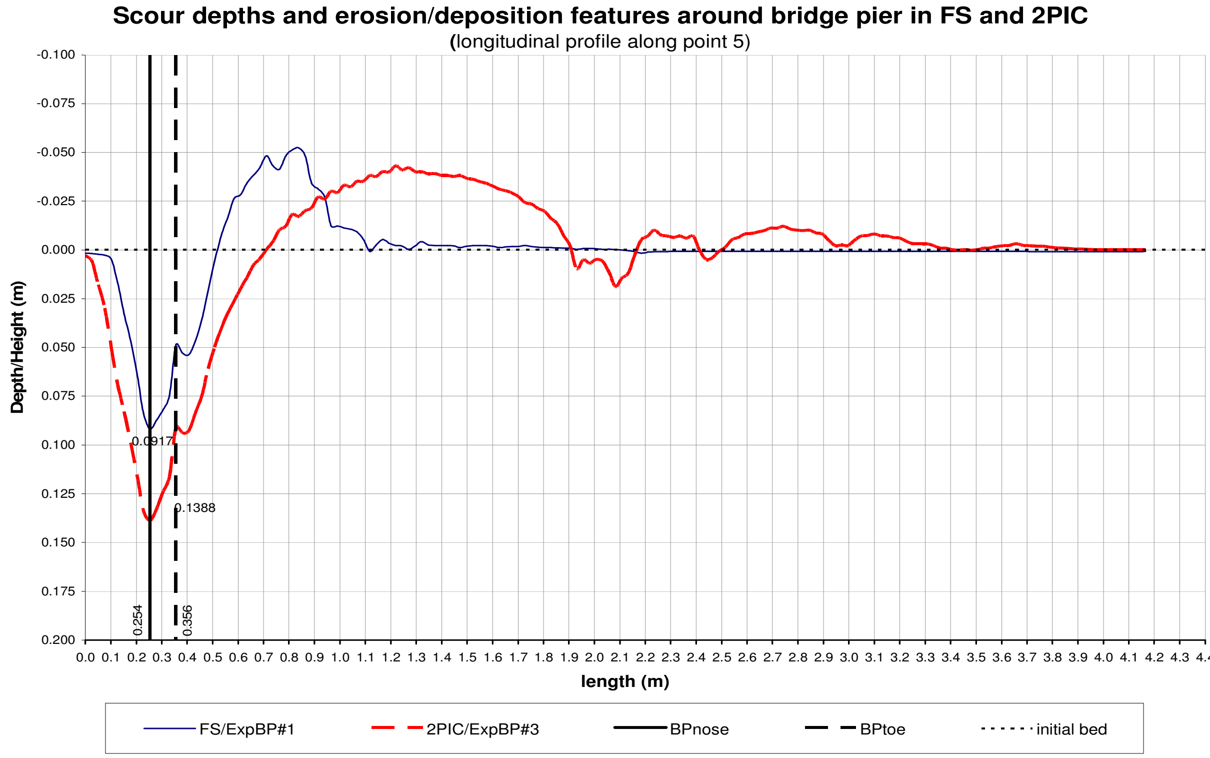


**Figure 3:** Scour depths at mid-width channel/2PIC (*ExpBP#3*) vs. FS (*ExpBP#1*)

Analyzing the erosion/deposition features behind the bridge pier, the results presented a considerably stronger activity in the 2PIC case than in the FS test at same critical conditions. As previously mentioned, the scouring process is acting in the central part of the flume, in the open-water region where the scour hole and the bar-shape deposition behind the pier are developed. All the other features under the ice-cover behind the pier resulted as an effect of the flow redirection due to the presence of the bridge pier. Therefore, under the ice-cover region, sediments were forming dunes due to higher flows directed in that region which resulted in increased velocities that produced further increased bed shear stress which exceeded sediment transport critical conditions.

Computations of geometrical characteristics of the activity behind the bridge pier showed the 2PIC configuration 4 times more extensive than the FS case. Quantitatively, computations showed 2.8 to 3 times more sand volume to be scoured from the upstream part and the sides of the pier in the 2PIC case. As for the deposition, 2.3 to 2.7 times more volume was deposited behind the pier when compared to the FS test. However, the height of the deposition bar was recorded approximately 20% higher in the FS configuration than in the 2PIC case. This behavior shows that the flow (higher velocity) requires more distance to redistribute its steady-state profile over the channel width behind the pier in the FS case. In the 2PIC case, the flow is forced under the ice-cover due to the bridge pier but once past the pier, the flow will redirect back in to the path of least resistance – the open-water region behind the pier. Thus, higher flow velocity will return quicker behind the pier which will impact the height of the deposition bar.

## CONCLUSION

The presence of an ice-cover in open channel might alter significantly the sediment transport characteristics of the bed channel or the scouring process around a bridge pier. In this study three different configurations were tested and the results show that the two sides partially ice-cover channel (2PIC) represents the worst case scenario from the sediment motion and scouring point of view compared to the total ice-cover (TIC) or free-surface (FS) cases.

The presence of the ice-cover on the sides of the channel induces a redistribution of the highest velocities towards the open-water region of the channel (less friction surfaces) where the bridge pier is located, and thus leading to higher available energy for the scouring phenomenon. The tests were conducted in clear-water conditions of $U/U_{cr}\approx0.9$ and the scour depths were recorded between 50 to 55% higher in the 2PIC configuration than in the FS case. The erosion/deposition features behind the bridge pier are again caused by redistribution of the velocities but towards the ice-cover region this time.

## ACKNOWLEDGEMENTS

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