PRELIMINARY STUDY ON THE INFLUENCE OF AN AIR-BUBBLE SCREEN ON LOCAL SCOUR AROUND A BRIDGE PIER

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Abstract

Flow interactions with a bridge pier and movable river bed result in local scour which can endanger bridge pier foundations. This scour is initiated by the downward flow and amplified by the so-called horseshoe vortex. A new method to reduce scouring around bridge piers has been assessed with preliminary tests. A bubble screen located upstream of the pier may counteract the downward flow and avoid the initiation of scour.

Laboratory experiments have been performed in a shallow flume with a physical scale model of a bridge pier under clear-water scour conditions. The bubble screen is generated by means of a collar linked to the pier and connected to a pressurized air system. Different water and air discharges have been tested. Vertical and horizontal location of the bubble screen have also been investigated. For each experiment, the final bed topography has been measured and compared to a reference experiment without the bubble screen.

The long-term experiments (approximately 56 hours) have revealed that a well-designed bubble screen may reduce the local scour around the bridge pier.

Introduction

Interactions amongst a bridge pier, the approach flow and the erodible bed result in local scouring which can endanger the stability of the foundations. The presence of the pier generates a three-dimensional turbulent flow, characterized by downward velocities that impinge on the bed and generate the scour, and the so-called horseshoe vortex which amplify the scouring effect (Melville & Raudkivi, 1977, Breuser & Raudkivi, 1991, Graf & Yulistiyanto, 1998, Graf & Istiarto, 2002).

According to previous studies, local pier scour is directly related to the magnitude of vertical flow (discharge and velocity) parallel to the pier face. Therefore, it should be possible to reduce the scour depth by reducing the magnitude of the vertical flow at the upstream pier face. It could be also blocked by using a barrier placed perpendicular to the pier face.

The two major controlling measures employed for preventing or minimizing local scour at bridge piers reported in literature are (i) bed armoring countermeasures (Lagasse et al., 2001, Lauchlan & Melville, 2001) and (ii) flow-altering countermeasures such as circular collars around piers (Zarrati et al., 2006, Heirdarpour et al., 2010), or cables wrapped spirally on the pile (Dey et al., 2006). However, they generally imply substantial constructive work.

The objective of the present preliminary study performed in the framework of a Master thesis is to have a first idea on the potential of a new technique that consists in counteracting the vertical velocities impinging on the bed by means of upward velocities induced by air-bubbles rising from a pressurized half collar situated near the bed.

This principle was successfully used to attenuate local scour in open-channel bends (Blanckaert et al., 2008, Dugué et al., 2011).

With respect to "hard" engineering techniques, bubble screens have the advantages of being controllable, ecological (oxygenation), reversible and non-permanent. Bubble plumes or screens have already been successfully applied in several hydraulic fields at large and small scales such as lakes destratification (Schladow, 1993), as a pneumatic barrier against saltwater intrusion (Nakai & Arita, 2002) or to prevent shoaling in navigation channels (Chapman & Scott-Douglas, 2002).

Experiments with mobile-bed morphology under clear-water scour conditions have been performed in a shallow flume with a circular bridge pier in its center. Morphologic comparisons are provided in this paper with the aim to answer the following questions:

Can a bubble screen reduce local scour near a bridge pier?

What is the influence of the base flow on the bubble screen behavior?

This paper first describes the experimental device and the bubble generation technique, then provides topographic comparisons between a reference experiment and several other ones with the bubble screen and finally presents visualization of the flow with the bubble screen near the bridge pier.

Experimental Set-up and Measurements

Experimental Set-up

Experiments were performed in a 29 m long and 2.5 m wide rectangular erodible-bed channel at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. This flume is described in Figure 1a. The same flume was used by Graf & Istiarto (2002) to investigate the flow patterns and turbulence around a cylinder in a scoured channel bed.

The sediment used for the experiments is uniform sand having a mean diameter of d_{50} = 2.1 mm and a distribution ratio of σ = 1.3. All experiments are performed under clear-water scour conditions.

The bridge pier, located 10 m after the entry of the channel has a diameter of D = 0.162 m. The bubble screen is generated by half a collar linked to the upstream side of the pier (Figure 1b). This collar is just a structural device required to generate the bubble screen but not intended to fix the bed in the entire zone covered by the local scour. Indeed, this collar was 4 cm wide, which is less than typical values for regular collar of 2 to 3 times the pier width (Zarrati et al., 2006).

The bubble screen can be generated by three different rows of 9 holes with an inner diameter of 4 mm (Figure 1b). The rows are located at three different positions from the upstream side of the pier (0.01, 0.02 and 0.03 m). To facilitate the generation of the bubble screen, the pier and the collar are entirely pressurized and connected to the pressurized air-system of the laboratory. Three different horizontal positions of the bubble screen have been previously investigated and the farthest from the pier (0.03 m) was found to be the most efficient and has been retained for all the presented tests.

Two different vertical positions for the collar and the bubble screen have been investigated. First, the collar was installed at the initial bed level (z = 0 m). In a second step, the collar was buried 5 cm below the mean bed level.

Instrumental devices

Water surface elevation was measured by means of a point gauge and final bed elevation measurements were performed on a refined grid with a Mini Echo Sounder.

Bubble screen behavior was documented by means of photographs.

The air pressure was regulated with a manometer and the air discharge measured with a rotameter.

Experimental conditions

Experiments have been performed continuously during 56 hours to obtain a morphology close to the equilibrium and to determine the maximal scouring depth under different configurations, with and without the bubble screen, but with similar air and water conditions. Configurations, main hydraulic and air parameters of these experiments are summarized in Table 1. For all tests, the initial condition was a flat bed.

Hydraulic conditions were chosen based on Istiarto & Graf (2002) experiments in which scour evolution was found to be asymptotic and 95 % of the maximal scouring depth was obtained before 56 hours of run. Based on these results, the tests were stopped after 56 hours of run to perform the bottom elevation measurements.

In addition, visualization of the influence of the base flow on the bubble screen has been performed for different air and water discharges, before the scour initiation.

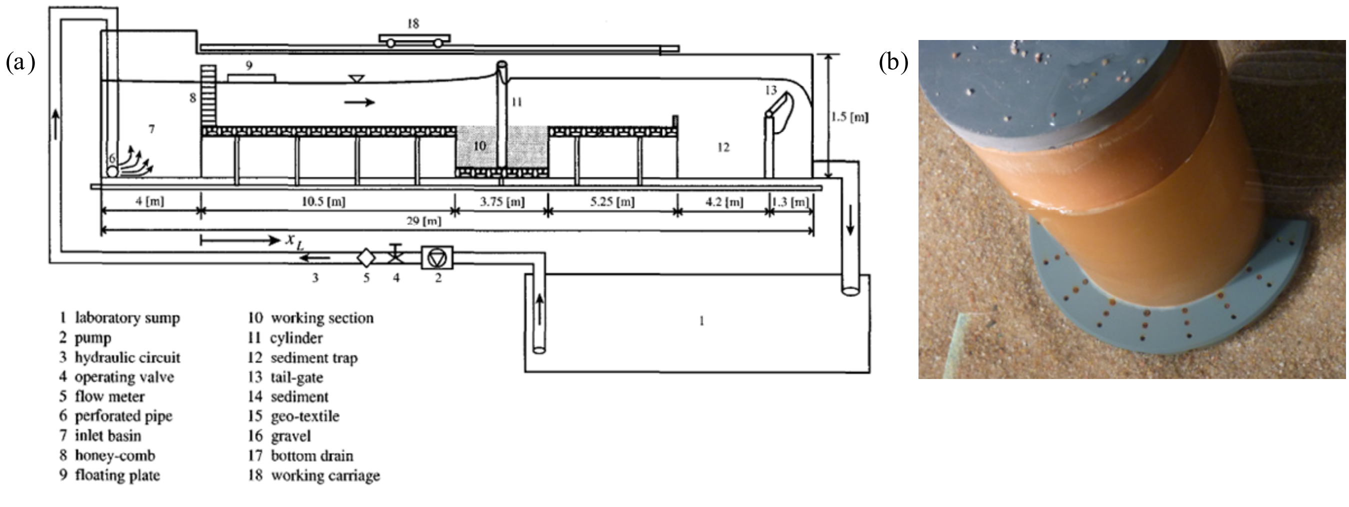

Figure 1: (left) General view of the channel (from Istiarto, 2001), (right) Photography of the pier with the collar and the bubble screen generation system

Table 1: Experimental conditions of the long-term experiments

Label	Q_w [m^3/s]	H_w [m]	U_w [m/s]	Fr_w [-]	Collar [-]	Collar elevation [m]	Bubble screen [-]	Q_a [$10^{-3}\ m^3/s$]
1 : Reference	0.2	0.24	0.34	0.22	-	-	-	-
2 : Collar	0.2	0.24	0.34	0.22	✓	0	-	-
3 : Collar + Bubble	0.2	0.24	0.34	0.22	✓	0	✓	2.25
4 : Buried collar	0.2	0.24	0.34	0.22	✓	-0.05	-	-
5 : Buried collar + Bubble	0.2	0.24	0.34	0.22	✓	-0.05	✓	2.25

Q_w is the water discharge, H_w is the flume-averaged water depth, U_w is the flume-averaged streamwise velocity, Fr_w is the water Froude number and Q_a is the air discharge.

Results and discussions

Influence of the different configurations tested on the local scour morphology

Figure 2 illustrates patterns of the bed topography for the five long-term experiments and compares the reference situation of a non-protected pier with the four different configurations (Table 1, tests 2 to 5). For each experiment, the bed reference (z=0 m) coincides with the initial bed level in the flume. As the topography is symmetrical on each side of the bridge pier, only the right side of the topography is represented in the figures.

In all experiments, the scour hole development starts at the sides of the pier and propagates rapidly around the upstream part of the pier to finally reach the centerline.

The reference case, without collar and bubble screen is presented in Figure 2a. A scour hole develops all around the pier with a maximal depth located upstream of the pier on the centerline axis, as observed in the literature (Breuser & Raudkivi, 1991). The upstream part of the scour hole has a streamwise slope close to the angle of repose of the sediment. The maximal scour depth measured was 15.5 cm under the initial bed level.

With the collar (Figure 2c), scouring still occurs but its spatial extent has decreased, especially downstream of the pier. The maximal scour depth has been decreased by 2 cm in comparison with the reference situation, which represents a reduction of 10%.

With the bubble screen added to the collar (Figure 2d), this spatial extent as well as the maximal scour depth is even more reduced, extending to 25 cm upstream from the pier and 20 cm downstream from the pier. However, the maximal scouring depth has not been modified by the bubble generation.

As found in literature (Zarrati et al., 2004), lowering the collar below the initial bed level increases the extension of the scour around the pier as well as the maximal scouring depth compared to a collar placed at the initial bed level (Figures 2c, e). The extension is especially increased downstream of the pier. In both cases, scour develops underneath the collar. However, when the bubble screen is used in addition to the buried collar (Figure 2f), the spatial extent of the scour hole is considerably reduced downstream of the pier. Moreover, the maximal scour depth reached 9.5 cm which represents a reduction of 39 % in comparison with the reference situation of a non-protected pier.

The streamwise evolution of the bed elevation at the centerline of the flume in the five experiments is represented in Figure 2b. The maximal scouring depth could not be measured very near the pile, except for the reference situation, because of the protrusion of the collar. In each experiment, scouring occurs near and upstream of the bridge pier but its maximal depth is evolving with the different configurations. Compared to a non-protected pier, the maximal scour depth is reduced when using the four different investigated configurations. In both bubble screen cases, the maximal scour depth has decreased in comparison to the reference case. It shows that the bubble screen does not have a negative impact on the erosion.

The minimal scour depth was obtained when using the bubble screen in addition to a buried collar. However, the maximal spatial extent was obtained for the buried collar without the bubble screen. This would imply a continuous use of the bubble screen and the non-permanent advantage of this countermeasure would be lost.

Finally, the optimal configuration would be the bubble screen used in addition of a collar with a small width (Configuration 3). The maximal scouring depth has only been decreased of 13% but the spatial extent of the scour is considerably reduced. Moreover, this configuration has the advantages to induce less fixed and permanent constructions in the river.

Consequently, the Configuration 3 has been chosen to perform the visualization of the bubble screen involving different air and water discharges.

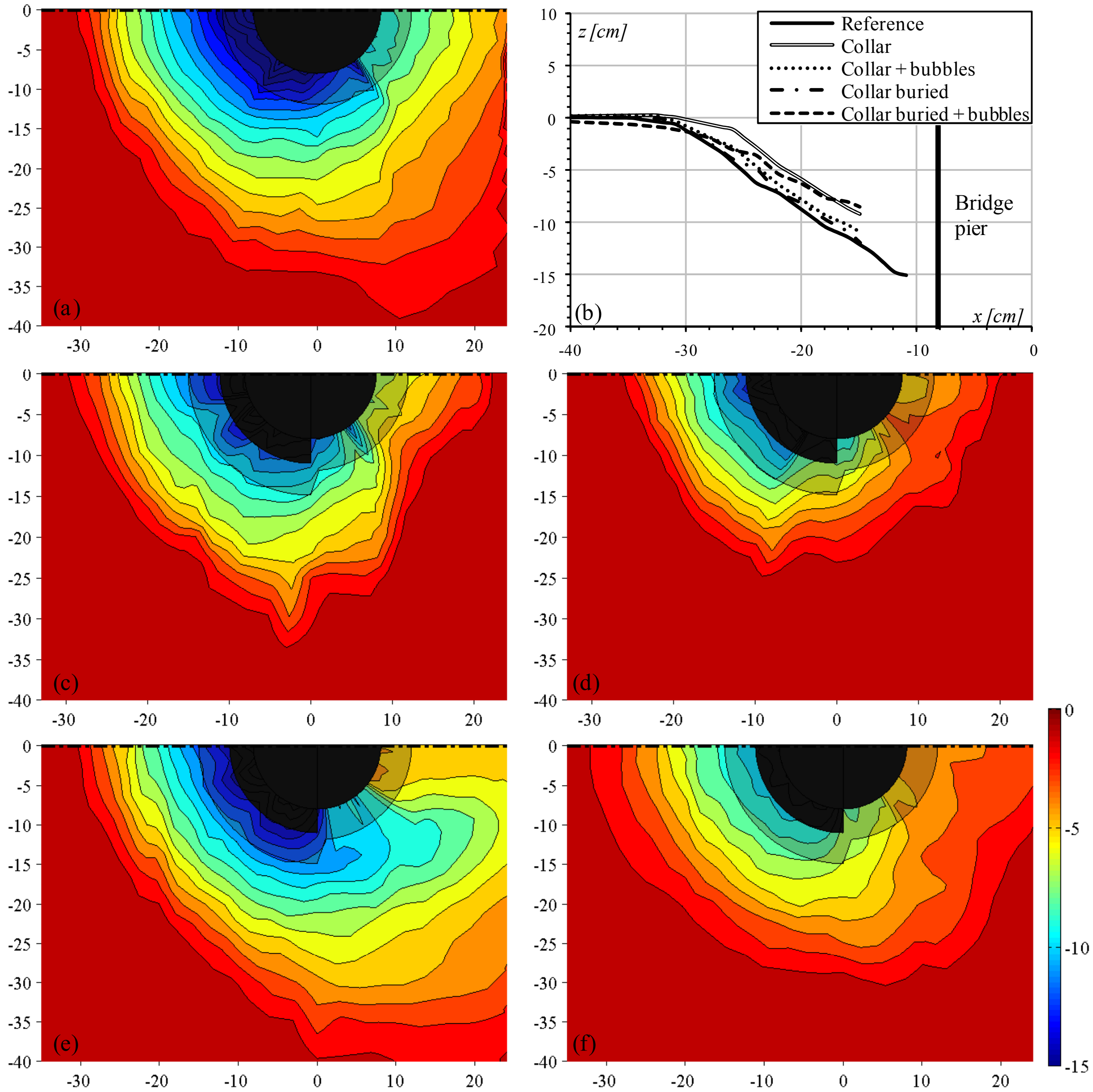

Figure 2: Isolines of the bed level with an interval of 0.01 cm derived from Mini Echo Sounder measurements for the reference (a), collar (c), collar + bubble screen (d), buried collar (e) and buried collar + bubble screen (f) experiments. The same color scale has been used to simplify comparison. The dashed area near the bridge pier indicates the area bridged by means of extrapolations. (b) Streamwise evolution of the bed slope at the center line of the flume

Influence of air and hydraulic conditions on the bubble screen behavior

The present section will investigate the impact of both air and river discharges on the bubble screen behavior and determines the different flow type induced. For these tests, Configuration 3, with the bubble screen used in addition to the collar installed on the bed reference level, was chosen.

In order to have a better visualization of the phenomenon involved, photographs have been taken before the scour initiation for different hydraulic and air conditions to illustrate the existence of the different flow types observed (Figure 3).

In a similar procedure, Nakai and Arita (2002) experimentally investigated the flow mechanism of a saline wedge intrusion in the presence of a transversal bubble screen. They classified interactions between the bubble screen and the river base flow into two types which have also been observed in the reported experiments.

First, flow behavior is controlled by the buoyancy flux of the bubble screen (Figure 3, sketch 1). Bubbles rise to the water surface and surface flow can be observed in either upstream or downstream direction. Moreover, a weak secondary flow can be observed in the upstream side of the bubble screen. This bubble-induced secondary flow can be

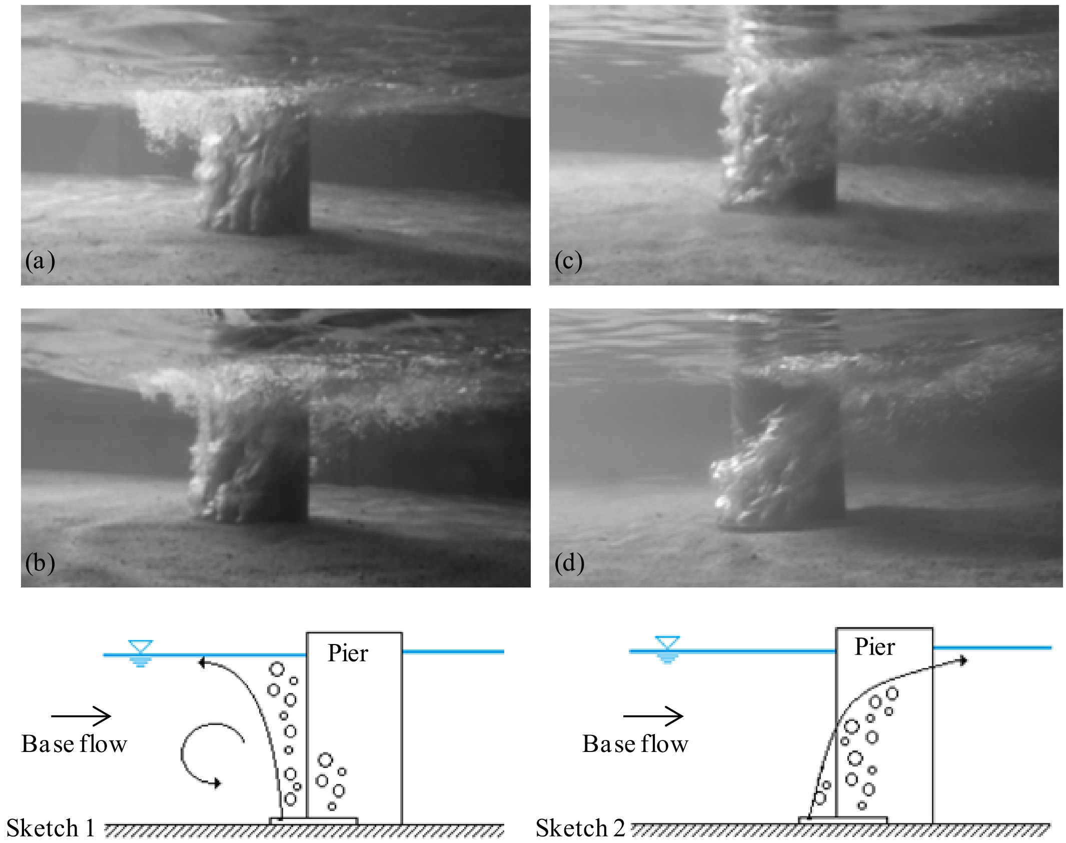

Figure 3 : (Top) Examples of different behavior of the air-bubble screen regarding the air and water discharges: (a) Q_w=0.1 m^3/s and Q_a=2.25 10^{-3} m^3/s, (b) Q_w=0.15 m^3/s and Q_a=2.25 10^{-3} m^3/s, (c) Q_w=0.2 m^3/s and Q_a = 3 10^{-3} m^3/s, (d) Q_w=0.18 m^3/s and Q_a=1.7 10^{-3} m^3/s. (Bottom) Schemes of the two different types of flow. Dominant effect of the bubble screen (Sketch 1), Dominant effect of the base flow (Sketch 2).

visualized on Figures 3a and 3b where surface current exits upstream of the pier.

Second, flow behavior is controlled by the inertial force of the river base flow (Figure 3, sketch 2). The surface flow induced by the bubble screen only exists in the downstream direction (Figure 3c). The upstream bubble-induced secondary flow is no longer observed. In extreme conditions (Figure 3d), the bubbles are no longer able to reach the water surface upstream of the pier. However, vertical upwards velocities can still be observed near the bed upstream of the pier. This indicates that the bubble screen may be efficient for a large range of river discharges. However, morphologic investigations have to be performed in order to conclude on the long-term occurrence of these observations.

Conclusion

In the reported study, morphodynamics around a bridge pier was experimentally investigated introducing a new technique to counteract erosion: a bubble screen. The concluding remarks obtained are as follows:

If the bubble screen is optimally located (distance from the pier, vertical elevation) and if the air discharge is carefully chosen, the local scour may be reduced. The maximal scouring depth obtained with the bubble screen buried 5 cm below the bed level was reduced by 40% in comparison to a non-protected pile.

Bubble screen and river discharges were found to be relevant to optimize the efficiency of this countermeasure. Indeed, two different types of flow behavior have been observed. When the buoyancy effect are dominant, the bubbles rise in front of the pier and surface flow spreads on both side generating a secondary flow in the upstream side of the pier. The efficiency of the bubble screen would then be optimal.

If the inertial force of the river base flow is dominant, bubbles are transported by the streamwise flow and the upstream bubble-induced secondary flow does not exist anymore. Only near bed upwards velocity still occurs.

In this report, several parameters, such as the horizontal and vertical location of the bubble screen, have been investigated in different configurations. However, interactions with other parameters, such as the bed material characteristics, the pier geometry and the mean water depth have to be investigated in order to clearly define the efficiency of the bubble screen to protect bridge pier against erosion.

Moreover, a better understanding of the redistribution of the velocity field induced by the bubble screen is relevant and is under investigation.

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