Flow patterns induced by a bubble screen in a sharply curved flume based on Acoustic Doppler Velocity Profiler measurements

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Open-channel bends are characterized by a bed morphology where erosion occurs near the outer bank and a point bar develops at the inner bend. This morphology is induced by complex interactions between the streamwise flow, the curvature-induced secondary flow and the bed topography. Several techniques already exist to counteract the development of bend scour, which can endanger foundations of structures. However, existing techniques mostly imply substantial construction works in the river. Preliminary laboratory experiments have shown that a porous tube placed near the outer bank can generate a bubble screen that modifies the flow patterns and leads to a substantial reduction of the bend scour. A better understanding of the hydrodynamic mechanisms induced by the bubble screen and involved in the morphological development will allow determining the range of application of the bubble-screen technique. Experiments performed in a sharply curved open-channel bend under live-bed conditions show that the bubble screen is able to redistribute the velocity patterns in the bend. The bed morphology is then partially modified, specially at the bend exit. This paper illustrates Acoustic Doppler Velocity Profiler measurements of the bubble-induced secondary flow and its interaction with the channel base flow in the most influenced cross-section.

Keywords: ADVP, Bubble screen, Erosion, Scour, Morphodynamics, Open-channel bends

1 INTRODUCTION

Open-channel bends are characterized by strong interactions between the streamwise flow, the curvature-induced secondary flow and the bed morphology. This interplay leads to the development of a typical bar-pool bed topography [1]. Outer banks are vulnerable to scour whereas sediment deposition occurs at the inner bank and may reduce the navigable width.

Several techniques to counteract the development of the typical bar-pool bed morphology, such as bottom vanes [2] or a fixed outer bank layer [3] have already been studied and applied. However, most of them imply substantial construction works in rivers. Previous experiments performed in a sharply curved laboratory channel at LCH-EPFL have shown that a porous tube placed near the outer bank can generate a bubble screen strong enough to redistribute the velocity patterns on a fixed horizontal bed [4] and can even modify the bed morphology and avoid bend scour on a mobile bed under clear-water scour conditions [5].

Similar experiments have been performed in the same sharply curved flume under live-bed conditions with and without the bubble screen in order to give insights in the underlying flow mechanisms involved in both cases. Comparisons of the bed morphology are provided in order to determine the efficiency of the technique. Velocity measurements performed with an Acoustic Doppler Velocity Profiler (ADVP) are provided in one cross-section where the morphological impact of the bubble screen was found to be the strongest.
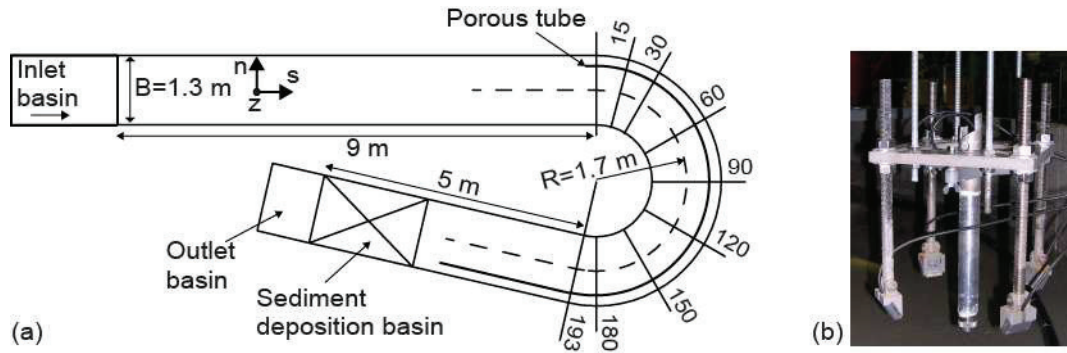
2 EXPERIMENTAL SET-UP

2.1 Experimental set-up

Experiments were performed in a sharply curved laboratory flume of constant width $B = 1.3$ m that consists of a 9 m long upstream straight reach, followed by a 193° bend with a constant centerline radius of curvature $R = 1.7$ m and finished by a 5 m long downstream straight reach (Figure 1a). The sediment used was uniform quartz sand with a mean diameter $d = 0.002$ m.

A curvilinear reference system (s, n, z) was adopted where s represents the streamwise direction, the transverse n-axis point in the outward direction and the vertical z-axis in the upward direction.

The bubble screen was generated by means of a porous tube placed at 0.2 m from the outer bank starting 0.2 m before the entry of the bend. It was connected at both ends to a pressurized air circuit in order to have a quasi-uniform bubble generation along the entire length of the porous tube. The air pressure was controlled by means of a manometer and the air discharge was measured with a rotameter.

	Q	q_s	Pa	H	U	R/B	R/H	B/H
Label	[l/s]	[kg/(m.s)]	[kPa]	[m]	[m/s]	[-]	[-]	[-]
LB_NB	75	0.025	-	0.14	0.41	1.31	12.1	9.2
LB_B	75	0.025	600	0.14	0.41	1.31	12.1	9.2

Figure 1: (a) Plan view of the curved channel with the porous tube. (b) Acoustic Doppler Velocity Profiler (ADVP). Experimental conditions (Q is the water discharge, q_s is the sediment discharge, Pa is the chosen air-pressure, H is the final flume-averaged flow depth, U is the flume-averaged velocity ($U = Q/BH$), In the labels, LB stands for live-bed, NB for no bubble screen, and B for bubble screen experiments)

2.2 Instrumentation

Flow characteristics were measured in several cross-sections around the bend by means of an Acoustic Doppler Velocity Profiler (Figure 1b). The ADVP, developed at EPFL, consists of a central emitter surrounded by 4 receivers and measures the quasi-instantaneous velocity vector along an entire profile. From these measurements, the mean velocity vector with its three components (v_s, v_n, v_z) can be obtained as well as the bed elevation. A detailed description of the working principle of the ADVP and its experimental accuracy can be found in literature [1, 6-8].

Due to constraints imposed by the size of the ADVP, velocity profiles were measured every 0.05 m only in the range $n = -0.45$ m to $n = 0.45$ m in the reference experiment and in the range $n = -0.45$ m to $n = 0.4$ m when using the bubble screen. Indeed, velocity measurements were not possible near the bubble screen because the bubbles interfered with the acoustic signal of the ADVP.

The bed morphology was measured with a laser distometer on a refined grid.

2.3 Experimental conditions

Main hydraulic and air parameters are summarized in Figure 1.

Two experiments have been performed under similar hydraulic and sediment conditions. The reference experiment LB_NB was performed without the porous tube and the bubble screen whereas the bubble screen LB_B experiment was performed with the porous tube and the bubble screen.

For both experiments, the bed was initially flat.

Experiments were then performed under live-bed conditions with constant sediment feeding at the entrance of the flume ($q_s = 0.025$ kg/(m.s)) until morphological equilibrium was achieved.

3 RESULTS

3.1 Influence of the bubble screen on the bed morphology

Figure 2 illustrates the final bed morphology for the two experiments. The bed reference level for each experiment ($z = 0$ m) coincides with the flume-averaged bed level.

The streamwise evolution of the transverse bed slope (Figure 2a) indicates two deep scour holes in the LB_NB experiments located in the cross-sections at 90° and 180° in the bend, as found in literature [1, 3]. The existence of these two scour holes is related to the sudden change of curvature at the entry and the exit of the bend.

In the LB_B experiment, the first scour hole is as deep as in the reference experiment. However, the second scour hole due to the disappearance of curvature is strongly reduced by the influence of the bubble screen.

The bubble screen influence is further illustrated in Figures 2b and c where the water surface and bed elevations in two cross-sections at 90° and 180° in the bend are represented. In the cross-section at 90°, only small differences in the bed morphology can be observed and are due to mesoscale bedforms migration.

However, in the cross-section at 180°, the bed has been substantially modified under the influence of
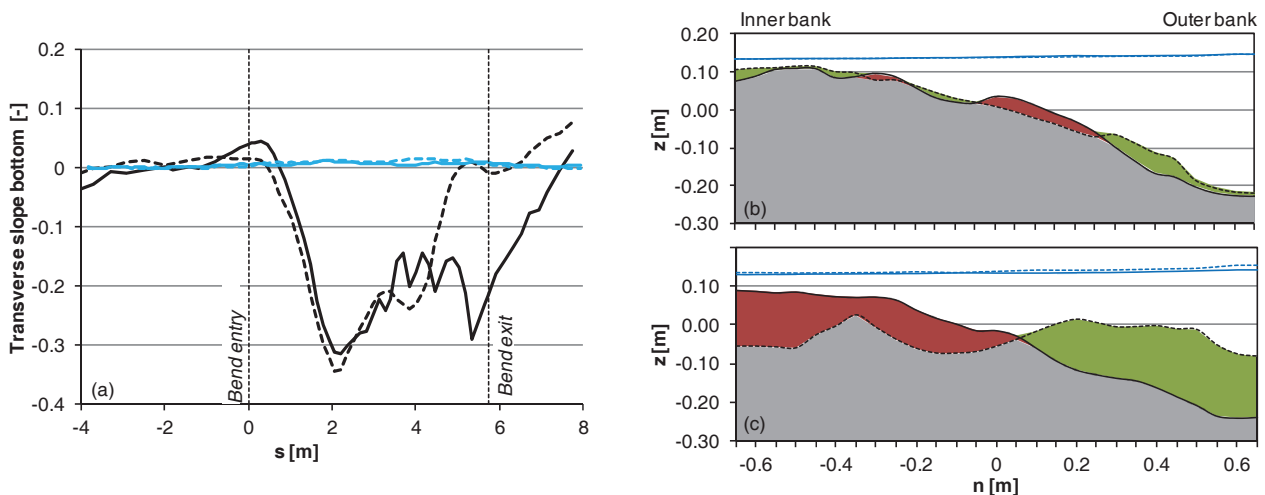
Figure 2: Morphological comparison of the reference (full line) and the bubble screen (dotted line) experiments (a) Streamwise evolution of the transverse bed slope around the flume and bed and water surface elevations in the cross-section at 90°(b) and at 180°(c) in the bend. Red and green areas represents respectively erosion and deposition in comparison with the reference morphology without the bubble screen.

the bubble screen. Deposition near the outer bank and erosion of the bar at the inner bank lead to a more regular profile in the cross-section.

3.2 Influence of the bubble screen on the flow field

In order to explain the strong morphological difference induced by the bubble screen in the cross-section at 180° in the bend, the flow field measured with ADVP is shown in Figure 3. The three velocity components, as well as water surface and bed elevations are reported for the two experiments.

In the reference LB_NB experiment (Figure 3a), a pronounced transverse slope can be observed with a deep scour hole near the outer bank. Maximum streamwise velocities are located near the water surface and in the outer part of the cross-section. A secondary flow with strong outwards velocities near the water surface and inwards velocities near the bed can also be observed. Small downward velocities are located in the middle of the cross-section but the core of maximal downwards velocities is supposed to be located very near the outer bank due to mass conservation in the secondary flow cell. Also the core of maximum streamwise velocities is supposed to be located near the outer bank outside the measuring grid.

In the bubble screen LB_B experiment (Figure 3b), the bed morphology is flatter with three small scour holes located near each bank and at n = -0.05 m. The scour hole at the outer bank is supposed to be due to the outer bubble-induced secondary flow located between the porous tube and the bank. The scour hole located at the middle of the cross-section is due to the inner bubble-induced secondary flow. Indeed, inwards velocities are observed near the

water surface between the position of the porous tube (n = 0.45 m) and the position of the scour hole (n = -0.05 m) which is also characterized by maximum downward velocities. Outwards velocities are located near the bed.

The core of maximum streamwise velocities is observed from n = 0 m to the outer bank with a maximum value of 0.6 m/s. Low streamwise velocities not sufficient to enhance sediment transport are observed in the inner part of the cross-section. As a result, the bed remains almost horizontal in this location.

These observations confirm that the bubble screen can generate a secondary flow that can modify the base flow distribution and consequently have an effect on the bed morphology under live-bed conditions.

5 CONCLUSION

This paper compared ADVP measurements of the flow obtained in the same cross-section of an open-channel bend in a reference experiment and in an experiment involving an air-bubble screen placed near the outer bank. Velocities measurements have shown that the bend natural flow can be fundamentally modified by the bubble-induced secondary flow. In the cross-section at 180° in the bend, the core of maximum downward velocities has been shifted from near the outer bank to the middle of the cross-section, resulting in a flatter bed profile and a reduction of the outer bank scour hole.

The capabilities of an Acoustic Doppler Velocity Profiler (ADVP) in the investigation of flow structures induced by a bubble screen in a curved open-channel flow are highlighted in the present paper.
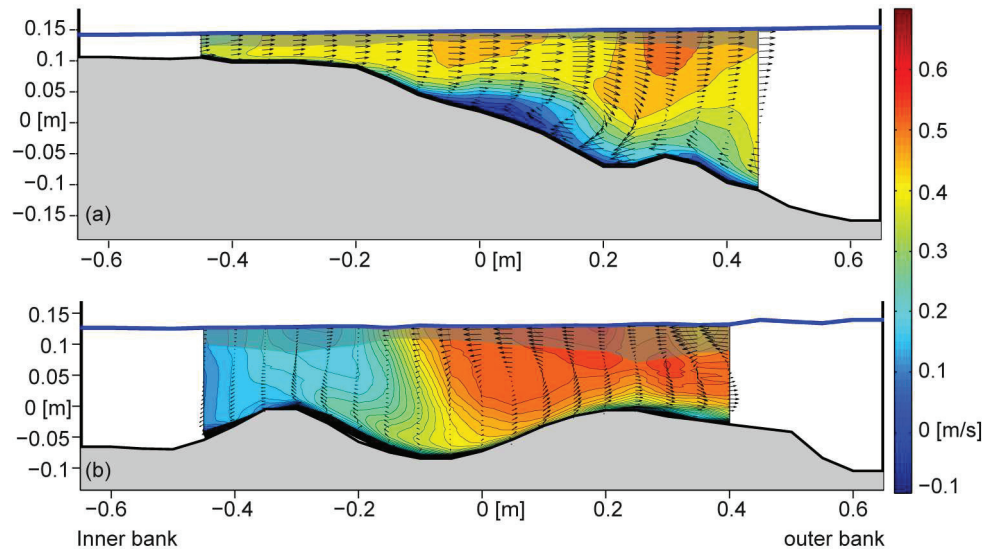
Figure 3: Downstream view of the mean streamwise flow velocities v_s (contours) and cross-sectional velocities v_n, v_z (vectors) in the cross-section at 180° in the bend for the reference LB_NB experiment (a) and for the bubble screen LB_B experiment (b). The bed elevation has been estimated from ADVP measurements (thick black line) and from the laser distometer measurements (thin black line). The shaded area near the water surface indicates extrapolated values.

6 ACKNOWLEDMENT

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