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Influencing bend morphodynamics by means of an air-bubble screen - Topography and velocity field

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ABSTRACT: Interactions between curvature-induced secondary flow, streamwise flow and bed morphology in open-channel bends lead to the development of a typical bar-pool bed morphology, shaped by scour at the outer bank and deposition at the inner bank. This typical bar-pool bed morphology may endanger the stability of the outer bank or reduce the navigable width of the channel. Preliminary laboratory experiments in a sharply curved channel with a fixed horizontal bottom (Blanckaert et al. 2008) have shown that a bubble screen located near the outer bank can generate secondary flow with a sense of rotation opposite to the curvature-induced secondary flow. The reported study investigates the application of bubble screens in configurations with mobile-bed morphology under live-bed and clear-water scour conditions. Velocity measurements show that the bubble-induced secondary flow decreases the strength of the curvature-induced secondary flow, and shifts it in inwards direction. Maximum scour occurs where the curvature-induced and bubble-induced secondary flow cells meet. At this same location, the maximum streamwise velocities and maximum vertical velocities impinging on the bed occur, which indicates their importance with respect to the formation of bend scour. The application of the bubble screen resulted in a reduction of the maximum bend scour by about 50%. Moreover, the location of maximum scour is shifted away from the outer bank and does not endanger its stability anymore. These preliminary experiments show the potential of a bubble screen to influence and modify the bed morphology.

1 INTRODUCTION

Low-gradient rivers often develop a meandering morphology. Each curve of the meander is thereby characterized by a particular morphological profile. Outer banks are vulnerable to scouring whereas deposition occurs near the inner bank. This so-called bar-pool morphology is related to the existence of a curvature-induced secondary flow, which is defined as flow perpendicular to the streamwise axis. This secondary flow redistributes the velocities and the boundary shear stress (Rozovskii, 1957, Blanckaert and Graf, 2004, Blanckaert and de Vriend, 2003, 2004).

Several techniques exist to reduce adverse impacts of the typical bar-pool morphology, such as increased risk of erosion at the outer bank or a reduced navigable width, but they generally imply substantial constructive works. Techniques reported in literature include bottom vanes (Odgaard and Spoljaric, 1986, Odgaard and Wang, 1991), fixed layers (Roca et al., 2007) and submerged groynes (Przedwojski, 1995). However, these techniques have the disadvantages of being fixed constructions on the bed and to represent a possible threat for navigation.

This paper describes a new way to manipulate the secondary flow and thus the morphology. Previous laboratory experiments in a sharply curved channel with a horizontal fixed bed have shown that an additional secondary flow cell opposed to the curvature-induced secondary flow cell can be created by means of an air-bubble screen (Blanckaert et al., 2008). The air bubbles coming from a porous tube installed on the bed near the outer bank rise to the water surface and thereby generate this additional secondary flow cell. Thus, velocities and bed shear stresses are redistributed in the cross-section. Moreover, the cores of maximum descending vertical velocities and of maximum streamwise velocities, which are responsible for the development of the bend scour, are shifted from near the outer bank to the junction of both circulation cells.

With respect to "hard" engineering techniques, bubble screens have the advantage of being controllable, ecological (oxygenation), reversible and non-permanent. They have already been applied in several fields at large scales such as aeration and destratification of lakes and reservoirs (Schladow, 1992, Wüest et al., 1992) but also at smaller scales such as for venting aerosol mixtures into water pools in nuclear power plants (Smith, 1998). However, the application of bubble screens in shallow river morphodynamics has not yet been investigated or applied.

Considering the promising results of the preliminary study on a fixed horizontal bed (Blanckaert et al., 2008), similar experiments with mobile-bed morphology under live-bed and clear-water scour conditions have been carried out with and without the bubble screen in order to understand its influence on channel morphology. Morphologic and hydrodynamic comparisons are provided in this paper with the aim to answer the following questions:

1. Can the bubble screen influence the morphology of the bend?
2. How does the bubble-induced secondary flow cell redistribute the velocity patterns in a cross-section?

This paper briefly describes the laboratory flume and the experimental conditions, presents the results for the reference and bubble screen experiments and discusses the impact of the bubble screen on the morphology and hydrodynamics of the bend.

2 EXPERIMENTAL SET-UP AND MEASUREMENT TECHNIQUES

2.1 *Experimental Set-up*

Experiments were performed in a sharply curved laboratory flume at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. This flume (Figure 1) is composed of a straight inflow reach of 9 m, followed by a 193° bend with a centerline radius of curvature R=1.7 m and a straight outflow reach of 5 m. The whole flume has a rectangular cross-section with a constant width of B=1.3 m. The same flume was used by Blanckaert et al. (2008) to investigate the influence of the bubble screen on the flow in a configuration with fixed horizontal bed.

An orthogonal curvilinear (s, n, z) reference system is adopted, where the downstream s axis coincides with the flume's centerline, the transverse n axis points in the outward direction, and the vertical z axis is upwards.

The sediment used for the experiments is quartz sand of nearly uniform diameter 1.6 mm < d < 2.2 mm with a mean diameter of 2 mm. When conducting experiments with sediment recirculation, sand is continuously fed into the flume near the entrance.

The bubble screen is generated by means of a porous tube placed on the bottom of the channel, ballasted with a chain to avoid large-amplitude movements, and connected at both ends to a pressurized air system of the laboratory to guarantee the same air pressure over the entire length of the tube. The air pressure was regulated with a manometer and the air discharge measured with a rotameter. For experiments with a bubble screen, the porous tube was placed at 20 cm from the outer bank. The bubble screen extended from 5 m upstream of the bend entry to 2.5 m downstream of the bend exit.

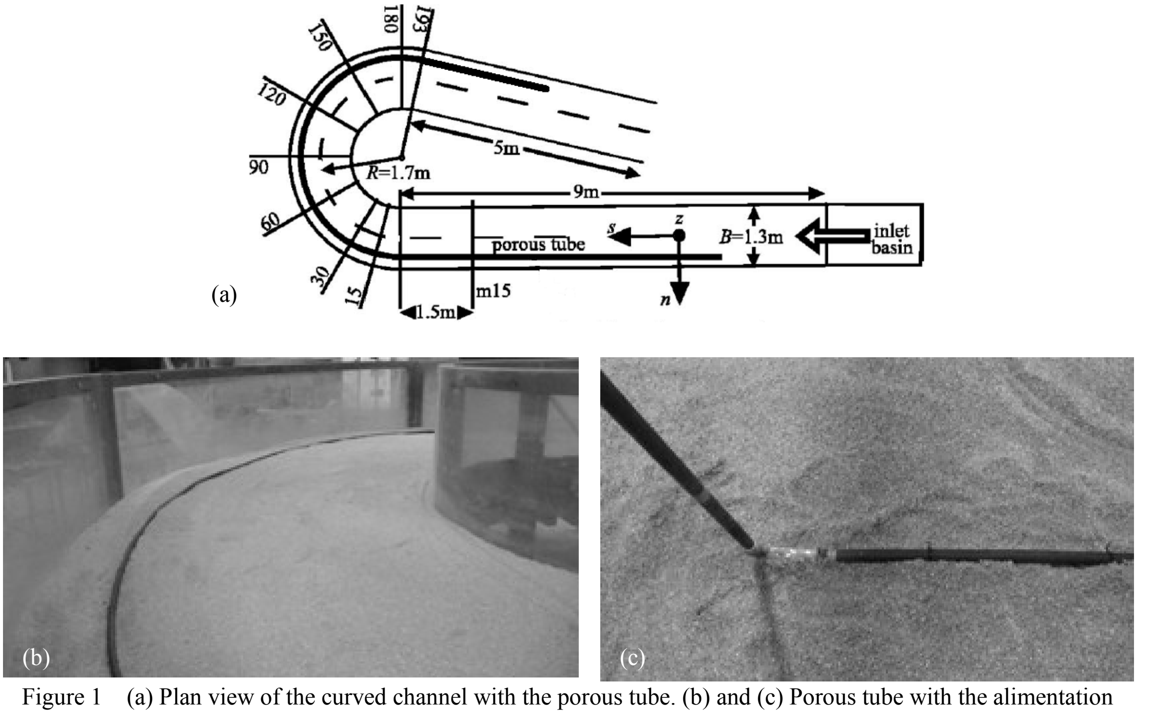

Figure 1 (a) Plan view of the curved channel with the porous tube. (b) and (c) Porous tube with the alimentation system existing at the two sides of the tube

2.2 *Velocity, Water Surface, and Bathymetry Measurements*

For each experiment, flow characteristics were measured by means of an Acoustic Doppler Velocity Profiler (ADVP). The ADVP, developed at EPFL, consists of a central emitter surrounded by 4 receivers, and measures the quasi-instantaneous velocity vector. From this measurement, 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 Lemmin and Rolland (1997), Hurther and Lemmin (1998), Blanckaert and Lemmin (2006), and Blanckaert (2010). For hydrodynamic investigations, velocity measurements were performed in one single cross-section at 70° in the bend. Velocity measurements were not possible near the bubble screen because the bubbles interfered with the acoustic signal of the ADVP. As a consequence, no velocities were measured between the porous tube and the outer bank.

The water surface was measured around the whole flume by using a point gauge. The bed topography was measured using a laser distometer on a refined grid (every 5° in the bend and every 5 cm in the cross-sectional direction).

2.3 *Experimental conditions*

Three experiments were performed under different conditions of sediment supply and bubble generation, but with similar hydraulic conditions in order to simplify the comparison between experiments. Experimental conditions are listed in the Table 1. The M63_10_00 experiment without bubble generation was performed under live-bed conditions with a constant rate of sediment feeding at the entrance of the flume; the M57_14_00 experiment without bubble generation was performed under clear-water scour conditions, and the MB55_14_00 experiment with bubble generation was also performed under clear-water scour conditions. For all experiments, the initial condition was a flat bed.

Table 1 Experimental conditions

Label	Q [L/s]	q_s [kg/(m.s)]	Pa [kPa]	H [m]	U [m/s]	S [10^{-4}]	R/B [-]	R/H [-]	B/H [-]
M63_10_00	63	0.023	-	0.10	0.49	28	1.31	17.2	13.2
M57_14_00	57	-	-	0.14	0.31	7.36	1.31	11.9	9.1
MB55_14_00	55	-	500	0.14	0.31	1.61	1.31	12.2	9.3

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, S is the flume-averaged water slope.

Clear water scour conditions were determined based on the hydraulic conditions of the first experiment M63_10_00 and on the critical dimensionless Shields parameter, τ_c, which is approximately 0.04 according to Shields diagram (Breusers and Raudkivi, 1991). The dimensionless Shields parameter τ in the straight upstream reach was larger than its critical value, $\tau > \tau_c$, in the M63_10_00 experiment with sediment recirculation (τ =0.074) whereas it was smaller in experiments without recirculation, $\tau < \tau_c$ (τ =0.032 for the M57_14_00 experiment).

3 RESULTS AND DISCUSSIONS

3.1 *Influence of the bubble screen on the bed morphology*

Figures 2 and 3 illustrate patterns of the bed topography for the three experiments. The bed reference for each experiment (z = 0) coincides with the flume-averaged bed level.

The streamwise evolution of the transverse bed slope (determined by linear fitting) in the three experiments is drawn in Figure 2a. The live-bed M63_10_00 experiment and the clear-water scour M57_14_00 experiment are characterized by similar morphological features that are typical for sharply curved open-channel bends (Roca 2007, Blanckaert 2010): a typical bar-pool bed topography is characterized by two deep scour holes located near the entry and the exit of the bend, creating a pronounced transverse slope (Figure 2a, Figure 3a,b). The bubble screen considerably reduces the transverse bed slope in the bend. Some scour occurs in the straight inflow reach in the region between the bubble screen and the outer bank, leading to non-zero values of the transverse bed slope (Figure 2a).

The morphological modification induced by the bubble screen can be further observed in Figure 2b, in which the cross-section at 70° in the bend is drawn for the three experiments. The water surface represented is the one measured in the M57_14_00 experiment. The bubble screen dramatically modifies the bed morphology. The location of maximum bend scour has been shifted away from the outer bank towards the center of the flume, where it does not endanger bank stability anymore. Moreover, the maximum bed scour is reduced by about 50%.

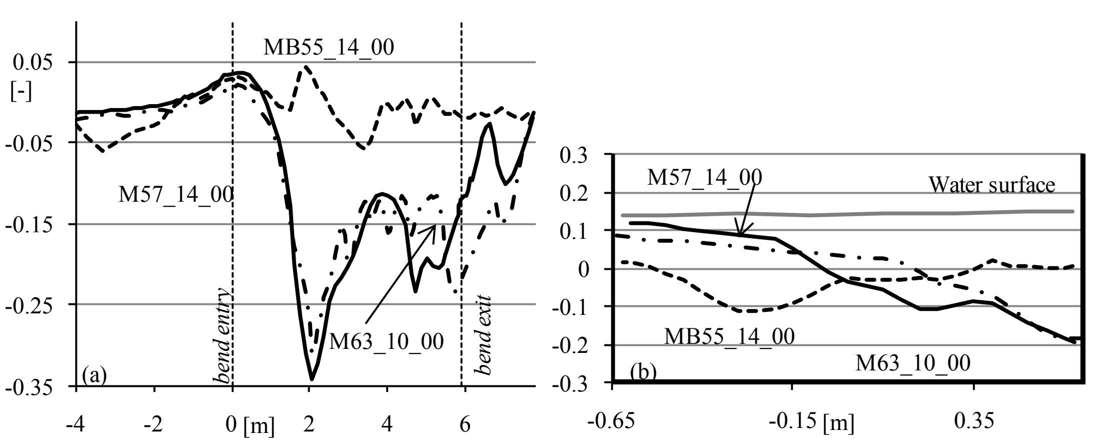

Figure 2 Comparison of the reference M63_10_00 and M57_14_00 experiments without the bubble screen and the MB55_14_00 experiment with the bubble screen, (a) Streamwise evolution of the transverse bed slope around the flume and (b) water surface and bed elevations in the cross-section at 70° in the bend

Due to the bubble-screen induced velocity redistribution, the critical shear stress for sediment transport was not attained anymore in the outer-part of the cross-section in the clear-water scour MB55_14_00 experiment, which explains the nearly flat bed. In the inner part of the bend, the sediment deposition is reduced. As a result, the bubble screen reduces morphologic gradients.

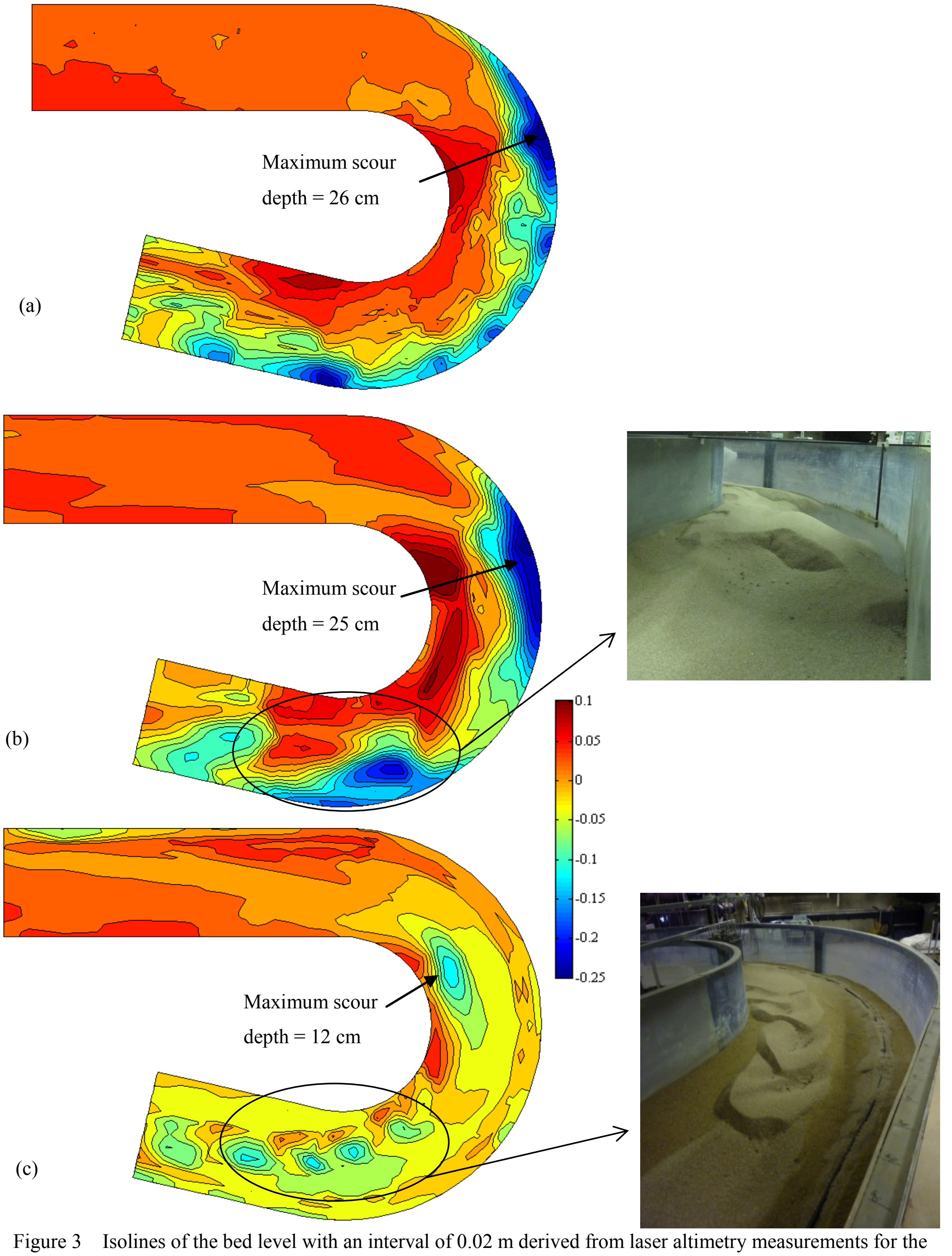

Figure 3 Isolines of the bed level with an interval of 0.02 m derived from laser altimetry measurements for the M63_10_00 (a), M57_14_00 (b) and MB55_14_00 (c) experiments. The same color scale has been used to simplify comparison. The inserted pictures on the right provide visualization of the mesoscopic bedform features in the downstream part of the bend

Figure 3 illustrates in detail the morphology for three experiments. In both experiments without bubbles screen, a bar is formed at the inner bank between the cross section located at 30° and 150°in the bend. Maximum scour depth is about 25 cm under the flume-averaged level. In the bubble experiment, the bed level is in general much flatter than in the reference experiment. However, a scour hole with a maximum depth of 12 cm under the flume-averaged level associated to a small bar can be noticed in the upstream part of the bend.

Mesoscale bedforms occurred in all experiments (see photos in Figure 3). In the M57_14_00 experiment without bubbles, large amplitude dunes can be distinguished in the downstream part of the bend. In the MB55_14_00 experiment with bubbles, dunes had a smaller wavelength and smaller amplitude. The inwards shift of the location of the dunes is reminiscent of the inwards shift of the location of the core of maximum streamwise velocities.

3.2 *Influence of the bubble screen on the velocity redistribution*

In order to explain the morphological influence of the bubble screen, the present section will investigate its influence on the flow field. Figures 4, 5 and 6 illustrate the bed topography, the water surface elevation and the three normalized components (streamwise, transverse and vertical) of the velocity vector in the cross-section at 70° in the bend for the M57_14_00 and MB55_14_00 experiments. Flow patterns in the M63_10_00 experiment are similar to those in the M57_14_00 experiment and are not shown. In the M63_10_00 experiment the depth near the inner bank was too shallow to measure by means of the ADVP. In the MB55_14_00 experiment the velocities in the vicinity of the bubble screen could not measured because of interference between the bubbles and the ADVP signal.

In the reference experiment, the secondary flow typical of open-channel bends was observed, with secondary flow at the surface toward the outer bank and at the bed toward the inner bank (Figure 4a and Figure 5b,c), which is constrained to the deepest part of the cross-section. In the bubble experiment, the curvature-induced secondary flow is weakened (Figure 5b,c vs. Figure 6b,c) and an additional counter-rotating secondary flow was observed (Figure 4b and Figure 5b,c), with a transverse extent from about n = -0.2m to about n = 0.45m (position of the porous tube). The core of maximum vertical velocity impinging on the bed defines the limit of the two secondary flow cells. These vertical velocities impinging on the bed are due to the combined effect of the two counter-rotating secondary flow cells. Their amplitudes, however are smaller than the ones observed near the outer bank in the reference experiment, which could partially explain the observed reduction in the maximum scour depth.

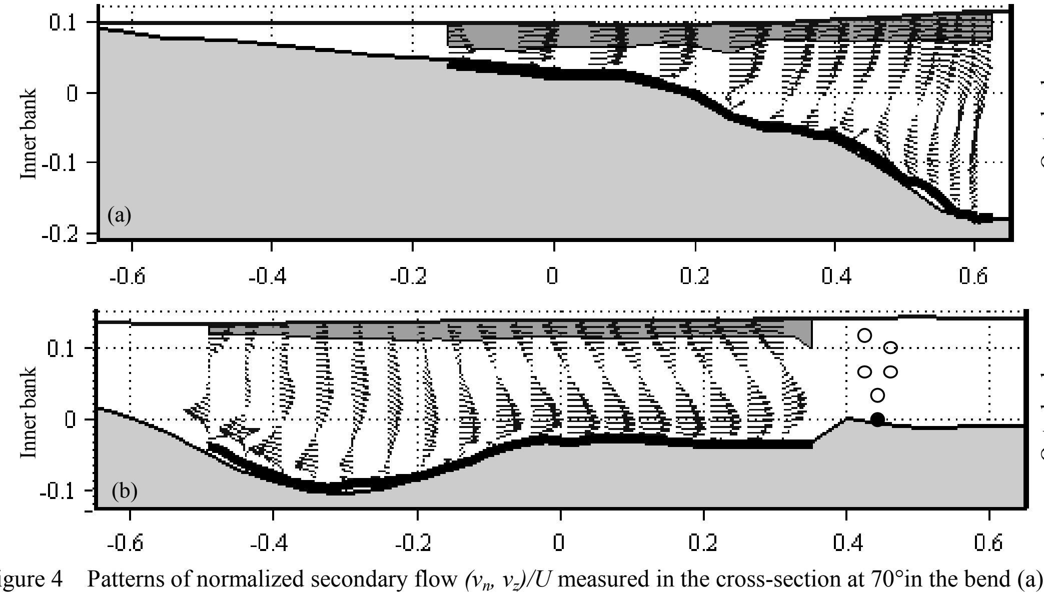

Figure 4 Patterns of normalized secondary flow $(v_n, v_z)/U$ measured in the cross-section at 70°in the bend (a) for the M63_10_00 experiment without bubbles and (b) for the MB55_14_00 experiment with bubbles. The dashed area near the water surface indicates the area bridged by means of extrapolations

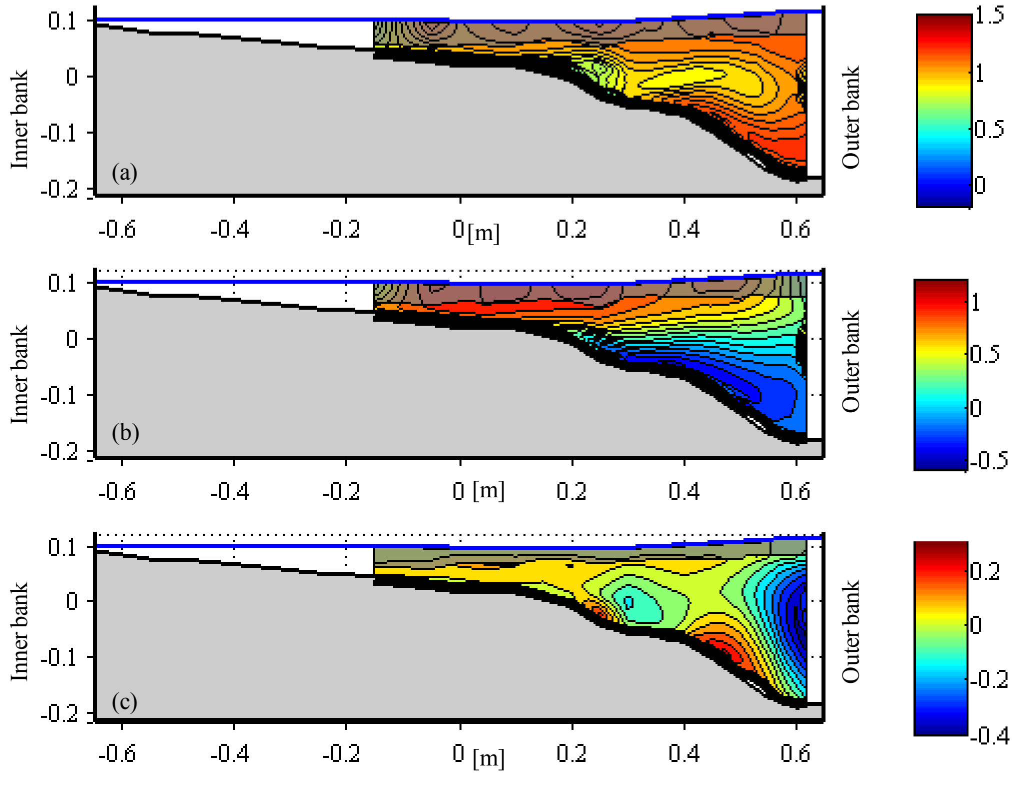

Figure 5 Measured patterns of the normalized (a) streamwise, (b) transverse, and (c) vertical velocities in the cross-section at 70° in the bend in the M63_10_00 experiment. The dashed area near the water surface indicates the area bridged by means of extrapolations

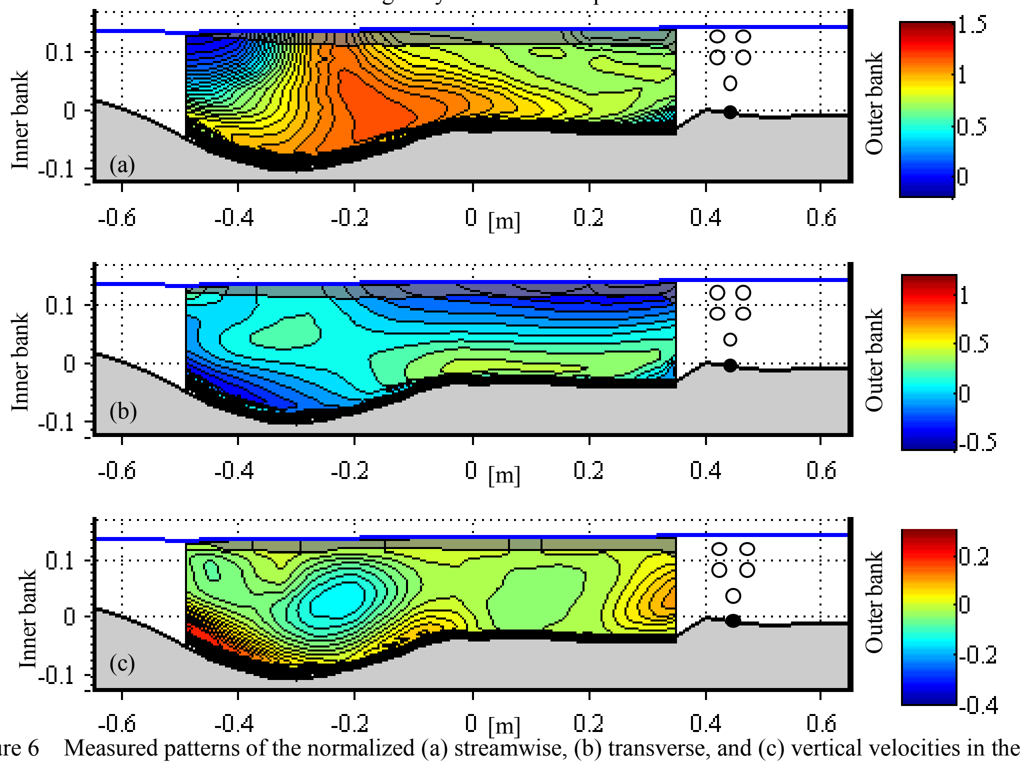

Figure 6 Measured patterns of the normalized (a) streamwise, (b) transverse, and (c) vertical velocities in the cross-section at 70° in the bend in the MB55_14_00 experiment. The dashed area near the water surface indicates the area bridged by means of extrapolations

Secondary flow is known to be efficient in redistributing velocities (Blanckaert and de Vriend 2003, Blanckaert and Graf 2004). This is confirmed by the patterns of the streamwise velocity in both experiments. In the reference experiment, the curvature-induced secondary flow (Figure 4a) advects high near-surface velocities in outward direction. As a result, the core of large streamwise velocities v_s occurs near the outer bank (Figure 5a), where it promotes scour. In the bubble experiment, advective redistribution by both secondary flow cells causes the core of maximum streamwise velocities to occur at the border between both secondary flow cells (Figure 6a).

4 CONCLUSIONS

Flow in open-channel bends is characterized by strong interactions between streamwise velocities, secondary flow and bed morphology. The presence of a bubble screen near the outer bank, with its rising velocities, generates a secondary flow that rotates in the sense opposite to the curvature-induced secondary flow. The bubble-induced secondary flow cell causes an inwards shift of the cores of maximum streamwise velocity and maximum vertical velocity impinging on the bed, both of which play an important role in the generation of scour in the bend.

This flow redistribution induced by the bubble screen acts directly on the morphology of the bend. The maximum scour is considerably reduced and occurs further away from the outer bank, resulting in a reduced flow attack on the outer bank. Moreover, the sediment deposition in the inner part of the bend is reduced, resulting in less shallow flow.

These preliminary experiments suggest that a bubble screen can be applied to actively influence and modify the morphology in rivers. These preliminary results need to be confirmed by additional experiments that investigate the influence of live-bed conditions, hydraulic parameters including the flow depth and velocity, air supply conditions, the position of the porous tube, scale effects, etc.

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