Influence of outer-bank inclination and roughness on cross-stream cells in open channel bends

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ABSTRACT

The influence of outer-bank geometry on hydrodynamics in open-channel bends is poorly known. Its study is relevant for the design of bank protection schemes in river restoration projects.

This paper investigates the influence of outer bank roughness and inclination on the cross-stream circulation cells in a sharp laboratory open-channel bend by means of high-resolution three-dimensional velocity measurements with an Acoustic Doppler Velocity Profiler. Three test conditions were analyzed where only the outer-bank characteristics were varied: 1) vertical outer-bank with smooth PVC; 2) vertical outer-bank with 3-cm stones simulating riprap; 3) 30°-inclined outer bank with 3-cm stones.

In all measurements the pattern of cross-stream circulation is characterized by the existence of two cells: center-region cell and outer-bank cell. For rectangular channels, with increasing outer bank roughness the outer bank cell amplifies and widens considerably constraining the center region cell and so increasing the protective effect on the outer bank zone. In trapezoidal channels the outer-bank cell is smaller and weaker than in rectangular experiments regardless the outer-bank roughness, however, still protecting the outer-bank. A term-by-term analysis of the downstream vorticity equation suggests that the centrifugal force and the cross-stream turbulent stresses drive the outer-bank cell for all experiments.

INTRODUCTION

Nowadays straight channels are transformed into curved channels in order to allow them some controlled freedom in their alluvial plane and to enhance flood defense systems by providing buffer capacity. However, river rehabilitation projects require cutting edge engineering tools to simulate complex three-dimensional flow patterns, boundary and bank shear stress, sediment transport, bank erosion, etc. The development of such engineering tools is linked with high quality experimental data and with better understanding of 3D flow mechanisms. In a curved flow two important cells exist, the center-region cell and the outer-bank cell, which determine the primary flow and the shear stress distribution along the bend. The center-region cell is generated by the interplay between centrifugal force and pressure gradient induced by the superelevation of the water surface (Rozovskii 1957, Blanckert and

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Graf, 2004) whereas the outer-bank cell is either generated by skewing as well by turbulence (Blanckaert and de Vriend, 2004).

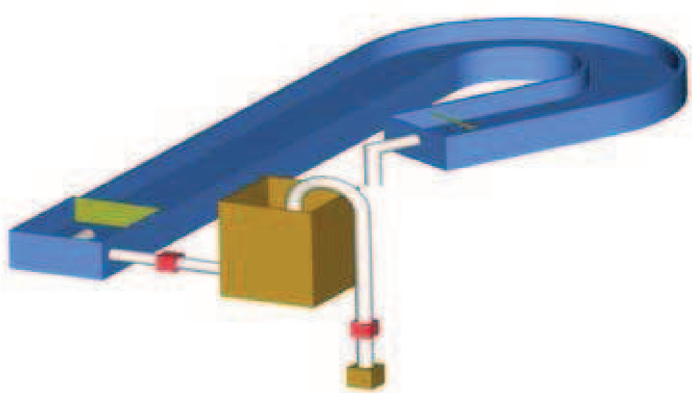
However, the understanding of the circulation cells is mainly based on investigations made in rectangular channels with smooth outer-banks. So, it is not clear what happens in more realistic experiments wherein the influence of outer-bank inclination and roughness is systematically varied.

This paper investigates experimentally curved open-channel flows where the outer-bank inclination and roughness are varied. Three test conditions are studied wherein all hydraulic parameters are constant except the outer-bank characteristics: 1) vertical outer-bank with smooth PVC; 2) vertical outer-bank with 3-cm stones simulating riprap; 3) 30°-inclined outer bank with 3-cm stones. This paper gives a special focus on the mechanisms of the circulation cells by investigating the main terms of the downstream vorticity equation.

Hence, this paper addresses the following questions: What is the effect of the outer-bank inclination and roughness on the circulation cells? Are the mechanisms of the circulation cells postulated by Blanckaert and de Vriend (2004) confirmed for bends with varying outer-bank inclination and roughness?

EXPERIMENTS

Experiments were carried out in a 19 m long laboratory open-channel flume, see Figure 1. It consists of a 9 m long approach channel, followed by a sharp 193° (R/B>1) bend with constant centerline radius of curvature of R=1.7 m and a 5 m long straight exit channel. The flume width at the free surface is 1.3 m, and the bottom width is 1.3 m and 1.03 m for vertical and 30°- outer bank inclination configurations, respectively. The bed of the flume has glued quasi-uniform sediments of d_{50} = 0.002 m whereas the inner-bank is made of smooth Plexiglas. The outer-bank is either smooth Plexiglas or 3-cm stones are attached on the wall in order to simulate riprap. The approach channel has a downstream bed slope of 0.22%, whereas the bed in the bend and out-flow is horizontal.



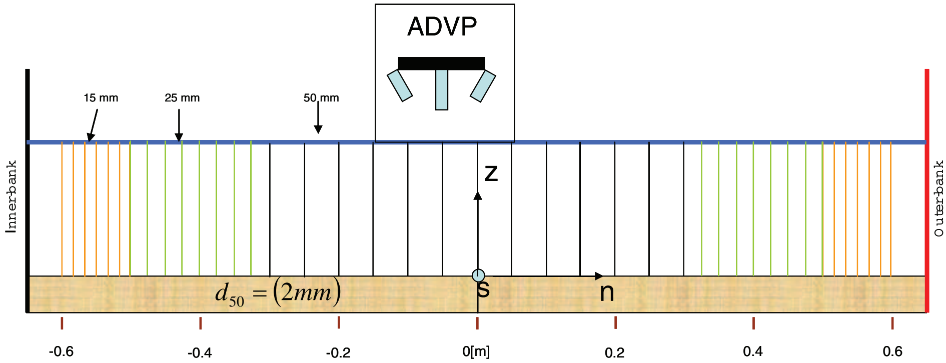


Figure 1 (up) Scheme of the laboratory flume; (down) Set-up of the Acoustic Doppler Velocity Profiler (ADVP), refined measuring grid and reference system.

Table 1 Experimental set-up and conditions

Label	Q [ls^{-1}]	H [m]	U [ms^{-1}]	u_* [ms^{-1}]	C [m$^{1/2}$s^{-1}]	E_s [‰]	Re [10^3]	Fr [-]	R/H [-]	B/H [-]	*Bank angle* [°]	Ks [mm]
Test 1	89	0.159	0.43	0.037	36	1.01	69	0.33	10.3	8.1	90	PVC
Test 2	89	0.155	0.44	0.042	33	1.42	69	0.35	10.9	8.1	90	30
Test 3	78	0.156	0.44	0.038	36	1.21	68	0.35	10.8	7.4	30	30

Reach-averaged water-surface gradient on the centerline, S_s ; Chézy friction factor, $C = \sqrt{g}.(U/u_*)$;Reynolds number, $\mathrm{Re} = U \cdot H / \upsilon$; Froude number , $Fr = U/\sqrt{gH}$

All three experiments have been investigated under similar hydraulic conditions with an overall mean velocity of U ~ 0.42 m/s and flow depth of H~0.16 m.

Three dimensional velocity measurements were made using Acoustic Doppler Velocity Profiler (ADVP) developed by EPFL/LHE (Rolland 1994, Shen 1997, Hurther 2001). It is a non-intrusive technique despite of minor flow perturbation produced by the ADVP system slightly intrusion on the water free-surface. The ADVP is capable of measuring the entire flow profile with high spatial resolution, one measuring point every 3 mm. The sampling frequency is 31.25 Hz and the acquisition time is 180 s. Blanckaert and de Vriend (2004) have estimated the uncertainty in quantities derived from the time-averaged velocities and turbulent stresses, yielding an uncertainty of 20% in the streamwise vorticiy ω_s and of about 40% in the different terms in the transport equation for streamwise vorticity. The uncertainty in ADVP measurement, and notably in turbulence measurements, increases progressively towards the bottom in the lower 20% of the water column.

Cross-section at 90º has been measured on a refined grid with vertical profiles at about n = [-0.6:0.015:-0.5; -0.475:0.025:-0.3;-0.25:0.05:0.25 0.3:0.025:0.475; 0.5:0.015:0.6] m, see Figure 1. The choice of cross-section at 90º for all experiments is based on the cross-section where maximum cross-stream circulation intensity occurs (Duarte, 2008). In all Figures shown hereafter shaded zones covering the water zones close to the water surface and to the channel bottom were added. These shaded zones indicate where data extrapolations were performed in order to correct erroneous measurements from the ADVP's box slight disturbance of the free-surface or from the increasing measuring error in flow zones close to the bed.

THEORETICAL

In the framework of the present paper the influence of the outer-bank inclination and roughness on the mechanisms underlying the circulation cells is investigated by means of the transport equation for the streamwise vorticity, written as Blanckaert and de Vriend (2004):

$$\frac{\partial \omega_s}{\partial t} = ADV + CFG + SKW + ANIS + SHEAR + NU + DISS \quad (1)$$

$$CFG = -\frac{1}{1+n/R}\frac{\partial}{\partial z}\left(\frac{v_s^2}{R}\right) \quad (2) \qquad ANIS = \frac{\partial^2}{\partial z \partial n}\left(\overline{v_n'^2} - \overline{v_z'^2}\right) + \frac{1}{1+n/R}\frac{1}{R}\frac{\partial \overline{v_n'^2}}{\partial z} \quad (3)$$

$$SHEAR = \left\{\frac{1}{1+n/R}\frac{\partial^2}{\partial z^2} - \frac{\partial}{\partial n}\left(\frac{1}{1+n/R}\frac{\partial}{\partial n}\right)\right\}\left[(1+n/R)\overline{v_n' v_z'}\right] \quad (4)$$

From Equation 1 the relevant terns are CFG, ANIS and SHEAR representing centrifugal effects by the mean flow, generation and/or dissipation of ω_s by the cross-sectional turbulence anisotropy and generation and/or dissipation of ω_s by turbulent shear stress, respectively. All other terms are at least an order de magnitude smaller and so considered negligible.

RESULTS

In Figures 2 the patterns of normalized downstream vorticity, $\omega_s H/U$, of cross-section at 90° for all experiments are shown. The isolines reveal the existence of two circulation cells. The negative values at channel center correspond to the center-region cell whereas the positive values in the upper outer zone correspond to the outer-bank cell. The separation between the center-region cell and the outer-bank cell is defined by the $\omega_s = 0$ contour line visible in the upper corner near the outer bank.

For rectangular channels increasing outer-bank roughness increases the outer-bank cell size and decreases the center-region cell, see Figures 2 (top and middle). On the other hand, decreasing bank inclination decreases the outer-bank cell size and shifts its center inward, however, its inward limit is similar, and so, the center-region cell size is unaffected, see Figures 2 (middle and bottom).

The intensity of the center region cell, $\omega_s H/U$, is about -1.75 for the two rectangular channels, Figures 2 (top and middle), regardless of the outer-bank roughness. The intensity of the center-region cell is about -1.25 for (30°-inclined outer bank with riprap) Test 3, Figure 2 (bottom). The differences of intensity are within the uncertainty.

The intensity of the outer-bank cell, $\omega_s H/U$, increases from 0.25 to 0.5 with increasing outer-bank roughness between rectangular channels, see Figures 2 (top and middle). The intensity of the outer-bank cell for Test 3 is 0.2, Figure 2 (bottom), which is inferior to Figure 2 (middle) suggesting that a trapezoidal channel generates a weaker outer-bank cell than a rectangular channel as the difference is higher than the uncertainty. However, its location is unaffected and so the center-region cell location is also unaffected regardless of the outer-bank cell intensity.

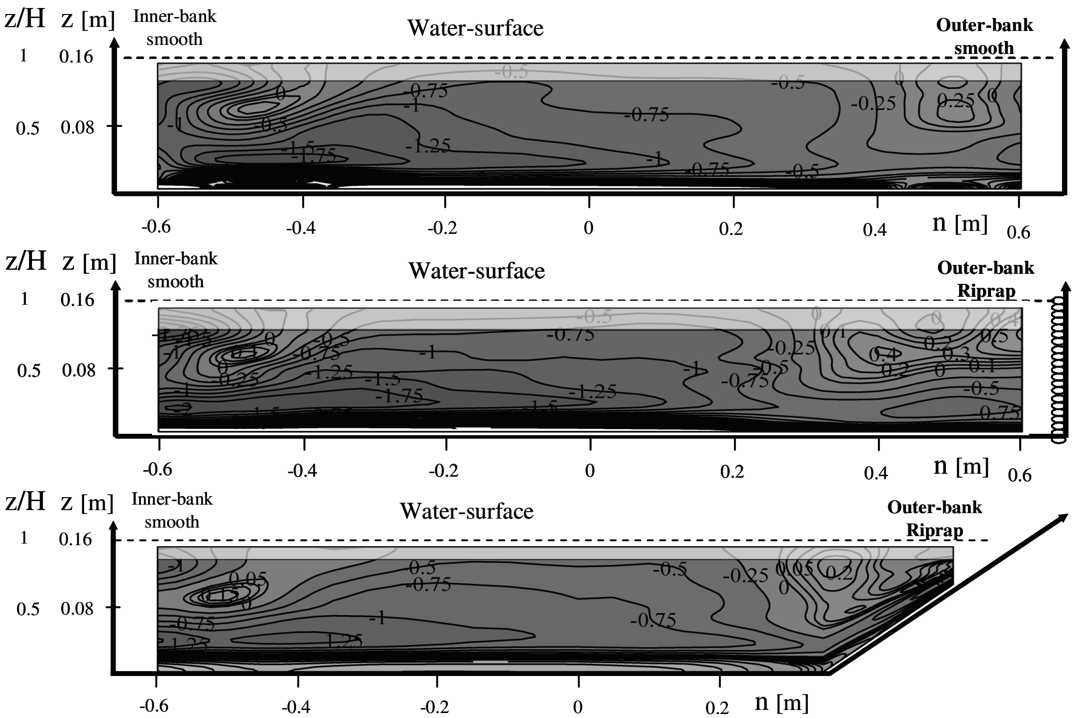


Figure 2 Cross-section at 90°. Isolines of normalized downstream vorticity $\omega_s H/U$. Test 1 (Top); Test 2 (Middle) and Test 3 (Bottom)

Figures 3 show normalized centrifugal force, $CFG/\left(U^2/H^2\right)$. The negative and positive values at channel center and upper-outer zone correspond to the center-region cell and the outer-bank cell, respectively, being in agreement with the ω_s negative and positive values (Figures 2). The negative and positive values suggest that the center-region cell and outer-bank cell sense of rotation are both favored by the CFG. The CFG positive values increase in size and strength between Figures 3 (top and middle), and decrease between Figures 3 (middle and bottom) correlating well with the outer-bank cell trend shown in Figures 2. The maximum value is 2 for Figure 3 (middle) against 0.1 Figure 3 (bottom). CFG-0 isoline also shows the separation between the center-region cell outward location and the outer-bank cell besides showing well the outer-bank cell shape.

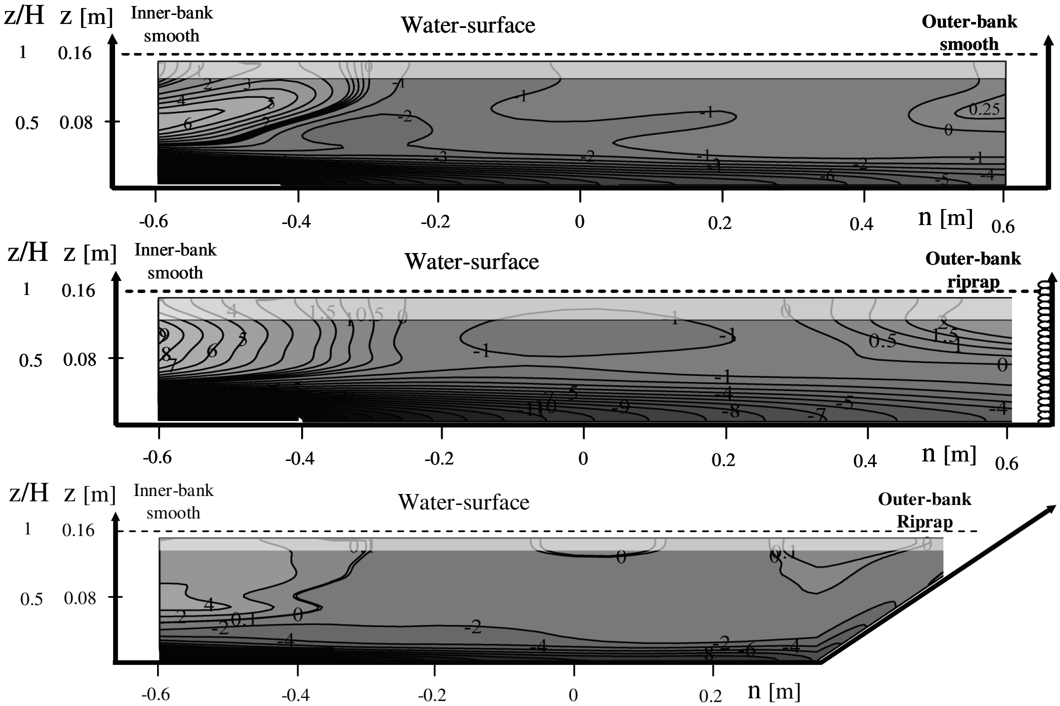


Figure 3 Cross-section at 90°. Isolines of normalized centrifugal term. $CFG/\left(U^2/H^2\right)$. Test 1 (Top); Test 2 (Middle) and Test 3 (Bottom)

Figures 4 and 5 show ANI, and SHEAR results respectively. For the center-region cell center ANI is about 0 and SHEAR is about 0.75. SHEAR being positive means that opposes the center-region cell sense of rotation for all test conditions (as ω_s is negative at channel center). This is in agreement with simplified models for the center-region cell (e.g. Rosovskii, 1957 or Blanckaert and de Vriend, 2004).

In the outer-bank cell zone ANI values are always negative for all tests and so suggesting that outer-bank cell is not favored by the ANI (as ω_s is positive in upper-outer channel zone). The ANI negative values in the upper outer zone have roughly the shape of the outer-bank cell for all experiments.

In the outer-bank cell zone the SHEAR values are positive for tests 1 and 3 indicating that favors the outer-bank cell rotation (as ω_s is positive in the upper-outer channel zone). This result suggests that outer-bank cell is driven by CFG and SHEAR, and so in agreement with de Blanckaert and de Vriend (2004) even for non-rectangular channels. However, for test 2 SHEAR values are negative and so not favoring the outer-bank cell rotation sense. This disagreement could be explained by the exceptional high CFG values found at outer-bank cell center, see Figure 3 (middle), which obliges ANI and SHEAR sum to have the same order of magnitude of CFG. However, the uncertainty of these quantities is too high to enable any solid conclusion.

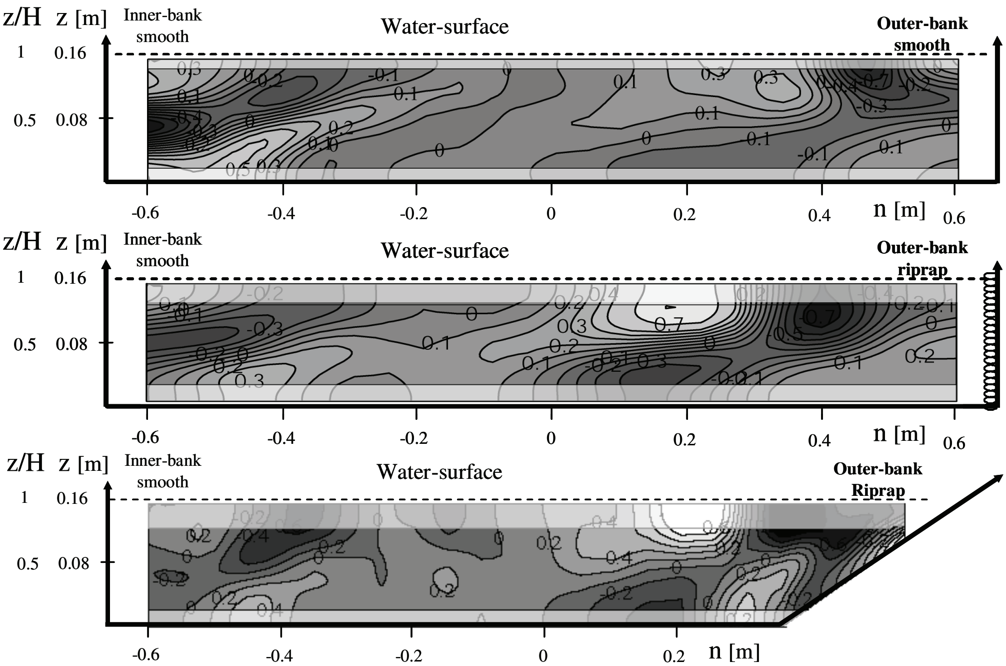


Figure 4 Cross-section at 90°. Isolines of normalized cross-stream turbulence anisotropy term $ANI/\left(U^2/H^2\right)$.Test 1 (Top); Test 2 (Middle) and Test 3 (Bottom)

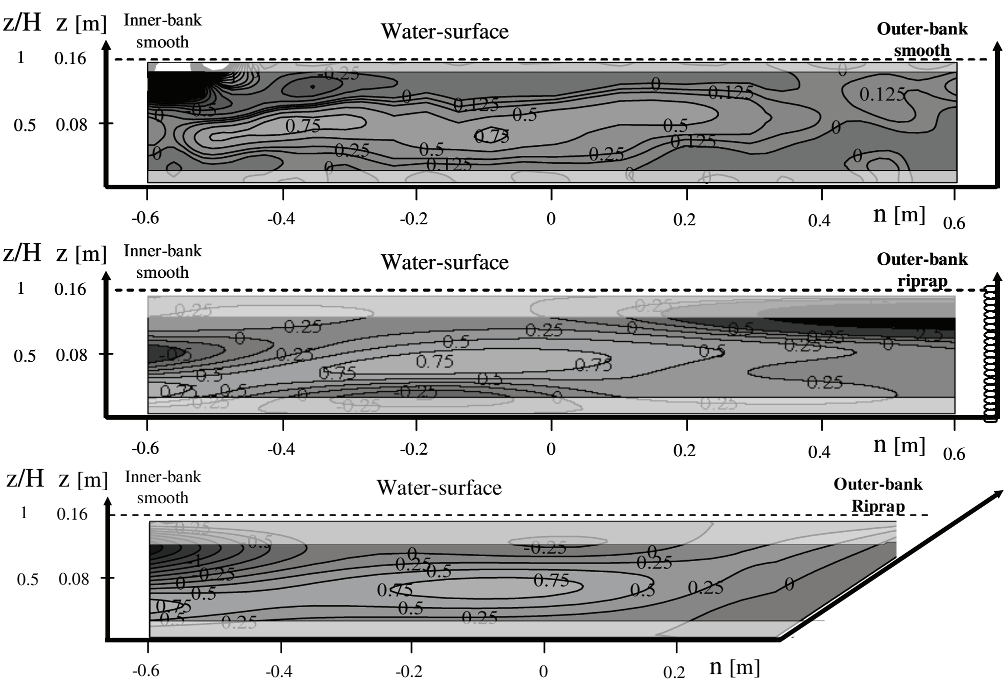


Figure 5 Cross-section at 90°. Isolines of normalized cross-stream turbulence shear stress term $SHEAR/\left(U^2/H^2\right)$. Test 1 (Top); Test 2 (Middle) and Test 3 (Bottom)

CONCLUSIONS

Three experiments were carried out in a sharply 193°-curved laboratory bend with varying outer-bank characteristics: 1) vertical outer-bank with smooth PVC; 2) vertical outer-bank with 3-cm stones simulating riprap; 3) 30°-inclined outer bank with 3-cm stones.

The experiments were carried out under similar hydraulic conditions and boundaries roughness values for inner-bank and bed. Only cross-section at 90° was investigated in detail as it presents the highest circulation cell's intensity for all experiments.

The results reveal:

1) The pattern of cross-stream circulation is characterized by the existence of center-region cell and a counter rotating outer bank cell for all experiments.

2) With increasing outer bank roughness the outer-bank cell increases in size between rectangular channel experiments. The center-region cell outward limit is pushed inwards.

3) With decreasing outer bank inclination the outer-bank cell decreases in size and its center moves inward, however its inward spanwise location remains the same, thereby, the center-region cell is unaffected.

4) Downstream vorticity equation main terms, centrifugal force, anisotropy and shear stresses justify the circulation cells' shape and intensity for all experiments.

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