Influence of bank roughness and inclination on straight channel flows

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EPF Lausanne, IGB Berlin, TU Delft and WL Delft are undertaking an ambitious program on open-channel research, which main goal is improving the capabilities of numerical tools for predictions of hydrodynamics and morphodynamics in natural-like rivers. Inserted in the objectives of the above-mentioned cluster program, this paper investigates the influence of bank inclination (vertical, 45° and 30°) and bank roughness (smooth and riprap) on straight open-channel flow characteristics by experimental measurements. The instrumentation used is Acoustic Doppler Velocity Profiler, which enables three-dimensional velocity measurements with high spatial and temporal resolution. The results reveal that the pattern of downstream velocity is influenced strongly by the bank inclination and roughness. The mean and maximum shear stress force values on the wetted perimeter are also influenced by the geometry shape and bank roughness.

Keywords: straight channel, wetted perimeter shear stress, downstream velocity

1 INTRODUCTION

A characteristic feature of straight channel flows is the secondary currents. Due to its convective capacity, it plays an essential role in mixing and transport processes. It also changes the velocity distribution, the shear exerted on the wetted perimeter and as consequence on morphology. A large portion of engineer projects is concerned with the sediment transport and bank erosion. Herewith we report on an experimental study of the dynamics of the streamwise velocity and wetted perimeter shear stress distribution as function of wide channel cross-section shape and wetted perimeter roughness distribution. The lack of experimental data combined with the difficulty to find a theory which explains the secondary currents evolution in wide channel justifies the poor design criteria validity range for trapezoidal cross-section nowadays. It is not found in literature criteria for the influence of different bank/bed roughness ratio on the velocity and shear stress especially on the location and magnitude of maximum shear stresses.

This paper aims at showing the influence of trapezoidal cross sectional shape and roughness distribution on wide channel primary velocity and shear stress. This paper presents measurements from three different wide open-channel cross-section geometries, a rectangular and two trapezoidal with varying bank angle and bank roughness.

The data obtained is from a dense measurement grid, see Figure 1, with a state-of-the-art measuring technique, Acoustic Doppler Velocity Profile (ADVP) developed in LHE [2-3]. ADVP allows resolution measurements of quasi-instantaneous three velocity components. From there it is possible to evaluate all three mean velocity components, as well as all turbulent stresses components.

2 EXPERIMENTAL SET-UP

Experiments were performed in a B = 1.3 m wide laboratory set-up. A horizontal bottom of nearly uniform sand d_{50} = 2.1 mm was assembled. Three experiments were performed. Figure 1 shows the cross-section schematic of all three test conditions and Table 1 shows their important parameters. First test condition cross-section is rectangular with smooth banks and rough bed. Second test condition cross-section is trapezoidal. The inner bank is vertical and the outer is 45°-inclined regarding the horizontal bottom. Inner and outer banks are defined based on the n-axis sense shown in Figure 1. The inner bank and bed are smooth. The third test condition is a trapezoidal wherein the inner bank is vertical and the outer bank is 30°-inclined regarding the horizontal bottom. The inner bank is smooth whereas the outer-bank has riprap d_{50} = 3 cm elements. The cross-section has been measured on a refined grid with vertical profiles between 50, 25 and 15 mm for central, buffer and near-bank areas, respectively.

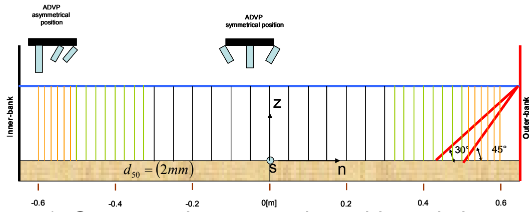

Figure 1: Cross-section measuring grids and shapes

3 RESULTS

Hereafter it is shown streamwise velocity and wetted perimeter shear stress from the three test conditions mentioned above. Figures 3*a,b,c* show the isolevels of downstream velocity normalized by U (mean velocity) and normalized wall shear stress by τ_0 over the wetted perimeter where $\tau_0 = \rho g R_h S_s$. R_h is the hydraulics radius and S_s is the downstream water surface gradient at cross-section centerline.

Shear stress is calculated by assuming an equation for the vertical profile of velocity. It is known that even straight channel flows have 3D flows but it is consider negligible in the lowest 20% of water depth. The velocity profile is shown to have the following form in the lowest 20% of water depth, [1].

$$\frac{U}{u_*} = \frac{1}{k}\ln\left(\frac{z}{z_0}\right) \quad (1)$$

where U is the velocity at distance z from the boundary, u_* is the shear velocity or shear stress, *k* is the turbulent exchange coefficient or von-Kármán constant and z_o is the distance at which log velocity profile indicates zero velocity.

Figures 3*a,b,c* do not show velocity-dip phenomenon. It is in agreement with [4] as the aspect ratio B/h is greater than 5.5, its critical value, for all experiments even for the trapezoidal cross-sections.

Experiment F16_90_00, Figure 3*a*, reveals non-uniform, wavy distributions over width suggesting the existence of circulation cells. This fact is not in agreement with [1]. The maximum velocity, $Vs\max/U$, is equal to 1.2U being located at about the free-surface along the cross-section width. Lower downstream velocity zones from where the contour lines bulge towards the free-surface are located at n (m) = [-0.35 -0.1 0.25 0.55]. Higher downstream velocity zones from where the contour lines bulge towards the bed are located at n (m) = [-0.5 -0.2 0.1 0.4]. These “bulges” correspond to upwelling and downwelling, zones of lower and higher velocities, respectively.

Figure 3a also shows that spanwise bed shear stress undulation is of $0.2\tau_0$, being in agreement with [1]. The upwelling and downwelling are also seen in the shear stress distribution. Bank shear is lower than bed shear. Bank shear stress is always lower than the threshold value, $\tau_0 = 1$, and it increases from the bank toe till the mid-depth where the maximum is located.

Figure 3b shows the 45°-bank inclination trapezoidal case with smooth outer-bank, Experiment F16_45_00. The maximum normalized downstream velocity, $Vs\max/U$ is 1.3U and it is located at about n (m)= [-0.2 0.2] close to the free-surface contrasting with the rectangular cross-section Experiment F16_90_00 case. The number of upwelling and downwelling is inferior to Experiment F16_90_00. Three downwelling are located at about n (m) = [-0.6 -0.3 0.3] and three upwelling are located at about n (m) = [-0.5 0 0.5].

Figure 3*b* also shows that spanwise bed shear stress undulation is $0.2\tau_0$. Bed shear stress evolution shows two maximum at the same downstream velocity maximum spanwise locations. Bank shear is lower than bed shear and always lower than the threshold value. It increases from the bank toe till z/h=0.3, where the maximum outer bank shear stress is located, followed by decreasing values till the free-surface.

Figure 3*c* shows the 30°-bank inclination trapezoidal case with riprap elements on the outer-bank, Experiment F16_30_30. The maximum normalized downstream velocity, $Vs\max/U$, is equal to 1.4U and it is located at about channel center and close to the free surface. The number of bulges decreases in comparison with the two-different shape geometries presented before, vertical bank and 45°-inclined bank.

Figure 3*c* also shows two downwellings at about n (m) = [-0.55 0] and upwelling at n (m) = [-0.4 0.35]. Bed shear stress evolution amplitude range is higher than $0.5\tau_0$. At about channel center the bed shear stress reaches $1.8\tau_0$. Between the channel center and the bank toe a sharp shear stress decrease of $0.7\tau_0$ exists. Bank shear stress is lower than the bed shear stress and lower than the threshold value and its maximum is located at about z/h=0.2.

Table 1: Experiments conditions

Label	Q [ls^{-1}]	H [m]	U [ms^{-1}]	u_* [ms^{-1}]	C [$m^{1/2}s^{-1}$]	Re [10^3]	Fr [-]	R/B [-]	R/H [-]	B/H [-]	k_s,bank [m]	Θ_{bank} [°]
F16_90_00	90	0.16	0.42	0.029	46	69	0.33	1.31	10.3	7.9	PVC	90
F16_45_00	85	0.16	0.42	0.028	48	69	0.33	1.39	10.3	6.75	PVC	45
F16_30_30	80	0.16	0.42	0.035	38	69	0.33	1.46	10.3	6.24	0.030	30

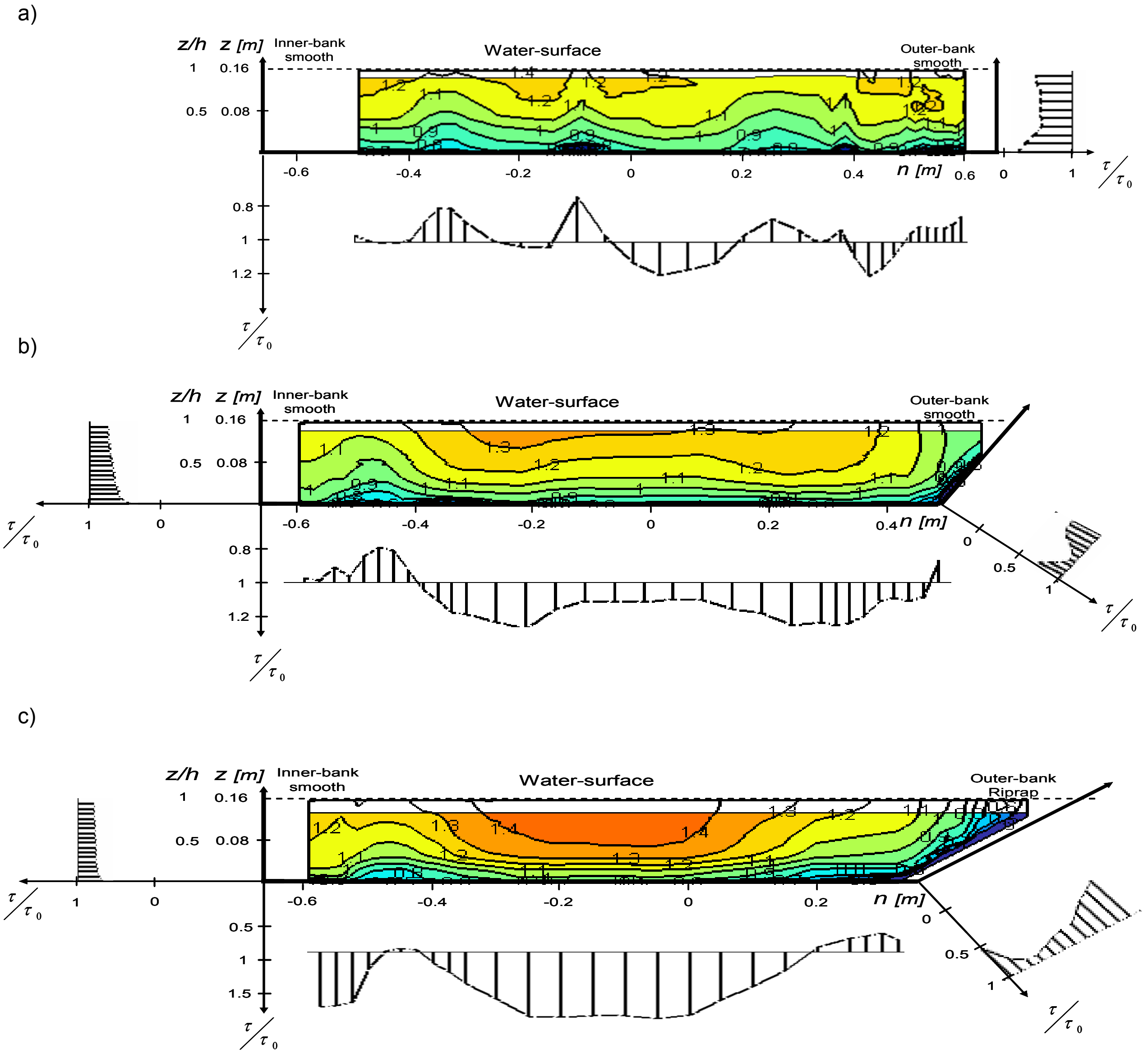

Figure 2: Contour lines of normalized downstream velocity & bed and wall shear stress values: a) F16_90_00;b) F16_45_00;c) F16_30_30

Table 2: Wall shear stress mean and maximum values

	$\overline{\tau}_{bed}/\tau_0$	$\overline{\tau}_{bank}/\tau_0$	$\max \tau_{bed}/\tau_0$	$\max \tau_{bank}/\tau_0$
F_16_90_00	1.05	0.39	1.3	0.49
F_16_45_00	1.13	0.82	1.31	0.9
F_16_30_30	1.34	0.4	1.8	0.8

4 DISCUSSION

Based on the results obtained, it is possible to analyze the effect of cross-section shape and bank roughness.

F16_45_00 and F16_30_30 results show typical trapezoidal cross-section primary flow characteristics because the maximum downstream velocity is concentrated close to the channel center at the free-surface whereas a rectangular cross-section has typically the maximum downstream velocity spread over the width at free-surface (for wide channel). These differences between rectangular to trapezoidal flow characteristics are well observed when comparing F16_30_30 with F16_90_00.

Bed shear stress spanwise undulation is also affected. Less bulges and higher amplitude range, from 0.2 τ_0 (rectangular cross-section) to higher than 0.5 τ_0 (trapezoidal cross-section), are observed between F16_90_00 with F16_30_30. Please note that bank shear stress magnitude decreases. The maximum bank shear stress locus becomes closer to the bank toe with decreasing bank angles.

Table 2 shows the normalized mean and maximum bed and bank shear stresses. Table 2 shows that the highest normalized maximum bed shear is obtained for F16_30_30. By contrast, the normalized lowest maximum bank shear is obtained for F16_30_30.

4 CONCLUSIONS

The conclusions of this work are divided in two topics: The primary flow patterns and shear stress distribution on the wetted perimeter.

Primary flow patterns:

- Rectangular and trapezoidal channel flow patterns are different.
- Rectangular velocity patterns reveal several bulges known as upflows and downflows which number agrees well with aspect ratio and Literature
- Trapezoidal channels have less bulges than rectangular channels being in agreement with Literature
- Trapezoidal channels with rougher inclined bank than bed generate higher downstream velocity at about channel center.

Shear stress distribution on the wetted perimeter

- The bed shear stress spanwise evolutions are in agreement with primary velocity patterns
- The normalized bed shear stress oscillates between 0.8-1.2 τ_0 for rectangular cross-sections, which is in agreement with Literature.
- The normalized bed shear stress oscillates between 0.8-1.2 τ_0 for trapezoidal cross-sections with quasi-homogeneous roughness distribution.
- The normalized bed shear stress oscillates between 0.5-1.5 τ_0 for trapezoidal cross-sections with $k_{sbank} / k_{sbed} = 10$.
- The inclined bank shear stress evolution has a maximum in the vicinity of the bank toe for all trapezoidal cross-sections.
- The magnitude of inclined bank shear stress decreases with increasing bank roughness.

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