Flume flows between boundaries of very different roughness: evaluation of friction using ADV measurements

Vaclav Matousek* and Tomas Picek
Department of Hydraulics and Hydrology, CTU Prague, Thakurova 7, 166 29 Prague, Czech Republic
(*Corresponding author, e-mail: v.matousek@fsv.cvut.cz).

Two ADV probes (one side-looking probe and one down-looking probe) were used for measurements of the local velocities and turbulence characteristics in a boundary layer of a flume flow in order to determine friction conditions at the flow boundaries. Three configurations of the top of the flow were tested and mutually compared: the flow with free water surface (open channel flow), the flow with water surface covered by a smooth solid plate, and the flow with water surface covered by a very rough solid plate. The tests carried out for various installed flow rates and water depths showed that the presence of a solid plate (1-m long) at the top of the flow significantly affected the longitudinal-velocity distribution and turbulence characteristics in the flow. Hence the presence of the water-surface cover considerably increased the shear velocity at the bottom of the flow. This would increase a danger of the bottom erosion if the bottom was a mobile bed. The paper comments on the test results and quantifies the effects of the velocity-profile deformation on the friction conditions at the bottom of the flow.

Keywords: Bed shear stress, velocity distribution, turbulence characteristics, flume test

1 INTRODUCTION

A solution of many problems associated with flow of water through conduits of different geometries requires information on the distribution of local velocities (all three components) and turbulence characteristics throughout the flow.

At present, the most often used instrument for the measuring of local velocities in open-channel flows is a propeller velocity meter, or an electromagnetic probe. These instruments are capable to measure just one component of the local velocity. Moreover, the obtained value of the local velocity is time averaged and do not allow to take care of turbulence characteristics. Furthermore, the instruments have a large control volume and the sensed value of the velocity may be influenced by a deformation of the velocity field caused by the submerged volume of the probe itself.

The ADV (Acoustic Doppler Velocimeter) enables a measurement of all three components of the local velocity and determination of their time-averaged and fluctuating parts. The instrument is robust enough to be used in the field conditions. Experiences published in the technical literature [e.g. 1-4] suggest that the instrument may be used successfully in both filed and laboratory flows. For the lab tests the ADV technique can be a financially attractive alternative to the more sophisticated techniques as LDV (Laser Doppler Velocimeter), PIV (Particle Image Velocimetry) or UVP (Ultrasonic Velocity Profiler).

The investigation described in this paper was set to analyze an applicability of the ADV for the purposes of laboratory tests simulating flows influenced by irregularities (e.g. flows under barriers of floating debris developed at the water surface of an open channel and accumulated in front of hydraulic objects like bridges during a flood event).

2 EXPERIMENTAL FACILITIES

2.1 Laboratory flume

The laboratory flume used for our ADV tests is rectangular, 0.25 m wide, and 6.3 m long. The bottom and side walls of the flume are hydraulically smooth. The probe was positioned to the vertical axis of the flume cross section.

2.2 ADV probe

The entire experimental program was carried out using the Nortek 3-D side-looking probe with the sampling frequency 25 Hz and the control volume positioned 50 mm in front of the probe transmitter (Fig. 1). Since this was our first experience with the ADV probe, its measuring abilities were tested first by comparison with other measuring techniques before carrying out the actual experiments. The comparison of velocity profiles measured using the side-looking probe with the down-looking probe [5], the LDA [6], and the series of different propellers [5], confirmed that after elimination of a certain systematic error in the longitudinal-velocity measurement the side-looking probe produces velocity profiles in undisturbed channels with a satisfactory accuracy. Thus it was suitable to use for a mutual comparison of profiles of longitudinal velocity in flows of three different geometries of a boundary at the top of the flow through a laboratory flume.

The comparison of the local turbulence characteristics (fluctuating components of local velocities) showed a reasonable agreement between the LDA and the side-looking ADV probe in flows through undisturbed channels. Surprisingly bad match was found for the down-looking ADV probe that tended to underestimate heavily the values of the vertical fluctuating velocity. This was in accordance with the experience that others [7] had gained with this particular probe. Thus the down-looking probe in our possession is not suitable for turbulence-characteristics tests. The side-looking probe is acceptable for channels flows. However, its comparison with LDA revealed also that due to its relatively low sampling frequency the ADV probe is not suitable for measuring at locations of high intensities of turbulence in a flow (e.g. within wakes behind obstacles) [8]. Since such measurements are not included in our experimental program this finding does not disturb our tests.

A sensitivity analysis of the probe operating parameters suggested that the length of the control volume of 6 mm is the most suitable for the tests (the probe offers a choice of 3-, 6-, and 9-mm length). The sampling time of at least 40 second is required to collect representative data for both the time-averaged- and the fluctuating components of the local velocity. Our data were collected with the 90-second sampling time. An application of seeding particles is mandatory.

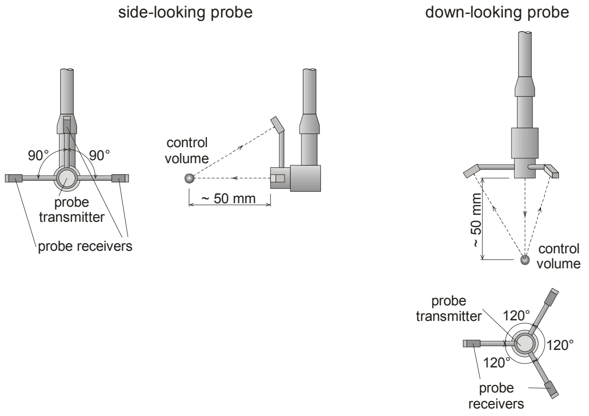


Figure 1: The side-looking probe used for experiments and the down-looking probe used for a comparison.

2.3 Different boundaries at water surface during tests

Three configurations of the top of the flow were tested and mutually compared: the flow with free water surface (open channel flow), the flow with water surface covered by a smooth solid plate, and the flow with water surface covered by a very rough solid plate. The smooth plate was a 1-m long plastic plate of the thickness of about 1 cm. The very rough solid plate was actually the smooth plate, used for the smooth-boundary tests, covered by the mattress Enkamat 7010 made of synthetic polyamide fiber of the diameter of about 0.7 mm. The mattress is 10 mm thick, thus the fibers penetrate the flow down to the 10-mm depth below the water surface.

3 RESULTS AND DISCUSSION

3.1 Methods for determination of bottom shear velocity

The main objective of the experiments is to determine the shear velocity at the bottom of the flow (u_{*b}) and to evaluate its variation with the changing boundary conditions at the top of the flow. Basically, there are two methods for the shear velocity determination from the measurements of local velocities along the vertical axis of the flow:

a. the comparison of measured- and theoretical distribution of longitudinal velocity across the flow,

b. the comparison of measured- and theoretical distribution of Reynolds shear stress across the flow.

ad a. the method is based on the assumption that there is the logarithmic distribution of the time-averaged longitudinal velocity u_y across a certain part of the boundary layer above the bottom of the flow. If the bottom is hydraulically smooth, the distribution can be expressed using the relation between two dimensionless parameters: $z^{+} = \frac{z \cdot u_{*b}}{\nu_f}$, and $u^{+} = \frac{u_y}{u_{*b}}$. The relationship is given e.g. by the Prandtl-Karman equation

$$u^{+} = 2.5 \cdot \ln z^{+} + 5.5 \qquad (1).$$

Considering that u_y is measured at various vertical positions z above the bottom of the flow, and the kinematic viscosity (ν_f) of the flowing water is known, Eq. 1 can be exploited to determine the u_{*b} value required to fit the measured velocity profile with the theoretical one.

ad b. the method is based on the assumption that the vertical distribution of the Reynolds shear stress ($\tau_{zy} = \rho_f \cdot \overline{u'_y \cdot u'_z}$) is linear across the most part of the turbulent flow (except the viscous sub-layer and the lower portion of the buffer layer) with the zero value at the hydrodynamic axis of the flow and the maximum value near the bottom of the flow. The distribution equation reads

$$\tau_{zy,b} = \tau_{zy} \cdot \frac{h_a}{h_a - z} \qquad (2),$$

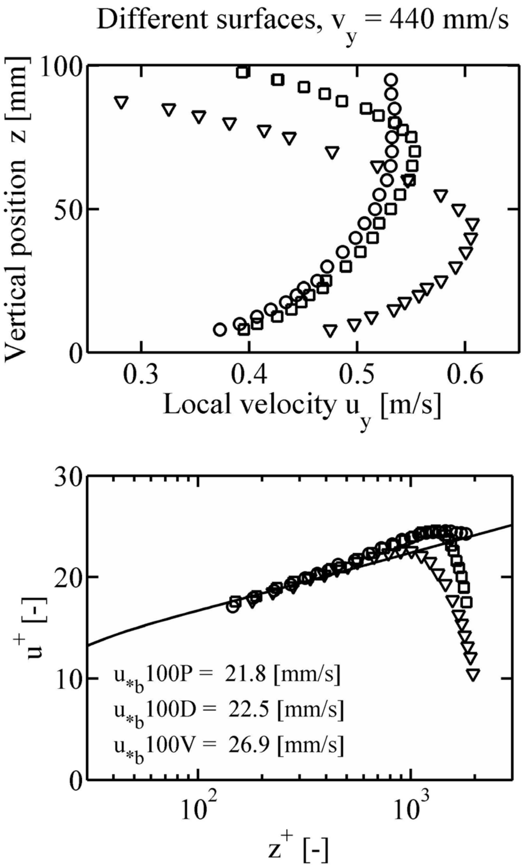
in which h_a is the height of the hydrodynamic axis above the bottom of the flow. The bottom shear velocity, $u_{*b} = \sqrt{\frac{\tau_{zy,b}}{\rho_f}}$.

Considering that the fluctuating components of the longitudinal-, and vertical local velocities (u'_y, and u'_z) are measured, and the density (ρ_f) of the flowing water is known, Eq. 2 can be exploited to determine the u_{*b} value required to fit the measured shear-stress profile with the theoretical one.

3.2 Bottom shear velocity from distribution of longitudinal velocity

Table 1: Positions of hydrodynamic axis (h_a) and values of bottom shear velocity (u_{*b}) for flows of constant depth H and flow rate Q (average velocity $v_y \approx 440$ mm/s); code P = free water surface, D = surface covered by smooth plate, V = surface covered by rough plate; see also Fig. 2.

Run code	H (mm)	Q (lit/s)	h_a/H (-)	$u_{*b(u)}$ (mm/s)
H100Q1100P	100	10.92	0.85	21.8
H100Q1100D	100	11.04	0.7	22.5
H100Q1100V	100	10.92	0.45	26.9

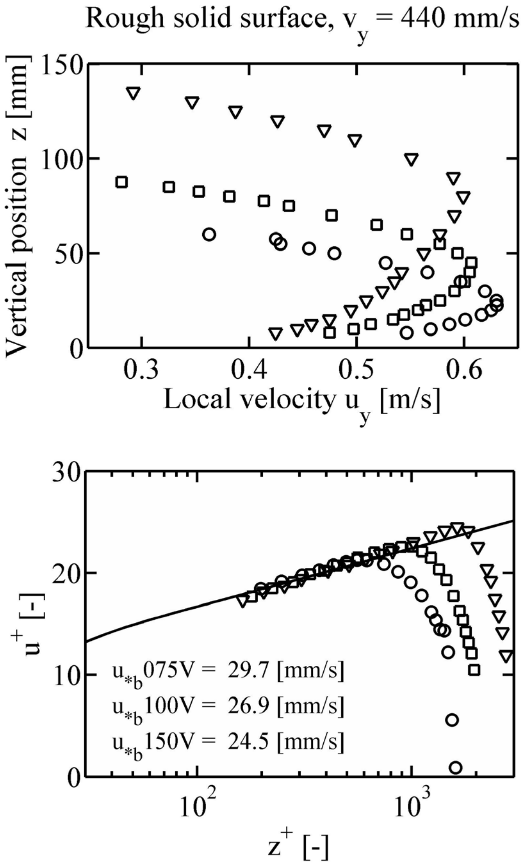


Legend:
○ –flow with free water surface, water depth H = 100 mm,
□ - flow below smooth solid plate, water depth H = 100 mm,
∇ - flow below rough solid plate, water depth H = 100 mm,
line - Prandtl-Kármán log law, Eq. 1.

Figure 2: Comparison of measured velocity profiles with Eq. 1 (flow properties are given in Tab. 1).

Table 2: Positions of hydrodynamic axis (h_a) and values of bottom shear velocity (u_{*b}) for flows of constant average velocity $v_y \approx 440$ mm/s but different Q and H below the rough plate, see also Fig. 3.

Run code	H (mm)	Q (lit/s)	h_a/H (-)	$u_{*b(v)}$ (mm/s)
H075Q0825V	74.7	8.15	0.30	29.7
H100Q1100V	100	10.92	0.45	26.9
H150Q1650V	150.6	16.40	0.53	24.5



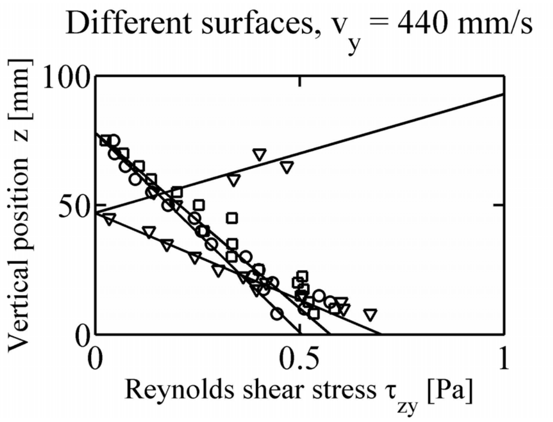
Legend:
○ – flow below rough solid plate, water depth H = 75 mm,
□ - flow below rough solid plate, water depth H = 100 mm,
∇ - flow below rough solid plate, water depth H = 150 mm,
line - Prandtl-Kármán log law, Eq. 1.

Figure 3: Comparison of measured velocity profiles with Eq. 1 (flow properties are given in Tab. 2).

3.3 Bottom shear velocity from distribution of Reynolds shear stress

Table 3: Positions of hydrodynamic axis (h_a) and values of bottom shear velocity (u_{*b}) for flows of constant depth H and flow rate Q (average velocity $v_y \approx 440$ mm/s); code P = free water surface, D = surface covered by smooth plate, V = surface covered by rough plate; see also Fig. 4.

Run code	H (mm)	Q (lit/s)	h_a/H (-)	$u_{*b(\tau)}$ (mm/s)
H100Q1100P	100	10.92	0.78	22.5
H100Q1100D	100	11.04	0.78	24.0
H100Q1100V	100	10.92	0.47	26.5

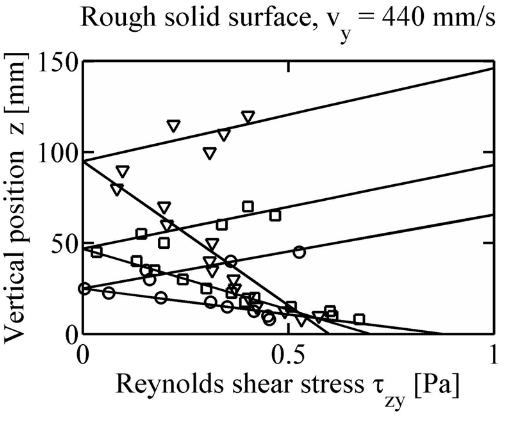


Legend:
○ –flow with free water surface, water depth H = 100 mm,
□ - flow below smooth solid plate, water depth H = 100 mm,
∇ - flow below rough solid plate, water depth H = 100 mm,
line - linear distribution of Reynolds shear stress, Eq. 2.

Figure 4: Comparison of measured τ_{zy} profiles with Eq. 2 (flow properties are given in Tab. 3).

Table 4: Positions of hydrodynamic axis (h_a) and values of bottom shear velocity (u_{*b}) for flows of constant average velocity $v_y \approx$ 440 mm/s but different *Q* and *H* below the rough plate, see also Fig. 5.

Run code	H (mm)	Q (lit/s)	h_a/H (-)	$u_{*b(\tau)}$ (mm/s)
H075Q0825V	74.7	8.15	0.33	29.7
H100Q1100V	100	10.92	0.47	26.5
H150Q1650V	150.6	16.40	0.63	24.5



Legend:
○ – flow below rough solid plate, water depth H = 75 mm,
□ - flow below rough solid plate, water depth H = 100 mm,
∇ - flow below rough solid plate, water depth H = 150 mm,
line - linear distribution of Reynolds shear stress, Eq. 2.

Figure 5: Comparison of measured τ_{zy} profiles with Eq. 2 (flow properties are given in Tab. 4).

4 DISCUSSION

The values of the bottom shear velocity acquired from the distribution of the longitudinal velocities differ with less than 7 per cent from the values obtained from the Reynolds shear stresses. The position of the hydrodynamic axis (h_a) differs with less than say 20 per cent.

The comparison of the processed ADV data with the corresponding theories indicates that the match is tighter for the longitudinal velocity profiles (the measured profiles compared with the theoretical logarithmic profiles using Eq. 1), than for the measured Reynolds shear stress profiles (the measured profiles compared with the theoretical linear profiles using Eq. 2).

5 CONCLUSIONS

The tests confirmed that covering an originally free water surface with debris or an ice cover (during the tests simulated by solid plates of different roughness) deforms the velocity distribution across the flow, changes the turbulence characteristics and increases the shear velocity at the bottom of the flow. The roughness of the covering plate influences considerably the value of the shear velocity.

Furthermore, the tests revealed that, for the particular ADV probe used, the determination of the bottom shear velocity was less accurate if derived from measurements of the turbulence characteristics than from measurements of vertical profiles of the time-averaged longitudinal velocity.

ACKNOWLEDGEMENT

The work was supported by the CIDEAS VS project 1M0579 of the Czech Technical University.

REFERENCES

[1] Strom BK, Papanicolaou AN: ADV measurements around a cluster microform in a shallow mountain stream, J. Hydr. Engrg. 133(12) (2007)1379-1389.
[2] Stone MC, Hotchkiss RH: Evaluating velocity measurement techniques in shallow streams, J. Hydr. Res. 45(6) (2007) 752-762.
[3] Meftah BM et al.: Experimental study of flexible and rigid vegetation in an open channel, Proc. River Flow 2006 (2006) 603-611.
[4] Carollo FG et al.: Analyzing turbulence intensity in gravel bed channels, J. Hydr. Engrg. 131(12) (2005) 1050-1061.
[5] Picek T, Matoušek V: Comparison of flow characteristics measured using horizontal- and vertical-oriented ADV probes, Proc. The 22nd Symposium on Anemometry, Holany-Litice (2008), in press (in Czech).
[6] Matoušek V: Determination of bed shear stress from velocity profiles and turbulence characteristics measured using ADV probe, Proc. seminar VC CIDEAS -VS Nejistoty modelů a přístupů aplikovaných v říčním inženýrství, povrchové a podpovrchové hydrologii, (2007) 47-54, ISBN 978-80-01-03924-3 (in Czech).
[7] Jirák J, Bareš V: Comparison of ADV and UVP method for turbulent characteristic measurement of free surface flow in circular pipe, Proc. The 20th Symposium on Anemometry, Holany-Litice (2006) 53-58 (in Czech).
[8] Chára Z, Matoušek V: A possibility of ultrasonic method to measure flow characteristics, Proc. The 21st Symposium on Anemometry, Holany-Litice (2007) 59-66, ISBN 978 80 87117 019 (in Czech).