Numerical prediction of compound channel flow in comparison with ultrasonic Doppler method measurement

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Determination of cross section flow capacity and depth-averaged velocity distribution are prevailing tasks of river hydraulics. Lateral Distribution Method (LDM) is one of the more sophisticated approaches proposed during the last few decades and belongs to the so-called 1,5D methods. Numerical solution of governing equation using FEM leads to the depth averaged velocity profile. The subject of our study is to evaluate potential benefit of the LDM applied under the circumstances of non-uniform flow using data obtained by Ultrasonic Velocity Profiling (UVP) method. Experiments were undertaken on the model of river reach with the non-prismatic compound channel. UVP was used to determine point velocities in selected gauging cross-sections. Three inclined probes enabled estimation of all three velocity vector components. Depth averaged velocities and total discharge were obtained integrating the point velocities. Discharge exchange between main channel and flood plains was identified as the prevailing source of the secondary currents with the clear effect on the main flow velocity distribution. Comparison of experimental and numerical simulation results showed great potential of LDM for the practical calculations of compound channel flow even under non-uniform flow conditions. UVP seems to be highly reliable and applicable to velocity field measurement in open channels.

Keywords: Velocity profile, compound channel flow, ultrasonic Doppler method, numerical simulation.

1 INTRODUCTION

For practical purposes, one dimensional modeling is still the prevailing approach to the tasks of river mechanics. As a component of the classical step-by-step method, cross section flow capacity has to be evaluated. Moreover, accurate prediction of the velocity distribution over a channel cross section is essential for flood risk assessment as well as for sediment transport and channel stability evaluation. Predictions of the usual computational methods are fallible especially in the case of heterogeneous velocity distribution which is typical of the compound channels. Better results can be obtained if momentum transfer in transverse direction is involved in numerical model. This is the case of so-called 1,5D or 1D+ methods which Lateral Distribution Method (LDM) belongs to.

LDM was introduced more than twenty years ago, but it has not become widely employed in practical computations yet. Benefit of LDM applied under the uniform flow condition is clear (see e.g. [1,2]). The object of presented study was to verify usability of LDM for depth-averaged velocity profile computation if non-uniform flow occurs.

2 NUMERICAL SIMULATION

As mentioned previously, LDM deals with momentum transfer in direction transversal to the main flow. Governing equation can be derived (see [3] for details) from depth-averaged Reynolds equation assuming uniform flow. Empirical or semi empirical model has to be adopted for turbulent stress and secondary currents term. According to [4], governing equation of the LDM can be written in the form of:

$$gHI_0 - \frac{f}{8}U^2\sqrt{1+I_{y0}^2} + \frac{\partial}{\partial y}\left(H^2\frac{\lambda}{2}\sqrt{\frac{f}{8}}\frac{\partial U^2}{\partial y}\right) = \Gamma \text{ . (1)}$$

Here y is the lateral direction coordinate, U is the depth-averaged velocity in the main flow direction, H is the depth, f is the friction factor, I_0 is the bottom slope in the main flow direction, I_{y0} is the bottom slope in the lateral direction and λ and Γ are the model parameters. The first term on the left side is gravity term followed by bottom shear term and turbulent shear term in vertical. The right side represents secondary flow term. Finite element method was employed to solve Eq. (1) (to find $U(y)$).

3 EXPERIMENTAL SETUP

3.1 Physical model

Experiments were performed on the model of left-handed reach of the Trebovka River (Fig. 1). The Thomson weir with a stilling box and the model were integrated into the hydraulic circuit of laboratory of CTU in Prague. The length of model was 8,2 m and width 1,2 – 2,0 m (scale 1:40). Compound channel cross section consisted of two flood plains with variable width and main channel of trapezoidal and rectangular shape. Roughness of concrete surface of the model was increased in floodplains to ensure heterogeneous velocity distribution. Discharge of 48.8 l/s was hold for all experiments, corresponding water depth was 50 ÷ 150 mm.

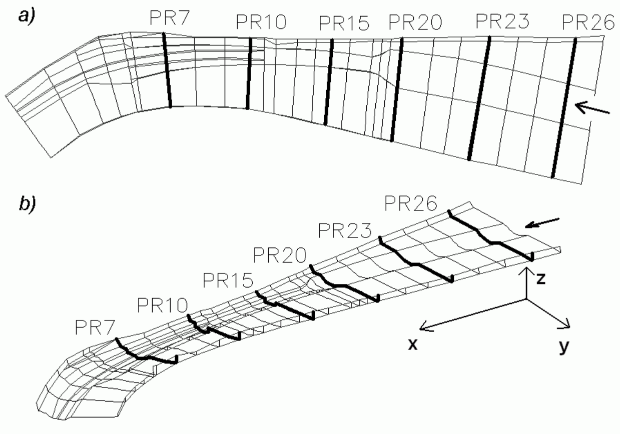

Figure 1: Physical model of Trebovka River. Gauging cross sections highlighted. a) Plan. b) Axonometric view.

3.2 Velocity measurement

Detail velocity distribution was investigated in six gauging cross sections (Fig. 1) using UVP monitor [6]. As UVP monitor provides only radial velocity component V_R (i.e. in direction of ultrasonic transducer axe), three independent probes P_1, P_2 and P_3 were employed to enable all three velocity component evaluation. Probes were fixed in special movable box and inclined from vertical at en angle θ = 25° (Fig. 2). Inner space of the box was filled with water and separated from flow by PVC foil 0,1 mm thin. As there is a minimum distance from probe, where measuring window can start, spacing of 25 mm was set between probes and foil. Thus, if the box was vertically positioned to foil just touched water surface, minimal disturbance was introduced into measured velocity field and measurement window covered entire water depth. To improve signal/noise rate, PVC reflection solids (ρ = 1350 kg/m^3, d = 100 μm) were supplied to the flow.

After the box with probes was positioned at the required vertical in actual cross section, velocity profiles in the probes axes direction were measured (sampling period t = 60 ms, number of samples n = 1000). Then, the box was moved to next vertical in 50 mm distance.

3.3 Other measurements

Thomson weir was used to discharge measurement. Model geometry and water surface profile were obtained using point gauge.

4 EXPERIMENTAL DATA EVALUATION

Equations relating velocity vectors components measured in probes axes direction V_{Rj} (j = 1, 2, 3) and components u_j, v_j, w_j in x, y, z direction can be derived from (Fig 2.):

$$V_{R1} = u_1 \sin\theta - w_1 \cos\theta \qquad (2a)$$

$$V_{R2} = -u_2 \sin\theta - w_2 \cos\theta \qquad (2b)$$

$$V_{R3} = -v_3 \sin\theta - w_3 \cos\theta \qquad (2c)$$

Following assumptions are necessary for evaluation of velocity vector components u, v, w:

● Only time averaged velocity is evaluated.

● Longitudinal slope of water surface and probes distance ΔL = 51 mm are so small, that for u and v at the same vertical position it is possible to write:

$$\overline{u}_1 \equiv \overline{u}_2 ; \overline{w}_1 \equiv \overline{w}_2 \qquad (3)$$

In fact, Eqs. 3 are satisfied only for the point of the probes axes intersection.

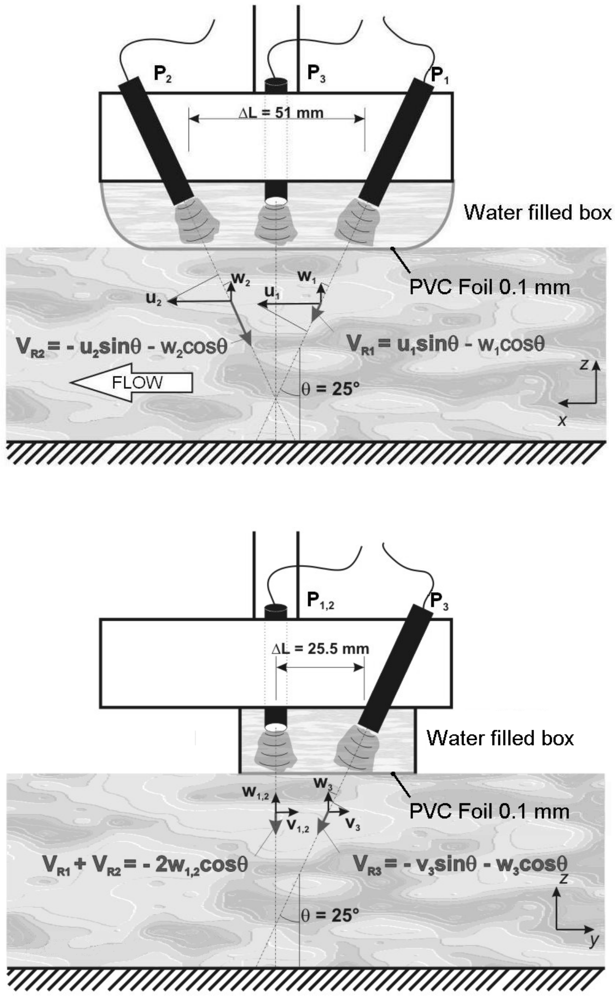

Figure 2: Scheme of probe fixation in movable box filled with water. Velocity vector decomposition. Up – vertical section in the plane normal to y axe (*u(z)* and *w(z)* evaluation). Down – vertical section in the plane normal to x axe (*v(z)* evaluation).

Relations for time averaged velocity vector components than read:

$$\overline{u} = \frac{\overline{V_{R1}} - \overline{V_{R2}}}{2 \sin\theta} \qquad (4a)$$

$$\overline{w} = -\frac{\overline{V_{R1}} + \overline{V_{R2}}}{2\cos\theta} \tag{4b}$$

$$\overline{v} = \frac{\frac{1}{2}\left(\overline{V_{R1}} + \overline{V_{R2}}\right) - \overline{V_{R3}}}{\sin\theta} \tag{4c}$$

After numerical integration of point velocities evaluated from Eqs. 4, depth averaged velocities in gauging verticals and total discharge in gauging cross-section can be obtained.

5 RESULTS

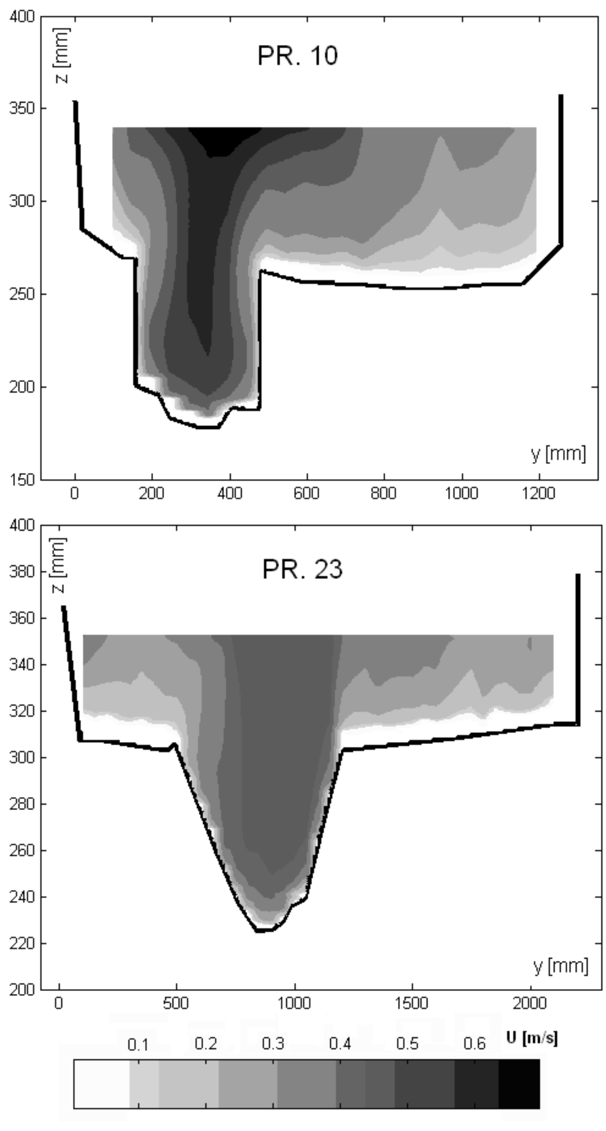

Figure 3: Main flow velocity distribution *u(y,z)* in cross sections PR. 10 and PR. 23. White space at the left and right side is out of measured area.

5.1 Total discharge evaluation

In each of six gauging cross sections total discharge was evaluated from UVP time averaged point velocities and compared with discharge deduced from Thomson weir. Excellent agreement was achieved between these two methods. Average relative error was only 0.21 %. Relative errors were less than 1% except of PR. 23 (error –2.95%).

5.2 Flow visualization

Distribution of velocity vector component in main flow direction can be seen in Fig 3. Flow is concentrated in the main channel. High roughness of floodplains causes lower velocity gradient near channel bottom than in the main channel, as can be also seen in Fig. 4. There is an apparent flow in the direction from right flood plain (from the left in Fig. 3 – upstream view) to main channel in cross section PR. 23. This observation is confirmed by Fig 5, where projection of velocity vectors into yz plane is plotted. This is an effect of changing channel geometry resulting in non-uniform flow. Figs. 3, 4 and 5 give clear demonstration of secondary flow influence on main flow near the flood plain and main channel interface.

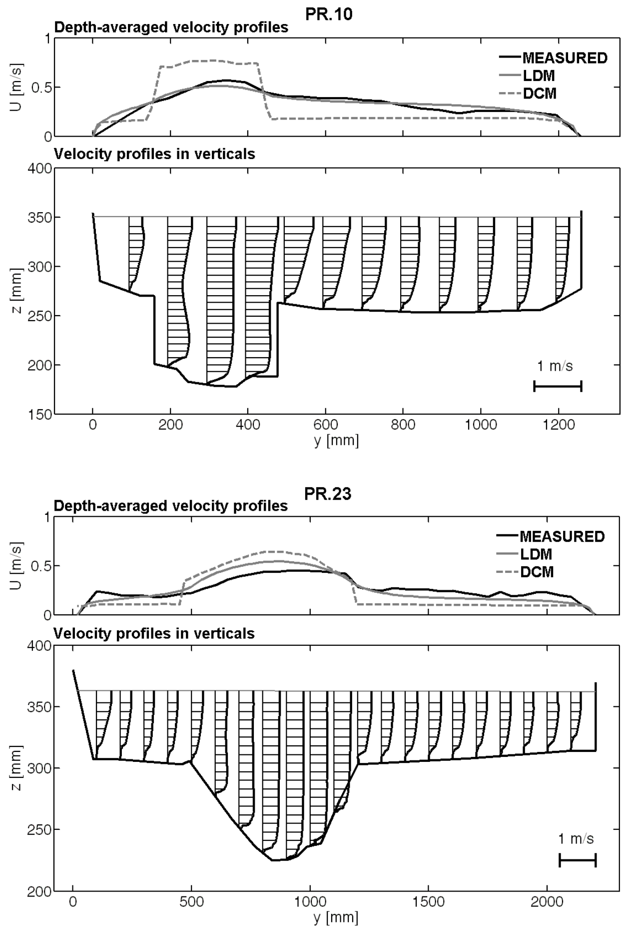

Figure 4: Main flow velocity components in verticals for cross section PR. 10 and PR. 23. Upper part – depth-averaged velocity profiles *U(y)*. Comparison of experiment and numerical simulation (LDM, DCM). Bottom – profiles of velocity component *u(y, z)* measured in verticals.

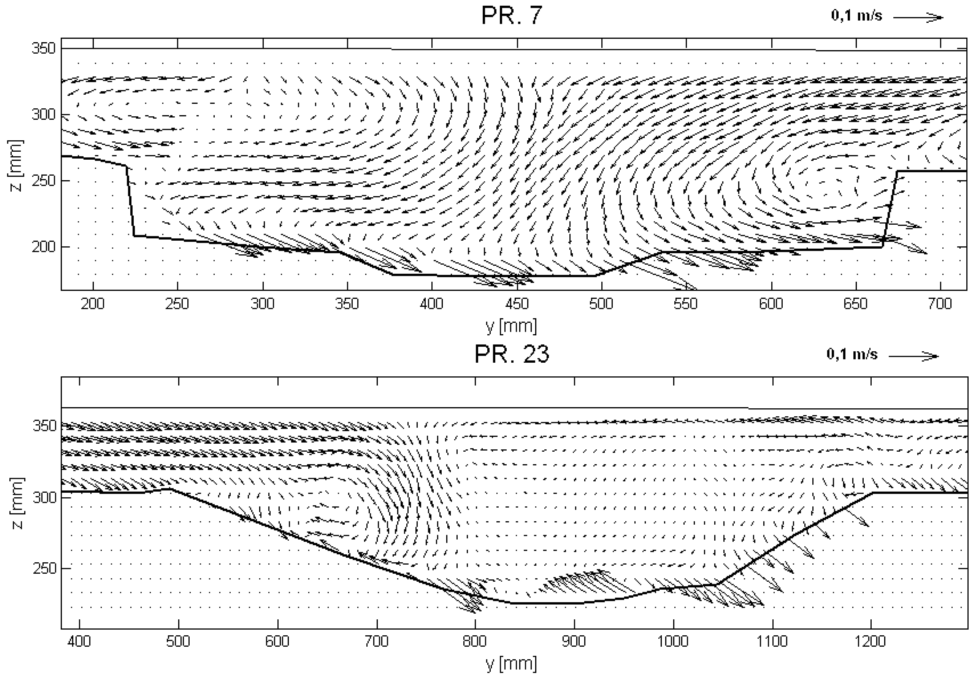

Figure 5: Projection of velocity vectors into yz plane. Upstream view. Unrealistic velocity vectors arise from problematic assignment of points measured by probe P_1 to points measured by probe P_2 near channel bottom.

5.3 Comparison of depth-averaged velocities

Comparison of numerical simulation and measurement proves that LDM provides very good prediction of the shape of the depth-averaged velocity profiles (Fig. 4). This is not the case of usual method based on dividing of compound channel to section (DCM). Significant deviation of LDM computed profile from measured one was observed only in cross section PR. 23 and 26. Water entered the model there and therefore flow in compound channel was not fully developed.

6 DISCUSSION

Accordingly to Hersberger [3], three probes inclined in angle θ were employed to 3D flow investigation in open channel. Accuracy in the estimation of velocity components *v* and *w* was reduced because of considerably smaller absolute value of these components. Discrepancy in vertical component (Eq. 4b) affects evaluation of transversal component (Eq. 4c). Visualization of secondary currents was not the main objective of our experiments. Usage of fourth vertical probe P_4 seems to be more appropriate for this purpose.

7 CONCLUSIONS

The potential of LDM for compound channel flow computations was evaluated using UVP method. Our experiments demonstrated high reliability of LDM depth-averaged velocity profile prediction in contrast to methods based on more simplified approach. Futher, it can be concluded, that UVP is able to describe this type of flow with high accuracy. The discrepancy between discharge evaluated from UVP and reference discharge measurement was 0.21%. Visualization of secondary currents has shown that UVP is sensitive enough to be able to describe three-dimensional vortex structures. Fixation of ultrasonic probes above water surface allows measurement in whole water depth with negligible disturbance of flow.

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REFERENCES

[1] Shiono K, Knight DW: Turbulent open-channel flows with variable depth across the channel, J. Fluid Mech. Vol. 222 (1991), 617 –646.
[2] Abril JB, Knight DW: Stage-discharge prediction for rivers in flood applying a depth-averaged model, Journal of Hydraulic Research Vol. 42, No. 6 (2004), 616–629.
[3] Bousmar D: Flow modeling in compound channels, PhD thesis, (2002).
[4] Conveyance User Manual (2004). DEFRA and HR Wallingford, www.river-conveyance.net (2004)
[5] Hersberger DS: Wall roughness effects on flow and scouring in curved channels with gravel bed. PhD thesis, EPFL Lausanne (2003).
[6] Lemmin U, Rolland T: Acoustic Velocity Profiler for Laboratory and Field Studies, J. Hydr. Engrg., ASCE, Dec 1997, 1089-1098.
[7] Takeda Y: Ultrasonic Doppler method for velocity profile measurement in fluid dynamics and fluid engineering, Experiments in Fluids 26 (1999), 177-178.