

# Velocity distribution in open-channel flow with intense sediment transport of granular material

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The knowledge of velocity distribution in open-channel flows with intense transport of sediment is essential for understanding the complexity of the transport process. The paper deals with the comparison and validation of experimental methods for velocity estimation in two phase flow with granular sediment. The results show very good agreement between the results obtained using Prandtl tube and ultrasonic Doppler methods. Furthermore, the suitability and uncertainty of the ultrasonic Doppler methods to determine the velocity components in the high concentrated layers is discussed.

**Keywords:** Velocity distribution; open-channel flow; intense sediment transport; acoustic Doppler anemometry

## 1 INTRODUCTION

Flood discharges in rivers and streams may induce intense transport of sediment and flow must be regarded as two-phase flow (flow of mixture of water and sediment). An increase in flow resistance can be expected in flows carrying a considerable amount of sediment, bed load in particular [1].

Intense bed-load transport is associated with high level of the bed shear stress [2]. This is related to higher rates of the erosion of the channel bottom and the channel side slopes. Transported particles are unevenly distributed along the water column. At low concentrations of the solid phase and/or the low shear stresses the vertical concentration profile is divided into the clear water zone near the water surface and the transport layer with the saltating particles only [3]. When increasing the shear stress (e.g., by increasing the longitudinal inclination of the bottom), the transport layer forms a second region above the sediment bottom, which can be characterized as a hyper-concentrated layer of moving particles [4].

For a detailed analysis of the mechanism of increased bed resistance and shear stresses, information on the velocity field and turbulent characteristics in and above the transport layer is required together with integral characteristics of the flow. Velocity measurements in the described two-phase flow using standard optical methods (LDA, PIV) face a number of problems, when the high concentrations of solid particles make the evaluation of the velocity of the flowing liquid impossible. Capart and Fraccarollo [2] used a modified method of PTV (Particle Tracking Velocimetry) to measure local velocities of sediment particles in the transport layer of coarse plastic grains. Yeganeh et al [4] carried out velocity measurements of the liquid phase of a two-phase flow with coarse-grained sediment ( $d =$

5 mm) using a Pitot tube and assumed that the evaluated velocity vectors correspond to local fluid velocities. Song et al [1] dealt with the use of ultrasonic techniques (Acoustic Doppler Velocity Profiler) in coarse-grained transport over erodible channel bottom. However, the measurement was restricted to the watery layer above the layer of moving sediment and hence omitted velocity measurement in a hyper-concentrated layer. Other applications of ultrasonic methods were mainly related to experiments with fine suspended particles at low sediment concentrations [5].

The present study examines the horizontal velocity component in open-channel flow with intense transport of coarse sediment of given grain size (other experiments with different grain sizes are planned). Measurement of the velocity distribution is performed using three independent methods (Prandtl tube, Ultrasonic Velocity Profiler, Acoustic Doppler Velocity Profiler). The aim of the experiments is to evaluate and compare the different methods for their potential to be used further in the project, which focuses to intense sediment transport phenomena.

## 2 MATERIAL AND METHODS

### 2.1 Experimental set-up

Experiments were carried out in an experimental tilting flume (Water Engineering Laboratory of Czech Technical University in Prague) constructed primarily for sediment transport research. The flume is an open channel with a rectangular cross section, its length is 8 m and its width is 0.2 m. The channel has a plastic bottom and glass walls. Range of adjustable longitudinal slope is between 0 -16.5 degree.

Supply of water and sediment is ensured through two circuits. One circuit is designed for clear water only. The second circuit is for the transport and measurement of mixture of sediment and water.

Measuring of the delivered concentration of solid phase is carried out in the vertical 8m-long U-tube [6]. The concentration of the solid phase is further verified by trapping the particles at the end of the open channel and weighting (TSCALE, CR- 100). To measure the flow of clean water and the mixture, 2 MID meters are used (clear water using Magnetoflow, Primo; mixture using KROHNE, OPTIFLUX 5000). The longitudinal channel slope is monitored by an electronic inclinometer (Pepperl&Fuchs, F99) and the water level is continuously measured using 4 ultrasonic sensors with external temperature compensation (Pepperl&Fuchs, UC500), which are located at the channel stationing  $x = 2.3, 3.3, 4.8, 6.3$  m from the inlet profile of the channel. The height of the sediment deposit is measured along the channel length with an intermediate distance of 0.5 m. Measured quantities are recorded on the control PC with A/D card using an application developed in Matlab Data Acquisition Toolbox.

## 2.2 Transport regimes and solid phase characteristics

The reported experiments HSF3\_20140401\_1 to HSF3\_20140424\_3 were measured in the range of flow rates from 6 to 8 l/s with different channel slopes and different volumetric transport concentrations of solid phase (1-18.7%). In experiment HSF3\_20140505\_1 conditions were modified to allow measurement with ADVP which requires greater flow depths.

The solid phase in presented experiments is represented by plastic granules (acetal copolymer, Hostaform) of the oval shape with a mean diameter of 3.18 mm, shape index 1.5 and density  $1358 \text{ kg/m}^3$  (Figure 1).

## 2.3 Velocity measurements

Velocity profiles presented in this article were measured at a distance  $x = 4.2$  m from the inflow cross section where the condition of steady uniform flow was confirmed. The velocity profile of the longitudinal velocity component was located to the vertical axis of the channel cross section. Three independent methods were used for measuring the velocity profiles.

*Prandtl tube (PT)* was used as a reference measurement of the flow velocity (outer diameter 6 mm, hole diameter 2 mm). It was connected to a differential pressure gauge (Siemens SITRANS P range 0.6 m). The vertical distance of the measured points was 5 mm in the zone with clear water and 2 or 3 mm within the transport layer.

*Ultrasonic velocity profiler (UVP)*: similar to PT, UVP was used to measure local components of

the longitudinal velocity. A 4 MHz transducer with internal active diameter of 5 mm (outer diameter 8 mm) was used. The ultrasonic signal was transmitted upstream parallel to streamlines. The velocity was evaluated at the distance of 33 mm from the head of the probe in the same point where the velocity was evaluated using PT. Each single point of the velocity profile was evaluated from 1,500 samples at a frequency of 60 Hz. Vertical distance of between each entry is 4 resp. 5 mm.

*Acoustic Doppler Velocity Profiler (ADVP)*: ADVP (NORTEK SA Vectrino Profiler) was employed to determine the velocity profile over the depth of 32 mm with a vertical resolution of 1 mm. Each measurement consisted of 4200 samples at a sampling frequency of 70 Hz. From the geometry of the ADVP sensor in experimental flume (Figure 2) it is evident that ADVP measurement is limited by the available flow depth. Consequently, it is not possible to evaluate velocity profiles in the vicinity of the water surface.

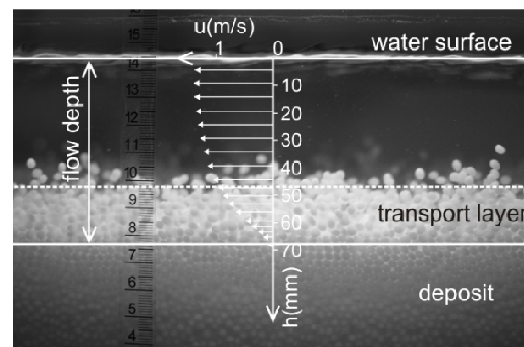


Figure 1: Scheme of the transport regime under open-channel flow conditions.

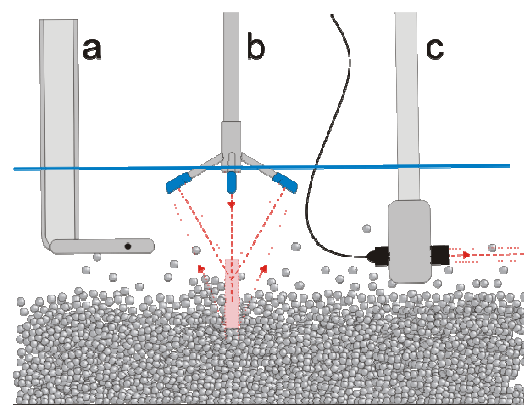


Figure 2: Detail of individual velocity probes a – PT, b – ADVP, c – UVP.

Table 1: Summary of conducted experiments with basic hydraulic characteristics of the two-phase flows.

Run	$Q_m$ [m <sup>3</sup> /s]	$U$ [m/s]	$h$ [m]	$l_e$ [-]	$h_{tr}$ [m]	$Fr$ [-]	$Re$ [-]	$C_{vd}$ [-]
HSF3_20140401_1	0.0084	0.822	0.051	0.0199	0.032	1.165	100511	0.047
HSF3_20140401_2	0.0082	0.821	0.050	0.0244	0.036	1.171	101841	0.066
HSF3_20140422_1	0.0072	0.582	0.062	0.0070	0.016	0.749	81791	0.010
HSF3_20140422_2	0.0071	0.710	0.050	0.0168	0.023	1.015	88475	0.038
HSF3_20140423_1	0.0070	0.779	0.045	0.0236	NA	1.171	89935	0.070
HSF3_20140423_2	0.0071	0.741	0.048	0.0314	0.032	1.084	90045	0.100
HSF3_20140423_3	0.0070	0.668	0.053	0.0387	0.039	0.930	88292	0.134
HSF3_20140424_1	0.0073	0.654	0.056	0.0403	0.038	0.882	89119	0.149
HSF3_20140424_2	0.0065	0.680	0.047	0.0417	0.039	0.996	86187	0.166
HSF3_20140424_3	0.0060	0.641	0.047	0.0470	0.037	0.942	82589	0.187
HSF3_20140505_1	0.0134	0.894	0.075	0.0145	0.018	1.044	140168	0.031

Legend:  $Q_m$  - discharge of the mixture,  $U$  - mean velocity in the cross section,  $h$  - flow depth,  $l_e$  - hydraulic gradient,  $h_{tr}$  - height of transport layer,  $Fr$  - Froude number,  $Re$  - Reynolds number,  $C_{vd}$  - delivered concentration of solid phase

### 3 RESULTS

#### 3.1 Velocity profiles for different flow conditions and transport regimes

For 11 experiments (Table 1), the time-averaged velocity profiles by PT and UVP were compared, while both instruments were used as point velocity probes. Figure 3 shows results for a number of different flow conditions and transport modes with different transport concentrations of the solid phase. The results demonstrate a very good agreement between the two experimental methods, particularly in the clear water zone above the transport layer and in the upper part of the transport layer where the particle concentration is significantly lower than in the lower part of the layer and in the deposit. The largest deviations are observed at the interface between the sediment deposit and the hyper-concentrated layer with maximum concentration; and in experiments with high delivered concentration (Figure 3, Table 1), where the UVP method is no longer able to reliably describe velocity vectors due to the high local concentrations of coarse solids. From the experiments it can be observed that the position of zero velocity varies and is probably related to the delivered concentration of the solid phase. An interesting fact is that this effect is detected by two independent experimental methods.

#### 3.2 Comparison of experimental methods

ADVP method was compared to the others in the experiment HSF3\_20140505\_1. With respect to geometric constraints of ADVP the velocity profile was evaluated only in the area at the fixed bottom, which corresponds approximately to the height of the transport layer. ADVP profiles were evaluated at two levels (Figure 4). In the range of 0.04 to

0.072 m, ADVP shows very good agreement with the profiles measured by PT and UVP. Slight differences can be observed in the lowest part of the transport layer. On the second range (0.063 to 0.095 m) the deviations are higher. UVP shows very good agreement with other methods, although quite significant differences can be observed near the bottom of the profiles, which are probably caused by fake echoes.

### 4 DISCUSSION

The results show good match for the measured data from various sources, including the data from the transport layer. One of the fundamental questions of this study was whether the ultrasonic methods are able to produce reliable velocity profiles in flows of coarse mixture. Therefore, Prandtl tube was used as a reference method for evaluating local velocities of the flowing liquid [4]. The results indicate that the local velocities obtained by the ultrasound methods should be local velocities of the liquid, not the particles. However, it is also possible that the local velocities of the liquid and the particles are very similar at the measured flow conditions and hence it is difficult to judge which local velocities were actually measured by the ultrasonic methods.

Naturally, both ultrasound systems used in this study are sensitive to the size and concentration of particles and to the associated scattering of the ultrasonic signal. Fake echoes were observed especially in data series captured within the transport layer. Therefore, further investigation must be related to the data filtering method which can improve obtained data sets from the transport layer.

### 5 SUMMARY

Based on the evaluation of the velocity profiles obtained using different experimental methods in open channel flows with intense transport of sediment we can conclude that:

The experimental methods show good agreement in measured data for various flow conditions. Major differences in the results by the three independent methods have been detected in the bottom zone of the transport layer for the experiments with high concentrations of transported sediment.

For UVP and ADVP methods, filtering of data from the transport layer is an important issue. A relevant data filtering method has to be tested.

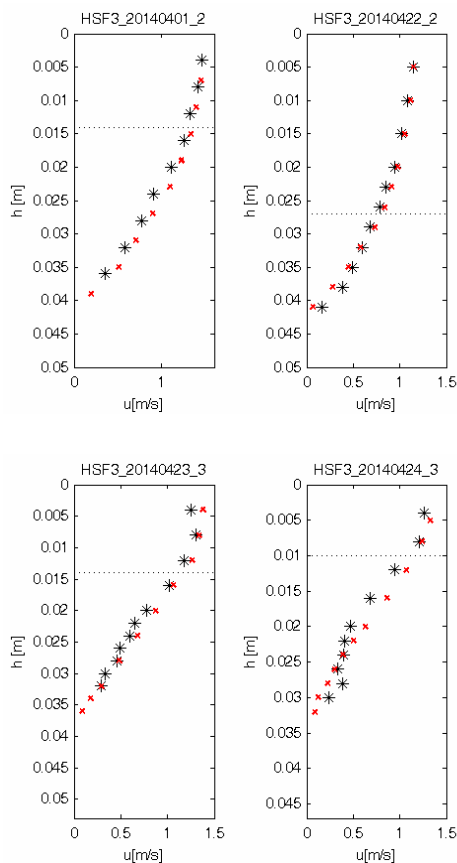


Figure 3: Velocity profiles in the vertical axis of the channel for selected experiments. Comparison of PT (x) and UVP (\*) method. Fixed bottom corresponds with the maximum value on the y axis. The observed top of the transport layer is indicated by dashed line.

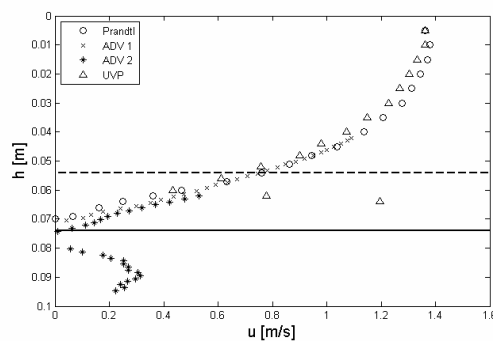


Figure 4: Vertical velocity profiles in the axis of the channel for the experiment HSF3\_20140505\_1 obtained by the PT (o), ADVP (x, \*) and UVP (Δ). Solid line corresponds with the top of fixed deposit, the dashed line with the top of transport layer.

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