

## Local velocity measurements in gravity-driven flows with intense bedload of coarse particles

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A broad dataset of sheet-flow experiments with granular material under steady and uniform conditions is presented in this paper with the focus on measurements of streamwise velocity component. Three different lightweight sediment fractions were used in total number of 128 experimental runs in wide range of sheet-flow modes which are being represented by dimensionless Shields parameter from 0.3 up to 2.3. The velocity information is obtained using three independent methods: Prandtl probe (PT), Ultrasonic Velocity Profiler (UVP) and Acoustic Doppler Velocity Profiler (ADVP). The measurement methods are compared to each other by means of their limitations and provided results in absolute and dimensionless velocity magnitudes. The results are consistent for all experimental runs and are further used for description of flow internal structure. The capability of individual measuring methods is demonstrated here on linear velocity distribution model in the transport layer with varying thickness of basal sublayer on the boundary of stationary bed and transport layer

**Keywords:** acoustic Doppler velocimetry; bed shear stress; bedload transport; particle/fluid flow; ultrasonic velocity profiling;

### 1. Introduction

Gravity driven flows with intense bedload of coarse particles so called sheet flows widely occur in both nature environment and industrial systems. The phenomena can be observed in rivers during floods, in steep mountain channels, in debris flows or in coastal waters [1]. In general, sheet flow regime of sediment transport is characterized by high bed shear stress which initiates a motion of layer of sediment particles with high solid concentration above a stationary sediment bed. Strong fluid flow smooths out ripples and dunes creating a sheet layer of bed-load grains in intense motion with high transport intensity [2].

However, the estimation of velocity vector (and sediment concentration distribution) in the sheet flow is governed by number of difficulties and is very rare so far especially for open channel flows [1]. The streamwise velocity magnitude is usually high (up to meters per second) because of steep bed channel slope which is needed to produce relevant transport conditions. Second, high variation of the total flow depth and/or the relative thickness of the transport shear layer occur when modelling sheet flows a wide range of flow conditions. In fact, the sheet flows with thin shear layer compared to flow depth are investigated frequently [3]. But, it is known that for high Shields numbers the thickness of shear layer can reach almost 100% of the flow depth [4,5]. Therefore, the velocity measurement system has to deal with velocity estimation in the sheet-flow layer over almost entire flow depth as well. Another difficulty is related to the limited transparency of fluid-particle mixture. Due to the high concentration of particles, the flow is opaque within the transport layer and widely used optical methods for velocity and turbulence measurements are disqualified for the region of fully developed turbulent flow in the central section of the open channel. In addition, the shear layer is

moving over a thick stationary sediment bed and the transported particles are relatively large compared to the flow depth and the thickness of transport layer.

Listing discussed sheet flow specifics, the difficulties of velocity estimation using relevant acoustic Doppler methods become obvious. Employing acoustic Doppler profilers with the access from the free surface is limited to narrow range of flow regimes. High surface velocities cause development of the air pockets around low submerged transducers head disabling the penetration of acoustic signal to flowing liquid. Furthermore, a so-called near field of acoustic transducers, where the estimation of velocity vector is impossible, consumes a large portion of flow depth. Therefore, the use of special boxes for submerging of acoustic transducers and removing the near field above the free surface is reported by several investigators [6]. Next to, the intense transport of granular material above the fixed bed disqualifies an application of acoustic methods from the channel bottom side which were reported in past for experiments with flow over rough fixed beds [6,7].

For the sheet flow experiment, Revil-Baudard et al. [3] employed two-component velocity measurements using an acoustic Doppler profiler placed above the free surface in a special housing to produce quasi-instantaneous 2D velocity and concentration profiles [8]. However, this experiment was fixed to narrow range of Shields parameter ( $\theta = 0.55$ ), intermediate velocity  $U = 0.52 \text{ m.s}^{-1}$  and high relative thickness of clear water layer compared to thickness of transport layer with plastic lightweight granulates. Single point Acoustic Doppler Velocimeter (ADV) for local velocity estimation was used by Cowen et al [9] to obtain validation data set for the borescopic method in suspension layer of water-sand flow.

In the present paper we deal with uniform, steady and turbulent sheet flows with significant vertical particle

stratification. A broad set of sheet flow experiments with three different plastic lightweight sediment fractions is presented including mean streamwise velocity profiles. The paper focuses on velocity measurements primarily in the transport layer which are rare in the literature. A comparison of results of different measuring methods is of special interest. We compare measurement data from two acoustic Doppler devices (Ultrasonic Velocity Profiler and Acoustic Doppler Velocity Profiler) and reference Prandtl probe (also called Pitot-static probe) in a broad range of flow and transport properties.

### 3. Material and methods

#### 3.1 Experiments

All experiments were conducted in the recirculating tilting flume with maximal bed slopes up to  $30^\circ$  [10]. The measuring channel of rectangular cross section 0.2 m wide and 8 m long is made of glass walls and PVC channel bottom. The water level, the position of the top of the bed and the position of the top of the transport layer are measured in five measuring cross sections with intermediate distance of 1 m.

Experimental results are presented for three tested fractions of plastic sediments (HSF30, TLT25, TLT50). All fractions are narrow-graded and of different size and similar density (Table 1). However, they differ significantly in grain shape. HSF30 grains are ellipsoidal, while TLT25 grains are more rounded, although asymmetrical. TLT50 particles have a significant cylindrical shape (Figure 1).

Table 1: Sediment characteristics.

Sediment	$d$ [mm]	$S_s$ [-]	$w_t$ [m.s <sup>-1</sup> ]
HSF30	3.22	1.36	0.131
TLT25	3.96	1.38	0.106
TLT50	5.35	1.307	0.149

Note:  $d$  – volume-equivalent sphere diameter;  $S_s$  – relative density;  $w_t$  – terminal settling velocity of particle;



Figure 1: Picture of three tested fractions of plastic sediments – from left to right HSF30, TLT25, TLT50.

For each sediment fraction we have made a series of experimental runs with wide range of flow and sediment transport characteristics (HSF30 – 67 runs (33 with velocity measurements); TLT25 – 43 runs (42); TLT50 – 54 runs (53)). For all three sediment fractions the ranges

of the fundamental parameters are similar. Averaged velocity in cross section  $U$  varied from 0.22 to 1.05 m.s<sup>-1</sup>. Flow depth  $h$  was in the range from 0.029 to 0.101 m. The volumetric flowrate  $Q_m$  of the mixture estimated by Magnetic Inductive (MID) flow meter was from 0.0013 to 0.0162 m<sup>3</sup>.s<sup>-1</sup>. Delivered volumetric concentration  $C_{vd}$  varied from virtually zero up to 29%. Within those spectra of flow variables and with respect to sediment properties we were able to model runs with wide range of dimensionless Shields parameter  $\theta$  from 0.21 up to 2.67. Using the criteria of Shield threshold value, we divided the experiments into two groups: i) runs with low or moderate sheet flow; ii) runs with intense sheet-flow process [10]. The threshold value of  $\theta_{th}$  is associated with the condition at which the transport layer reaches its limit for its expansion towards the water surface (for the definition of  $\theta$  and  $\theta_{th}$  see [11]). 23 experiments with HSF30 sediment Shields number  $\theta$  exceed  $\theta_{th}$ , similarly in 26 experiments with TLT25 particles and in 25 experiments with TLT50 granulates. Evaluating the thickness of transport layer  $h_{tr}$  normalized by total flow depth  $h$  we see that  $h_{tr}$  migrates from 14% of total flow depth  $h$  to almost 100% when no clear water layer is observed. Expectably, there is an existing relationship in between dimensionless Shields parameter  $\theta$  and relative thickness of transport layer  $h_{tr}/h$  (Figure 2).

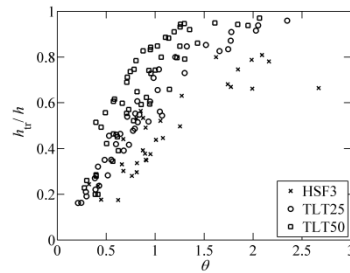


Figure 2: Dimensionless bed-load layer thickness  $h_{tr}/h$  related to increasing Shield parameter  $\theta$  for various sediment fractions (HSF3, TLT25, TLT50);  $h$  is the total flow depth.

#### 3.2 Velocity measurements

Three independent methods (Prandtl probe (PT), Ultrasonic Velocity Profiler (UVP, Met-Flow) with 4 MHz TDX and Acoustic Doppler Velocity Profiler (ADVP, Vectrino, Nortek) with acoustic frequency 10 MHz) were used to measure local velocities in the water layer and in the transport layer above the stationary sediment deposit in the laboratory flume. All instruments were located in the same measuring location - in the centre of width of the channel cross section 4.2 m behind the flume inlet (Figure 3). Each applied method (and instrument) has its limitations and its validity must be evaluated using specific criteria for particular conditions in the tested flows.

PT and UVP were employed in all experiments with velocity measurements. ADVP was used only for selected set of runs where sufficient thickness of flow depth and clear water layer occurs. From the perspective of sediment transport, we talk in general about runs with Shields parameter  $\theta < \theta_{th}$  with low relative thickness of transport layer  $h_{tr}/h$ .

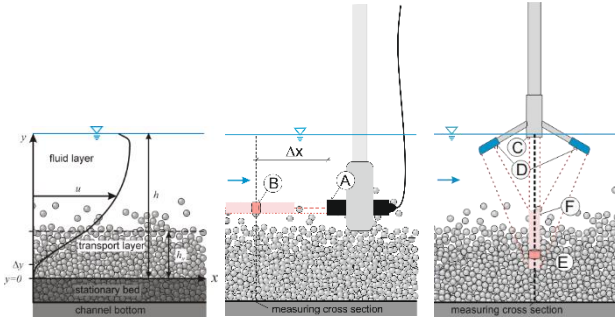


Figure 3: Theoretical velocity distribution and installation of acoustic velocity probes (UVP middle) and ADVP (right). Vertical dashed line represents measuring cross section. A – UVP transducer 4 MHz, B – UVP measuring volume (cylinder of diameter 5.0 mm and of height 0.74 mm), C – ADVP transmitter, D – ADVP upstream/downstream receivers, E – ADVP measuring volume (cylinder of diameter 6.0mm and of height 1.00 mm), F – ADVP measuring region of height of 32 mm and diameter of 6 mm.

### 3. Results

#### 3.1 Comparison of velocity profiles

Estimated velocity profiles produced by above described experimental methods are compared for various flow conditions. Due to the limitations of ADVP, the ADVP data are available only for runs with low or moderate sheet flow transport (corresponding to  $\theta < \theta_{th}$ ) and they are constrained only to the lower portion of flow depth. Figure 4 represents the vertical velocity profiles of streamwise velocity component across the water column in both transport and fluid layer. Usually, we see a reasonable match between the PT, UVP and ADVP. A general course of velocity distribution also corresponds with earlier results obtained by using alternative measuring techniques [3,4,12]. In general, we observed slight systematic offset in between PT data and data from acoustic devices. This offset is independent of vertical stratification of flow.

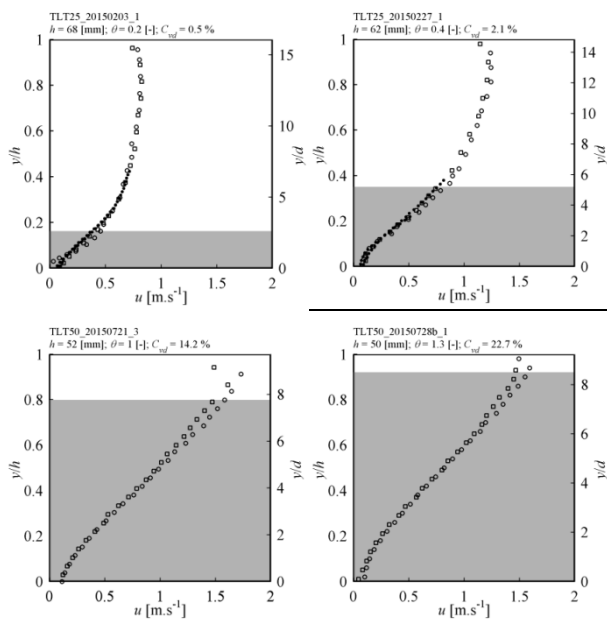


Figure 4: Mean vertical velocity profiles measured by PT and

UVP for moderate (top) and intense (bottom) sheet flow conditions for Shields parameter. Grey layer corresponds to the thickness of transport layer  $h_{tr}$ , PT (○), UVP (□), ADVP (●). Data are presented for TLT25 and TLT50 sediment fraction.

#### 3.2 Dimensionless velocity distribution in transport layer

Here we compare individual measuring methods to each other in dimensionless form of velocity distribution within the sheet-flow layer. Generally, the vertical distribution of streamwise velocity component can be approximated by a power-law distribution [10,12] as follows:

$$\frac{u}{u_{tr}} = \left( \frac{y - \Delta y}{y_{tr} - \Delta y} \right)^n \quad (1)$$

in which  $u_{tr}$  is local velocity at the position  $y_{tr}$  where the power profile typical for transport layer smoothly transforms to the logarithmic profile typical for the fluid layer. Position  $y_{tr}$  is equivalent to the top of bed-load layer of thickness  $h_{tr}$  which is observed visually. Position of zero velocity  $\Delta y$  represents the displacement of the origin of the power-law profile. Capart & Fraccarollo [4] define this variable as basal sub-layer thickness. Parameter  $n$  is power-law exponent.

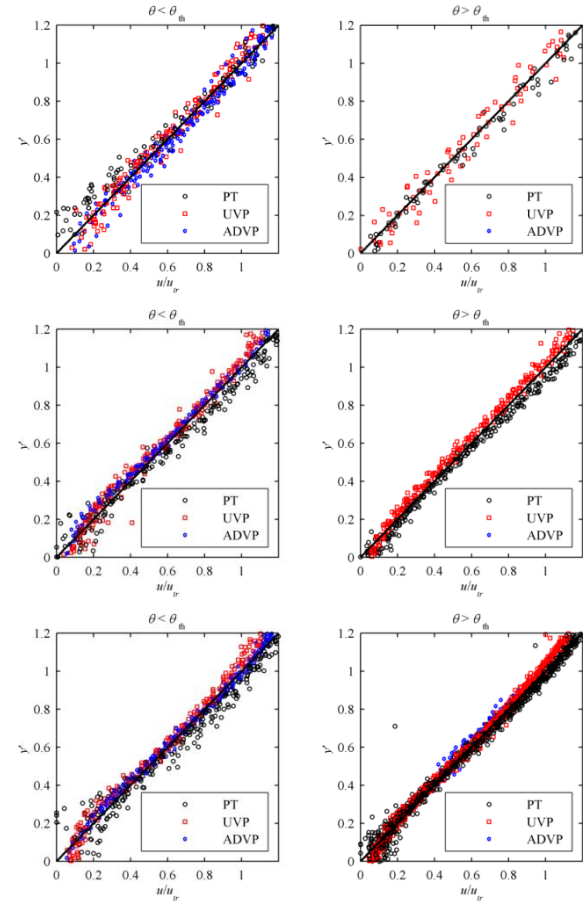


Figure 5: Streamwise non-dimensional velocity profile  $u/u_{tr}$  measured by PT, UVP and ADVP in transport layer for different sediment fractions (from top to bottom HSF, TLT25, TLT50) and all runs with dimensionless Shields parameter  $\theta$  lower (left) and higher (right) compared to threshold value  $\theta_{th}$ .  $y'$  is non-dimensional vertical dimension  $y' = (y - \Delta y)/(y_{tr} - \Delta y)$ .

By plotting dimensionless velocity profiles for all three sediment types (Figure 5) one can observe almost linear distribution with  $n = 1$  for both the low and moderate bed-load transport ( $\theta < \theta_{th}$ ) and for the intense bed-load ( $\theta > \theta_{th}$ ). This corresponds with experience of particle velocity profiles measured at very similar conditions by Capart & Fraccarollo [4]. Our observations show very tight relationship especially for runs with high value of Shields parameter  $\theta > \theta_{th}$  (except for HSF30 data). For runs with  $\theta < \theta_{th}$  one can observe more scattered data sets. Thin transport layer results in a low number of measuring points in the bed-load layer and therefore, a higher level of estimation uncertainty of velocity distribution parameters.

Figure 5 shows overall comparison of measuring methods for velocity estimation in transport layer. We can see very good agreement in general for all sediment fractions and sediment transport modes. However, several facts should be remarked. As we mentioned already, there is a slight offset in between data from acoustic devices and Prandtl probe. This is mostly evident for runs with TLT25 and TLT50 for  $\theta > \theta_{th}$ . For these runs we can observe also an increasing trend of the offset with increasing relative flow depth. In the near-bed region we can see deviation from linear distribution for both acoustic methods ( $y' < 0$ ) which is similar to observations of other authors [3,4]. PT probe provides more scattered data in this zone.

## 6. Discussion

Our results provide a straightforward comparison of Prandtl probe measurements representing fluid streamwise velocity and two widely used acoustic Doppler instruments. Their measurements contains velocity information of both the diffuse microparticles in fluid and the large plastic granulates. The comparison in the transport layer (Fig. 4) introduces slight slip in between acoustic methods and Prandtl probe for TLT25 and TLT50. Runs with HSF3 did not show such evidence. However, as can be seen in Fig. 4, there is also slight velocity offset in between individual methods for fluid layer where no granulates occur. Thus the velocity offset can originate from both the slip effect in between the particles and fluid or from the measurement uncertainty. Therefore, we suppose that the slip velocity is almost negligible in the sheet flows with lightweight particles which is also in agreement with previous experimental works.

## 7. Summary

A broad experimental data set for the gravity-driven sheet-flow experiments including flow characteristics, sediment flux and velocity measurement is presented in this paper. The experiments were fulfilled with three different plastic sediment fractions. The investigation focussed on the validation of three experimental methods for local velocity estimation under special conditions.

In particular, Ultrasonic Velocity Profiling (UVP) and Acoustic Doppler Velocity Profiling (ADVP) methods are compared to reference measurements using Prandtl probe. In general, we can conclude that all methods provide

comparable and valuable results in terms of local time-averaged streamwise velocity component which is of special interest in the sheet-flow process. We demonstrate the capability of all methods to describe the velocity distribution in the stratified granular-liquid flows.

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