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On local velocity measurement in gravity-driven flows with intense bedload of coarse lightweight particles

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ABSTRACT

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 during 128 experimental runs across a wide range of sheet-flow modes which were represented by dimensionless Shields parameter from 0.3 up to 2.3. The local velocity information was obtained using three independent methods: Prandtl probe (PT), Ultrasonic Velocity Profiler (UVP) and Acoustic Doppler Velocity Profiler (ADVP). The measurement methods were compared to each other using results in absolute and dimensionless velocity magnitudes. Limitations of the methods are discussed. The results were consistent for all experimental runs and are further used for a description of the observed flow internal structure. The capability of individual measuring methods is demonstrated here on an identification of a transport layer of a linear velocity distribution and of a basal sublayer at the transition between the stationary bed and the transport layer.

1. Introduction

Gravity driven flows with an intense bedload of coarse particles, called “sheet flows”, widely occur in both the natural environment and in industrial systems. This phenomena can be observed in rivers during floods, in steep mountain channels, in debris flows or in coastal waters [1]. In general, a sheet flow regime of sediment transport is characterised by high bed shear stress which initiates motion in a 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].

The internal structure of the sheet flow is characterized by strong vertical stratification [3]. The free surface region is basically free of transported grains with individual saltating particles [4]. Above the erodible bed plane one can observe a “transport layer” with highly concentrated water-particle mixture. This layer can be alternately be referred as the "sheet-flow layer" or using general term as the "bed-load layer" [2,5,6]. The layer between the free surface and the top of the transport layer is called the fluid layer herein. In the sheet flow regime, the relative thickness of the transport layer and the related solids load is associated with the non-dimensional Shields parameter θ [3,7,8]. The Shields parameter is defined as the ratio of the force exerted by the fluid on a particle at the bed and the apparent weight of a single particle: $\theta=\tau_b/(\rho_s-\rho_f)gd$ where τ_b is shear stress associated with channel bed, ρ_s and ρ_f are the density of the particles and fluid respectively, g is the acceleration due to gravity and d is the particle diameter. The transition between the bedform regime and the sheet flow is related to the Shields parameter around 0.4–0.5 [9,10].

To understand both the friction and the transport mechanism in detail, the streamwise velocity profile, next to the sediment concentration profile, crosswise of the layered flow structure is of special interest. Detailed velocity information combined with an estimate of turbulence characteristics and a concentration distribution is needed to understand the main friction mechanism in the shear layer.

However, the estimation of the velocity vector (and the sediment concentration distribution) in the sheet flow is problematic, and is therefore not often reported, particularly for open-channel flows [1]. The velocity measurement is difficult for several reasons. The first is because the streamwise velocity magnitude is usually high (up to meters per second) due to the steep bed channel slope, which is needed to produce relevant transport conditions. Secondly, high variations of the total flow depth and/or the relative thickness of the transport shear layer occur when modelling sheet flows under a wide range of flow conditions. In fact, sheet flows with thin shear layers compared to flow depth are investigated frequently [4]. However, it is known that for high Shields numbers the thickness of the shear layer can reach almost 100% of the flow

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Nomenclature

b [m]	width of rectangular channel
c [dimensionless; m s^{-1}]	local volumetric concentration of particles; velocity of ultrasound
C_{vd} [dimensionless]	delivered volumetric concentration of particles
d_{16} [m]	size fraction of sediment sample below which 16% of sample is smaller
d_{50} [m]	size fraction of sediment sample below which 50% of sample is smaller (median particle size)
d_{84} [m]	size fraction of sediment sample below which 84% of sample is smaller
d [m]	volume-equivalent sphere diameter
f_0 [Hz]	basic emission frequency
g [m s^{-2}]	acceleration due to gravity
h [m]	flow depth
P_{max} [m]	spatial range of Ultrasonic Velocity Profiler
Q_m [m^3 s^{-1}]	volumetric discharge of sediment–water mixture
S_s [dimensionless]	relative density of particles
u [m s^{-1}]	time-averaged local longitudinal velocity
u_{tr} [m s^{-1}]	time-averaged local velocity at the position ytr
u_{*b} [m s^{-1}]	bed shear velocity
U [m s^{-1}]	cross-sectional velocity
V_{max} [m s^{-1}]	velocity range of Ultrasonic Velocity Profiler
w_t [m s^{-1}]	terminal settling velocity of grain
y [m]	vertical position above the boundary
y_{tr} [m]	position of transition at composite velocity profile
Δy [m]	vertical displacement of the linear profile origin; thickness of basal sublayer
z [m]	acoustic impedance
θ [dimensionless]	Shields parameter
θ_{th} [dimensionless]	threshold value of Shields parameter

depth [5,11]. Therefore, the velocity measurement system has to deal with velocity estimation in the sheet-flow layer over almost the entire flow depth as well. Another difficulty is related to the limited transparency of the 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 not feasible for the region of fully developed turbulent flow in the central section of the open channel. In addition, the shear layer moves over a thick stationary sediment bed and the transported particles are relatively large compared to the flow depth and the thickness of the transport layer.

Despite that, the literature review reports several velocity measuring systems which were adapted to sheet flow conditions. A number of experiments was conducted in pipe flows. Pugh and Wilson [2] used a conductivity probe to estimate the streamwise velocity of the water–sand and the water–bakelite mixture.

In open channel flows, Yeganeh et al. [12] and Sumer et al. [3] carried out the sheet flow experiments using a Pitot probe for the local streamwise velocity measurements with different sediment particles (plastic, sand, glass or acrylic). Capart et al. [13] introduced a set of digital imaging methods derived from the Voronoi diagram for particle tracking velocimetry (PTV) for liquid-granular open channel flows with plastic particles. This work was further extended using stereoscopic cameras [14]. Recently, Cowen et al. [15] have developed a borescopic technique to measure the streamwise velocity profile inside the dense moving bed layer of the water–sand mixture. Capart and Fracarollo [5] used two high-speed cameras and a laser light sheet to measure detailed profiles of both granular velocity and solid concentration of PVC cylinders near the sidewall of rectangular laboratory flume.

Another approach is an employment of acoustic Doppler methods, which are broadly used for investigation of open-channel and two-phase flows in both the natural and the industrial systems. The use of acoustic Doppler profilers in the open channel flow over the fixed rough bed [16] or with the weak bed load transport [17] is reported often. However, there are a number of issues with utilizing acoustic Doppler profilers to characterize sheet flows. Employing acoustic Doppler profilers with the access from the free surface is limited to a narrow range of flow regimes. High surface velocities cause development of the air pockets around the low submerged transducer's head, disabling the penetration of acoustic signal to the flowing liquid. Furthermore, a so-called “near field” of acoustic transducers, where the estimation of the velocity vector is impossible, consumes a large portion of the 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 [18]. Additionally, 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 the past for experiments with flow over rough fixed beds [18,19].

For a sheet flow experiment, Revil-Baudard et al. [4] 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 [20]. However, this experiment was fixed to a narrow range of Shields parameters (θ=0.55), intermediate velocities U=0.52 m s^{-1} and the high relative thickness of the clear water layer compared to the thickness of the transport layer with plastic lightweight granulates. Single point Acoustic Doppler Velocimeter (ADV) for local velocity estimation was used by Cowen et al. [15] to obtain validation data set for the borescopic method in the suspension layer of water–sand flow.

In the present paper we deal with uniform, steady and turbulent sheet flows with significant vertical particle stratification [4,5,7,21,22]. A broad set of sheet flow experiments with three different plastic lightweight sediment fractions is presented including mean streamwise velocity profiles. This 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 the Prandtl probe, also called the Pitot-static probe [23], in a broad range of flow and transport properties.

The paper is organised as follows: in Section 2, the experimental setup and flow characteristics are described in detail. The methods for velocity estimation using acoustic probes are described in Section 2. In Sections 3 and 4, we present vertical profiles of the mean streamwise velocity and the non-dimensional velocity in the transport layer. The comparison of different methods for velocity estimation is analysed. Then the vertical structure of the flow is discussed by means of dimensionless velocity distribution measured for diverse flow conditions. In Section 5, the obtained results are discussed and the main conclusions of this paper are summarised in Section 6.