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Technical note

Dam-break flow experiments over mobile bed: velocity profile

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ABSTRACT

Knowledge of the velocity distribution is key for understanding and modelling any type of flow. For steady flows over fixed beds, theoretical and experimental approaches evidenced a logarithmic law in the inner region, in the vicinity of the bed. For flows over mobile beds or for unsteady flows, the velocity profile progressively adapts to the changing flow conditions. In the present paper, new experiments of dam-break flows over a bed made of coarse sand are presented. Detailed velocity measurements both in the clear water layer and in the moving sediment layer were obtained. The measurements show that a logarithmic velocity profile develops not only in the clear-water layer but also in the upper part of the moving sediment layer, in a similar way to previous observations in steady flow with sheet-flow sediment transport.

Keywords: Dam-break flow; experiments; mobile bed; particle image velocimetry (PIV); particle-laden flows; velocity measurements

1 Introduction

Velocity distribution in a free-surface flow is one of the most interesting and challenging problems in fluid mechanics. It is interesting because it allows for a better understanding of the flow structure and the flow resistance, and challenging because accurate measurements require non-intrusive techniques in order to prevent flow perturbation by the measurement itself.

Nikuradse (1933) has carried out numerous experiments in steady flow conditions in circular pipes covered on the inside wall with sand of a known grain size glued on the wall, the diameter of this sand grains being defined as the Nikuradse's equivalent sand roughness k_s . From his experiments and from Keulegan's (1938) experiments in a flume with steady uniform flow, a logarithmic velocity distribution was observed, in accordance with Prandtl's mixing-length theory (Streeter & Wylie, 1975). The zone where a log-law profile is defined is referred to as the inner region and is limited to a given value that is often

considered to be $z/h = 0.20$ (Graf & Altinakar, 1998), where z is the distance to the bed and h is the total water depth.

From classical measurements of the velocity profile in steady-flow conditions (e.g. Nikuradse, 1933), it was established that, for smooth walls, the flow profile is linear near the wall, in the so called laminar layer, while it is logarithmic outside this layer. For a boundary that is hydraulically rough, the wall irregularities break down the laminar layer and they determine directly the velocity profile. Equation (1) describes the logarithmic velocity profile that depends on k_s , which is the equivalent sand roughness, i.e. the grain size of the glued sand used by Nikuradse on the wall for representing the roughness:

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z}{k_s} \right) + B_r \quad (1)$$

where u_* is the friction velocity, z is the distance to the bed, $\kappa = 0.4$ is the von Kármán constant, and B_r is the integral

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constant for rough boundaries. If the wall is completely rough, which corresponds to the condition $u_* k_s / \nu > 70$, where ν is the water viscosity, the constant $B_r = 8.5$, according to Nikuradse results.

With the progresses of non-intrusive measurements based on imagery techniques, such as PIV (particle image velocimetry) based on autocorrelation between successive images (Adrian, 2011; Keane & Adrian, 1992; Raffel, Willert, Werely, & Kompenhans, 2007), and PTV (particle tracking velocimetry) following the particles in their trajectories (Capart, Young, & Zech, 2002), it became possible to investigate the velocity distribution also in unsteady flows. For instance, Tu (1991) investigated the velocity field in a gravel-bed flume for 13 typical discharge hydrographs as close as possible to natural ones. In his work, the velocity distribution revealed to be slightly different in the rising limb of the hydrograph compared to the falling limb, but the log-law distribution was observed to be still valid in the so-called inner region. Song and Graf (1996) proved that the log-law of Eq. (1) is valid also for unsteady flows in open channels with fixed gravel beds. They posed the reference level at a distance $0.25 k_s$ below the bed level (i.e. z is replaced by $z + 0.25 k_s$ in Eq. (1)) and the constant $B_r = 8.5 \pm 15\%$ in the inner region, this constant being almost independent of the flow unsteadiness. Following the authors, the dominant mechanisms for production of turbulence in the unsteady-flow turbulent boundary layers cannot differ greatly from those in the steady-flow boundary layer (Brereton, Reynolds, & Jayaraman, 1990). In particular, they found that, similarly to steady-flow cases, the logarithmic law is valid in the inner region near the bed, where $z/h \leq 0.2$.

Sumer, Kozakiewicz, Fredsøe, and Deigaard (1996) carried out extensive investigations in a tilting flume (10 m in length, 0.3 m in depth, 0.3 m in width) with recirculation of water and sediment, reproducing a steady uniform flow over a mobile bed. Using four types of sediment, 158 experiments were carried out to study the sediment transport near the bed, which takes place in a layer with a thickness much larger than the grain size, called the sheet flow layer. Sumer et al. (1996) measured velocity profiles not only in the clear water layer but also in the sheet-flow layer and they discovered that the logarithmic velocity profile is present as well in the water inner region as in the upper part of the sediment layer (Fig. 1), in line with the log-law in the water inner region. It must be noted that in their experiments the water surface was smoothened by a rigid lid. Following the authors, the upper part of the sheet flow layer and the inner region of the water flow present a logarithmic velocity distribution (Fig. 1b) similar to Eq. (1) but with a modified definition of z :

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \left(\frac{30(z - \Delta z)}{k_s} \right) = \frac{1}{\kappa} \ln \left(\frac{z - \Delta z}{k_s} \right) + 8.5 \quad (2)$$

where z is now the distance to the bottom of the sheet-flow layer, i.e. the limit between immobile and mobile sediments, and Δz is the theoretical level where the logarithmic law ends asymptotically to a zero value (Fig. 1a). This level depends on the Shield's

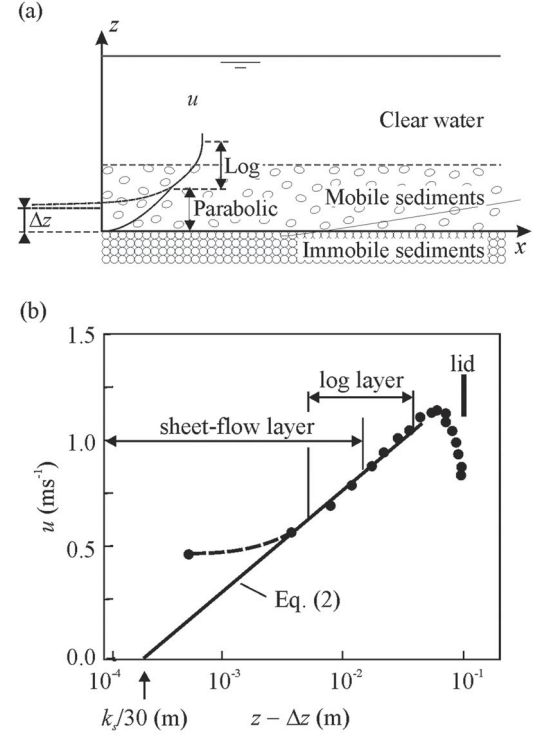


Figure 1 Typical velocity distribution with logarithmic law near bed in presence of a sheet-flow layer: (a) definition of variables, (b) observation by Sumer et al. (1996)

parameter, defined as:

$$\theta = \frac{\rho u_*^2}{g(\rho_s - \rho)d_s} \quad (3)$$

where ρ_s and ρ are the density of grains and water respectively, g the acceleration of gravity, and d_s the grain size. The equivalent sand roughness normalized by the grain size, k_s/d_s is evaluated as a function of the Shields parameter in Eq. (3) as $k_s/d_s = 5\theta$ according to Wilson (1988, 1989) and simply as $k_s/d_s = 2$ (if $\theta < 1$) according to Yalin (1992). Then, in the lowest part of the sheet-flow region, which constitutes the major part of the moving sediment layer, Sumer et al. (1996) propose a power law for the velocity distribution.

Also *unsteady* flows over mobile beds with weak bed-load transport, velocity profiles over the water depth have been studied by some authors, e.g. Nikora and Goring (2000), Qu (2003), and de Moraes Franklin, Tocchini de Figueiredo, and Spanó Rosa (2014). They analysed the effects of the granular mobility on the shear velocity u_* . Once again a logarithmic velocity profile was detected in the lower zone of the water flux with the bed friction affected by the granular mobility. For instance, Qu (2003) carried out a series of experiments with various hydrographs in a flume with a mobile bed. For the same flow depth, the velocity was observed as higher during the rising limb than during the decreasing phase of the hydrograph, but no significant differences were observed in the inner region between

experiments on fixed bed or mobile bed. The velocity distribution inside the sediment layer was not considered in this approach.

As regards *highly unsteady flows* such as dam-break flows, numerous experimental data are available for *fixed bed conditions*, generally flatbed (e.g. Aleixo, Soares-Frazão, & Zech, 2011; Bellos, Soulis, & Sakkas, 1992; Lauber & Hager, 1998; Stansby, Chegini, & Barnes, 1998), but there are fewer datasets of dam-break flow over a *mobile bed* (e.g. Capart & Young, 1998; Khan, Steffler, & Gerard, 2000; Leal, Ferreira, & Cardoso, 2006; Soares-Frazão, le Grelle, Spinewine, & Zech, 2007; Spinewine & Capart, 2013). Also, in these available experiments concerning either high concentration transport flow such as debris flow or bed load transport flow, the detailed velocity field is seldom measured. Spinewine and Capart (2013) carried out dam-break flow experiments over a bed made of PVC pellets with an equivalent diameter $d_s = 3.92$ mm and a density $\rho_s = 1580$ kg m⁻³. Due to the light weight of the PVC pellets used as sediment, a thick layer of moving grains was observed, up to about 0.05 m (i.e. about 12 d_s) close to the front. Using PTV they measured velocity profiles in the clear water layer and in the moving sediments layer, as well as concentration profiles. From their measurements, they concluded that the velocity was uniform in the clear-water layer, while linearly distributed inside the mixed layer with a velocity equal to the water velocity at the interface with the clear water. However, as the main focus of their work was on the sediment concentration in the moving sediment layer, the velocity profile in the clear water layer was not measured with the same resolution and level of detail as in the present work.

In the present study, new detailed dam-break flow experiments over a mobile bed made of coarse non-cohesive sediment are presented. The velocity distribution was measured as well in the water inner region as in the sheet-flow layer. The resulting profile shapes were compared to those obtained by Sumer et al. (1996) in steady flow conditions, and to those obtained by Spinewine and Capart (2013) for high concentration transient flow.

2 Experimental set-up and measurement devices

The experiments were performed in a dedicated flume at the hydraulics laboratory of the Université catholique de Louvain (Belgium). The dam-break channel (Fig. 2) has a total length $L = 6$ m, and a rectangular cross section of 0.25 m width with glass walls to allow for a wide optical access to the flow. A downward moving gate is used to simulate the instantaneous removal of a dam (Spinewine & Zech, 2007).

The channel is filled with a 0.1 m thick layer of non-cohesive sand with the following characteristics: quasi-uniform size distribution with a mean diameter $d_{50} = 1.72$ mm, density $\rho = 2682$ kg m⁻³, friction angle $\phi = 38^\circ$ and a bed porosity that was measured to be $\epsilon_0 = 0.42$. In order to ensure the

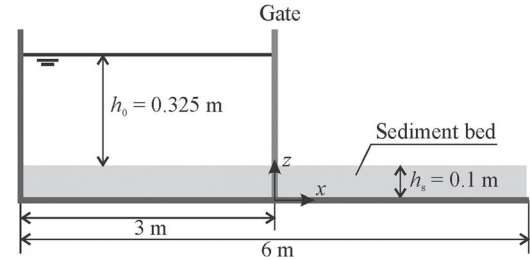


Figure 2 Experimental set-up

repeatability of the experiments, the sand on the bed is compacted and saturated following a well-defined procedure. The upstream reservoir is filled with a water depth $h_0 = 0.325$ m measured above the 0.1 m thick sand bed (Fig. 2). The origin of the axes is located at the gate toe, with $z = 0$ m corresponding to the fixed channel bottom. In the analysis, in order to compare the behaviour of the moving sediment to the observations by Sumer et al. (1996), the levels corresponding to the limits of the immobile and mobile sediments are defined as illustrated in Fig. 3, to account for the fact that the limit between immobile and mobile sediments is changing in time due to erosion and deposition processes.

The accuracy and the high frequency of the recorded images also allow for the measurement of the water and bed profiles that are rapidly evolving in space and time. Each image is treated in an automated way, based on the work of Soares-Frazão et al. (2007) and here improved, in order to determine the limits of the flow (Fig. 4).

From the experiments, the line corresponding to the water surface can be easily identified. Close to the bed, the area with moving sediments shows a thicker zone that is more difficult to delineate, due to some laser-light reflections on the sediment grains. In order to identify the real limits of the sediment bed the image is first blurred by a Gaussian-type function (Fig. 4a). A threshold colour is then applied (Fig. 4b) in order to distinguish the sediments from the flowing water. The moving sediment layer can then be isolated and the two lines corresponding to the upper and lower limits are determined (Fig. 4c). The final water surface (z_w) and upper ($z_{b,up}$) and lower ($z_{b,low}$) bottom profiles are successively compared to the measured velocity field, allowing to check the correct position of $z_{b,low}$ (Fig. 4d).

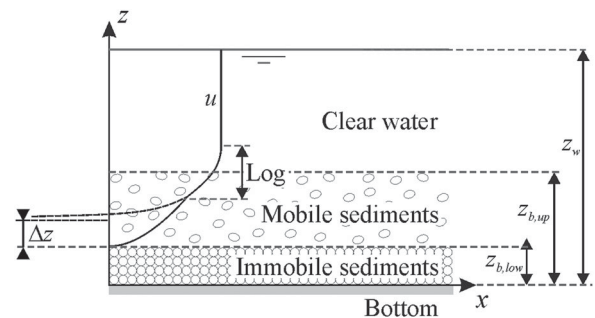


Figure 3 Variable definitions for the present experiments

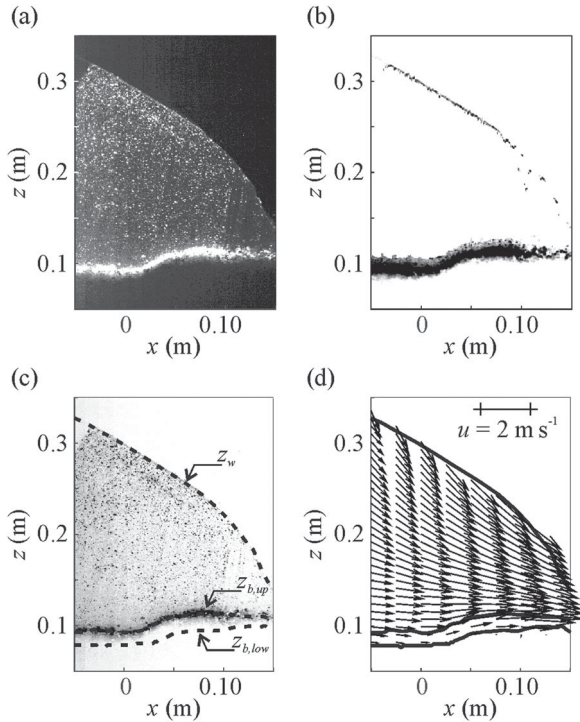


Figure 4 Automatic detection of the flow interfaces for one image ($t = 0.3 \text{ s}$) taken at the gate position ($x = 0 \text{ m}$): (a) rough image, (b) Gaussian-blur and threshold colour applied to image, (c) detected interfaces (dashed lines), (d) PIV velocity field and detected interfaces

For measuring the velocity field, time-resolved PIV was used (Keane & Adrian, 1992; Raffel et al., 2007). A continuous red laser sheet (power = 100 mW, wavelength = 660 nm) illuminates a section of the flow previously seeded with pliolite particles and the high-speed camera records images at regular short intervals of 500 frames per second. The PIV software used

Table 1 Maximum calculated uncertainty of the module of velocity $|\mathbf{u}|$

Time (s)	0.3	0.7	1.0	2.0	3.0
Uncertainty (10^{-2} m s^{-1})	0.1	2.1	2.2	2.3	3.7

in the present study is Davis 8.2 developed by LaVision. The detection of velocity vectors is made with sub-pixel accuracy by fitting a Gaussian curve to the correlation intensity distribution (Raffel et al., 2007). Moreover, the multi-pass technique is used to allow for a better survey of flow gradients by deforming and decreasing the size of the interrogation window in which the velocity vector is detected. The size of the interrogation window is decreased from an initial dimension of 96×96 pixels to the smallest dimension of 32×32 pixels, which corresponds to the final window surface of $1.4 \times 1.4 \text{ cm}^2$. The uncertainty of the resulting velocities is directly evaluated by the Davis 8.2 software as follows. The interrogation window is divided into smaller parts with displacement vectors of higher noise level. Then the “particle disparity” method goes to smaller scales, analysing individual particles and their spread in displacements. Finally the correlation statistics method zooms in even further to individual pixels and their fluctuating contributions to the shape of the correlation peak is derived. Some examples of the maximum calculated uncertainty of the module of velocity ($|\mathbf{u}|$) are listed in Table 1, at different times. The error on the velocity is very small (order of magnitude of 1–4%) and always located in few small spots, not on the entire flow domain, so the validity of the results is confirmed.

3 Analysis of the experimental results

3.1 Early stage of dam-break flow

At the beginning of the phenomenon, just after the gate removal, the water falls down with a vertical velocity component in the upper part of the water column much larger than the velocity in the lower part (Fig. 5, $t = 0.3 \text{ s}$). The velocity vectors present an angle between 0° and -30° with respect to the horizontal line (Fig. 5a, $t = 0.3 \text{ s}$). At this moment the assumptions of 1D shallow water flow are not applicable, as the vertical velocity components cannot be neglected. It is possible to represent the distribution of the horizontal component (Fig. 5c) but no clear velocity distribution law may be defined.

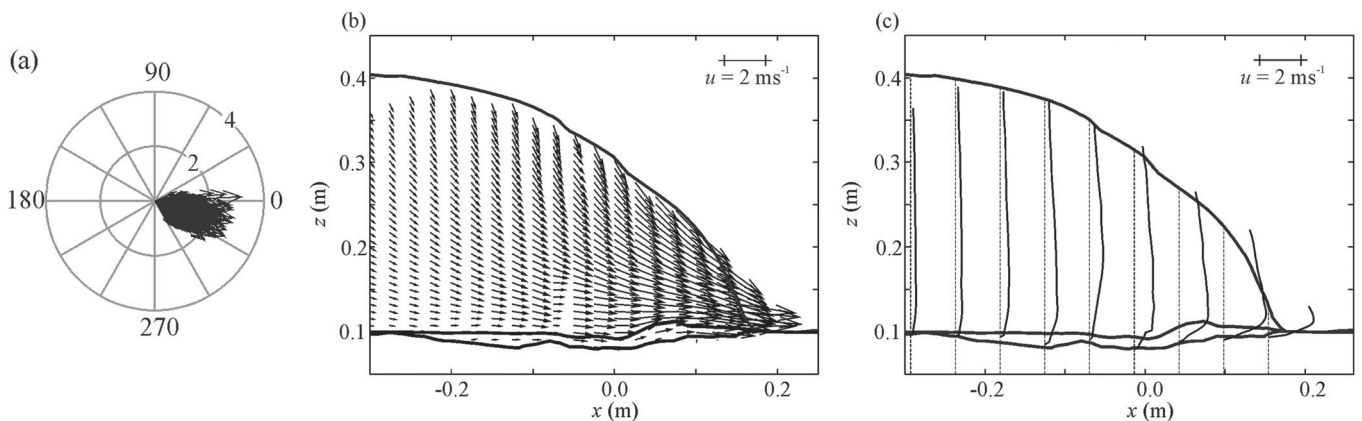


Figure 5 Experimental results at $t = 0.3 \text{ s}$: (a) polar plot of velocities (m s^{-1}), (b) measured velocity field, (c) profiles of horizontal velocity component

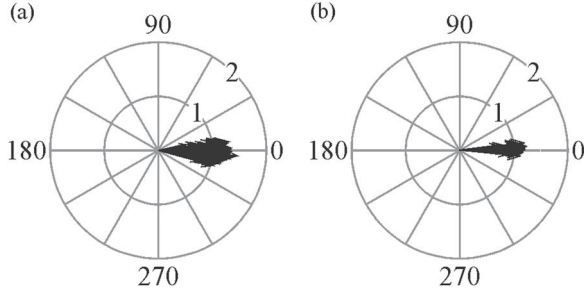


Figure 6 Polar plot of velocities (m s^{-1}) at (a) $t = 0.7 \text{ s}$ and (b) $t = 2.0 \text{ s}$

3.2 Shallow-water stage of dam-break flow

After 0.7 s , the polar plot of velocity vectors (Fig. 6) shows that the average direction of the velocities has become practically horizontal. Following Aleixo et al. (2011), beyond the non-dimensional time $t^* = t\sqrt{g/h_0} = 2.5$, the vertical velocity components become negligible. In the present case, this limit is reached for $t = 0.46 \text{ s}$, which corresponds to the non-dimensional time $t^* = 2.53$. The profiles of the horizontal velocity at $t = 0.7 \text{ s}$ and $t = 2 \text{ s}$ are shown in Fig. 7. We notice a good repeatability of the velocity profile in space and we can clearly distinguish the increasing velocity in the lower part, and the upper almost constant velocity. Figure 8 gives the evolution in time of the velocity profile at $x = 0 \text{ m}$, corresponding to the initial location of the removed gate. Again, it can be observed that the velocity profile inside the clear water layer (between the levels z_w and $z_{b,up}$) is practically uniform from $t = 0.7 \text{ s}$, i.e. greater than the limit of 0.46 s , corresponding to the time when horizontal velocity components clearly predominate. This is in line with previous observations, e.g. by Spinewine and Capart (2013). The magnitude of the velocity at this location is around 1.1 m s^{-1} , and remains almost constant during the main part of the event. The absolute value of horizontal velocity $u = 1.1 \text{ m s}^{-1}$ corresponds to a non-dimensional velocity $u^* = u/\sqrt{gh_0} = 0.62$, which is completely in accordance with the results proposed by Aleixo et al. (2011) and the Ritter solution.

However, looking closer to the moving sediment layer (between the levels $z_{b,up}$ and $z_{b,low}$ and just above the level $z_{b,up}$), similarly to the observations by Sumer et al. (1996) in

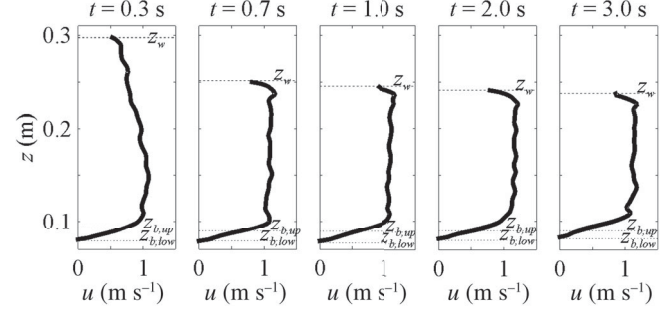


Figure 8 Horizontal-velocity profiles at different times at $x = 0 \text{ m}$. The free-surface and the limits of the moving sediment layer are indicated with dashed lines

steady flow cases, a log-law can be detected in the lower part of the water column and in the upper part of the sediment layer. Figure 9 shows the logarithmic profiles of the horizontal velocity components for times $t = 0.7 \text{ s}$, 1.0 s , 2.0 s and 3.0 s compared with logarithmic regression line computed from:

$$u = u_* \left(\frac{1}{\kappa} \ln \frac{z - z_{b,low} - \Delta z}{k_s} + B \right) = \frac{u_*}{\kappa} \ln (z - z_{b,low} - \Delta z) + u_* \left(B - \frac{1}{\kappa} \ln k_s \right) \quad (4)$$

where u_*/κ is the slope of the line from which we can extract the value of the shear velocity (u_* in Table 2). The Δz in Eq. (4) is introduced in a way similar to the Δz proposed by Sumer et al. (1996) as the theoretical level where the logarithmic law ends asymptotically to a zero value. The value of Δz is the one giving the best linear regression in Eq. (4) for the measured values of the velocity closest to the upper limit of the mobile bed layer $z_{b,up}$, considering at least eight measured points. Due to the transient conditions and the progressive mobilization of the sediment layer, this value of Δz evolves in time as well as the lower limit $z_{b,low}$. The shear velocity u_* is then used to calculate the Shield's parameter (Eq. (3)). At the beginning of the dam break flow, the shear stress is higher due to high unsteadiness of the flow. All the calculated values for the four considered instants are summarized in Table 2.

In Fig. 9, we also notice that in the lower part of the sediment layer, the velocity distribution deviates from the log-law.

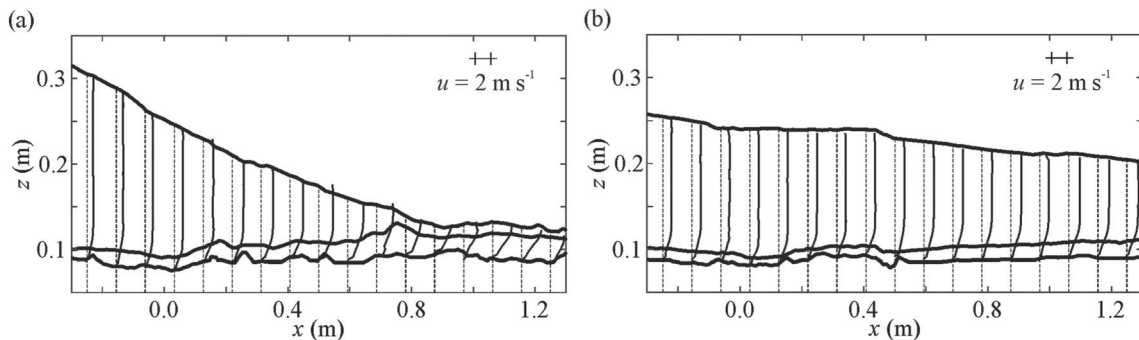


Figure 7 Distribution of the horizontal velocity component at (a) $t = 0.7 \text{ s}$ and (b) $t = 2.0 \text{ s}$

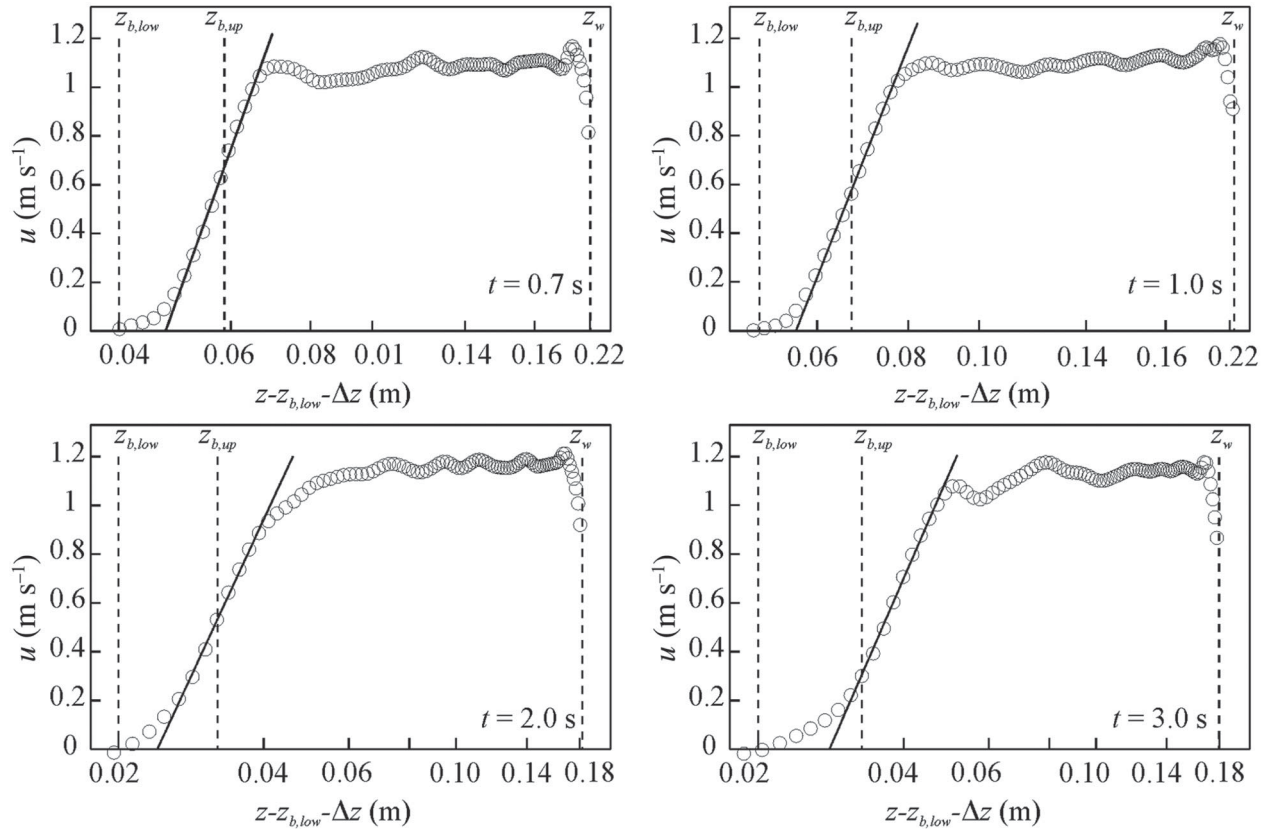


Figure 9 Semi-logarithmic plot of horizontal velocity for different times at $x = 0$ m. The limits of the moving sediment layer are indicated with dashed lines

Table 2 Evolution of the variables needed in the velocity distribution study and the consequent calculation of shear velocity and Shield's parameter

Time (s)	$z_{b,up}$ (m)	$z_{b,low}$ (m)	Δz (m)	u_* (m s ⁻¹)	θ (-)
0.0	0.010	0.010			
0.7	0.090	0.071	-0.04	1.26	57.26
1.0	0.089	0.072	-0.05	1.32	62.95
2.0	0.091	0.079	-0.02	0.74	19.91
3.0	0.091	0.078	-0.02	0.79	22.61

This was similarly observed by Sumer et al. (1996), as reproduced in Fig. 1b. However, this differs from the observations by Spinewine and Capart (2013) who detected linear velocity profiles in the sediment layer.

Finally, within the main part of the clear water layer the profile of the velocity is constant. Such a constant velocity profile above a semi-logarithmic profile is characteristic of the phenomenon of the fluid vein contraction and was also detected also by Spinewine and Capart (2013). This behaviour is explained by the fact that a dam-break wave travelling over a saturated but uncovered bed does not present a completely developed boundary layer since the beginning but rather a progressively developing boundary layer. It can indeed be observed that the log-law progressively develops into the clear water layer from the bottom, featuring the progressive production of turbulence

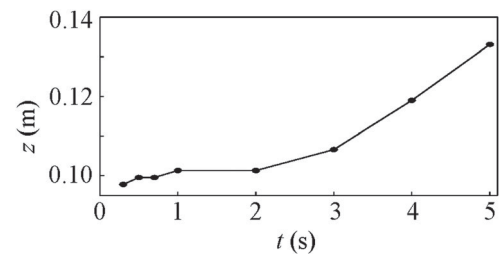


Figure 10 Position of the highest limit z of the semi-logarithmic velocity profile measured at the gate section ($x = 0$). Some examples of the limits of the semi-logarithmic profiles are shown in Fig. 9

from the bed roughness. But in the part of the clear-water layer not yet reached by this turbulence production the velocity is nearly uniform. For the first 5 s (non-dimensional time $t^* = 27.46$) of the experiment it is possible to follow the evolution of the velocity logarithmic profiles by tracking the position of the upper limit of this logarithmic part (Fig. 10). It can be observed that the position of this upper limit first slowly evolves and then, after the initial phase of flow, progressively invades the water column at a faster rate.

4 Conclusion

New dam-break flow experiments over a mobile bed made of coarse uniform sand were conducted with a special focus

on the velocity distribution. Using a non-intrusive PIV technique, the velocity profiles could be measured both in the upper clear-water layer and in the moving sediment layer. The measurements showed that in the clear-water layer the velocity distribution is quasi uniform, as described by some authors for unsteady flow over mobile bed. But, close to the bed and in the upper part of the sediment layer a log-law velocity profile develops, as already identified by some authors over mobile beds but only in steady-flow conditions.

The general investigation of the velocity field also allows two principal stages of the dam-break flow to be distinguished: at the beginning the vertical velocity components cannot be neglected, but after 0.7 s (corresponding to non-dimensional time $t^* = 2.53$) the average direction of the velocities has become horizontal and the assumptions of 1D shallow water flow can be applied.

More detailed measurements, with an increased spatial resolution, are required to verify the evolution of the parameter Δz in case of dam-break flow, and to further investigate the lower part of the sediment transport layer to see if a power-law profile develops as suggested by Sumer et al. (1996). Also, more experiments in different flow conditions will be performed in the future to confirm the present observations.

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Supplemental data

Supplemental data for this article can be accessed <https://orcid.org/10.1080/00221686.2018.1444677>.

Notation

θ	=	Shield's parameter (–)
κ	=	von Kármán constant ($\kappa = 0.40$)
ρ	=	water density (kg m^{-3})
ρ_s	=	sediment density (kg m^{-3})
ν	=	kinematic viscosity ($\text{m}^2 \text{s}^{-1}$)
B	=	integral constant for dam break flow (–)
B_s	=	integral constant for smooth boundaries (–)
B_r	=	integral constant for rough boundaries (–)
d_s	=	sediment diameter (m)
g	=	gravity acceleration (m s^{-2})
h	=	water depth (m)

h_0	=	initial water depth in the reservoir upstream the gate (m)
k_s	=	equivalent grain roughness (m)
L	=	total length of the channel (m)
t	=	time (s)
t^*	=	non-dimensional time (–)
u	=	velocity component in the x direction (m s^{-1})
u^*	=	non-dimensional velocity (–)
u_*	=	friction velocity (m s^{-1})
x	=	position along the horizontal axis (m)
z	=	position along the vertical axis (m)
z_w	=	water surface level (m)
$z_{b,up}$	=	level of moving sediment (m)
$z_{b,low}$	=	level of the non-mobile bed (m)
Δz	=	theoretical level where the logarithmic law ends asymptotically to a zero value (m)

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