Coherent structure and particle turbulence interaction in suspended sediment-laden laboratory open-channel flows

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Abstract: In order to simulate fine sediment dynamics over an armored bed in a river during the passage of a flood wave, quasi-instantaneous profiles of velocity and sediment concentration were taken simultaneously and co-located using acoustic Doppler and imaging methods. Flow visualization and PTV measurements were made in parallel. Systematically higher friction velocities were observed in accelerating flow than in decelerating flow for comparable mean flow velocities. This indicates that the same change of relative submergence generates different flow dynamics in both flow ranges. In the final phase of the accelerating flow range, fine sediment suspension from the bed started in bursts and rapidly created nearly stationary ripples. Vortices shedding from the ripple crests produced most of the sediment suspension in the form of events, making suspension intermittent. Due to the ripple structure, high sediment suspension continued to occur during the decelerating flow even though the flow velocity decreased.

Keywords: fine sediment, suspension, accelerating and decelerating flow, acoustic Doppler methods, PTV (Particle Tracking Velocimetry).

1. INTRODUCTION

Understanding the dynamics of unsteady sediment-laden water flows and characterizing the velocity of suspended particles is essential for enhancing the predictive accuracy of sediment transport and its impact on physical, chemical, biological and ecological processes in the water column. Although bed load transport has been the subject of much research, less attention has been paid to the suspension of sediment under unsteady flow. Nezu & Nakagawa (1993) found that the log law is still valid in unsteady open-channel flows. This was confirmed by Afzalimehr & Anctil (2000) who studied spatially accelerating shear velocity in gravel-bed channels. Nezu & Nakagawa (1993) estimated the friction velocity $u^*$ and the wall shear stress $\rho u^* v^2$ as a function of time. In oscillatory closed-channel flows, Jensen & Sumer (1989) and Akhavan et al. (1991) observed that the mean velocity obeyed the log law distribution, except at the very early phases of the acceleration range and the late phases of the deceleration range. By measuring the turbulence structure over a smooth wall in unsteady depth-varying open-channel flows, Nezu et al. (1997) established that in the rising stage, the wall shear stress attains its maximum ahead of the flow depth. They also detected hysteresis loop properties of velocity and turbulence profiles in unsteady open-channel flows.

Suspension of sediment particles occurs when the local bottom shear stress exceeds the critical value. Initiation of sediment motion which occurs due to unsteady turbulent water flows is an important aspect of river and coastal engineering. Under steady flow conditions, suspension may be caused by secondary currents (Nezu & Nakagawa 1993) or coherent structures (Nezu & Nakagawa 1993, Cellino & Lemmin 2004, Nezu 2005). Sediment transport studies in unsteady flow (Sutter et al. 2001) indicate a hysteresis loop in sediment concentration, similar to that observed in turbulence intensities by Nezu et al. (1997). All these studies demonstrate that determining the structure of turbulence in unsteady flow is important in order to advance the understanding of sediment flux development.

This study focuses on some hydrodynamic aspects of unsteady open-channel flows without and with sediment transport using high spatial and temporal resolution velocity profile data in order investigate sediment flux development. First, the instruments used and the experimental procedure will be briefly described. The results will be discussed thereafter.
2. EXPERIMENTAL SET-UP

The measurements were carried out in a glass-walled open-channel which is 17 m long and has a rectangular cross section 0.6 m wide and 0.8 m deep. The bottom is covered with a 0.1 m thick gravel layer (size range 3 to 8 mm; $D_{50} = 5.5$ mm). The channel is operated in closed circuit mode. Discharge is modified by changing the rotational speed of the pump by computer. A shallow weir at the end of the channel controls the water level. The water level in the channel is measured with four ultrasonic limnimeters spaced along the channel axis. The bed of the channel is horizontal.

2.1. Acoustic Doppler particle flux profiling in unsteady flow

The Acoustic Doppler Velocity Profiler (ADVP; Lhermitte & Lemmin 1994) measures 3D instantaneous velocity profiles. By combining acoustic backscattered intensity profiles which can be inverted into particle concentration after calibration (Shen & Lemmin 1996, Hurther et al. 2007) with the ADVP, a particle flux profiler which was developed at our laboratory determines the 3D velocity field and the suspended particle concentration field co-located in the same scattering volumes of the profile, even at high particle concentrations (Shen & Lemmin 1996).

The emitter and the receivers of the ADVP are placed in a water-filled housing which is installed above the water surface, and which slightly touches the flow. The ADVP follows the surface in the depth-varying region of the hydrograph (Figure 1) by a computer-controlled system. ADVP profiling was carried out on the centerline of the channel about 15 m from the entrance where turbulence is well developed. A 1 cm thick layer of the water column near the water surface was omitted from the analysis, because the flow in this layer is slightly perturbed by the instrument.

![Figure 1. Schematics of the ADVP instrument in unsteady flow](image)

2.2. Experimental procedure

The hydrograph for the experiment consists of 5 parts. The flow is first maintained at the base discharge with $h = h_b$ for 30 s, followed by the rising stage of the unsteady flow where the discharge is linearly increased. The peak discharge is then kept steady at $h = h_p$ for 60 s. Thereafter the discharge is linearly decreased during the falling stage of the unsteady flow to the initial base discharge. Two different accelerating and decelerating times, 30 s and 60 s, were investigated. The discharge, ADVP, and limnimeter data are simultaneously recorded during the hydrograph. In order to obtain reliable data during the unsteady phase, the same experiment is repeated several times and the data are averaged. Since the experiment is computer controlled, the deviations between individual experimental runs were less than 3%.

Table 1 gives the range of the discharge, water depth, and Reynolds number at the base and peak flow of the hydrograph investigated here. In order to investigate the suspension of fine sediment particles, a layer of sand with $D_{50} = 0.16$ mm was spread on top of the coarse bed on a surface area of the channel extending about 1 m upstream from the location of the ADVP. For the present study, this layer was thick enough to fully cover the coarse bed by about 4 mm and thus smoothed out bed roughness. No sediment transport occurred under the initial conditions. The acoustic measurements were complemented by simultaneously taking high-speed videos with a light sheet (30 cm long and 8 - 10 mm thick) in the center of the channel, just upstream of the ADVP location. White light was passed through a series of optical fibers aligned along the light sheet axis. A cylindrical lens focused the light
into a light sheet with homogeneous light distribution. The velocity vectors within this sheet will be determined.

Table 1  Range of variations of discharge, water depth and Reynolds number

<table>
<thead>
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<th></th>
<th>Base</th>
<th>Peak</th>
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<tbody>
<tr>
<td>Pump discharge Q</td>
<td>(l sec⁻¹)</td>
<td>10</td>
</tr>
<tr>
<td>Water depth</td>
<td>c(cm)</td>
<td>12</td>
</tr>
<tr>
<td>Reynolds Number</td>
<td></td>
<td>1.5 × 10⁴</td>
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Two sets of experiments were carried out. In the first set, no fine sediment was placed on the rough bed. During these experiments, hydrogen bubbles were generated as flow tracers for the ADVP measurements (Blanckaert & Lemmin 2006). In the second set of experiments, fine sediment was added to the bed as described above and no hydrogen bubbles were produced. In these experiments, only sediment particles served as tracers for the ADVP measurements. Thus, only the flow field which activates sediment suspension is documented in these experiments. All ADVP data were de-aliased (Franca & Lemmin 2006) and de-noised (Blanckaert & Lemmin 2006) to improve data quality.

Even though the pump discharge is varied linearly in the course of the accelerating and decelerating ranges, water depth changes non-linearly throughout these periods. When the pump discharge was kept constant at peak flow, water depth still slowly increased and did not reach steady state. The discrepancy between the variation of the pump discharge and the observed water level over time indicates that flow adjustment over the rough bed takes place along the channel.

3. RESULTS

3.1. Velocity measurements

From the instantaneous velocity profile data measured by the ADVP instrument for twelve identical runs, mean profiles over ten individual profiles are calculated for each run. Subsequently, the corresponding mean profiles are averaged over all twelve runs, thus subdividing the whole data set into a series of time slices for the following analysis. In this paper, results of unsteady accelerating and decelerating flow ranges for two different accelerating and decelerating time scales were compared.

It was found that during the unsteady flow, all mean velocity profiles followed a logarithmic law in the inner layer (Bagherimiyab & Lemmin 2010). Figures 2 and 3 show the distribution of longitudinal velocity against depth variation \( \frac{\Delta h}{\Delta h_p} = \frac{(h - h_b)}{(h_p - h_b)} \) for five depth levels representative of the wall region, the intermediate region and the outer region. These figures indicate that the velocity increases more in the accelerating range than in the decelerating range at the same flow depth for both the 30 s and the 60 s hydrographs, forming a loop, as found by Nezu et al. (1997). The loop is wider for the 30 s hydrograph because of the greater unsteadiness. The spreading of the curves for the different levels in the profiles indicates that velocity profiles in accelerating ranges have much steeper angles than in the decelerating ones. Initially, velocity in the accelerating range increases steeply, then more slowly, particularly for the 30 s hydrograph. The decrease in the decelerating range is smoother. The velocity profiles in the 30 s and 60 s decelerating ranges are similar, but in the accelerating ranges they are quite different. This is the effect of unsteadiness which is greater in the 30 s hydrograph than in the 60 s one. A similar behavior is seen for the friction velocity which was determined using the logarithmic mean velocity profile method in the inner layer for all time slices (Figure 4). The peak of the friction velocity is attained before the maximum of the water level, as was found by Nezu et al. (1997). Again, friction velocity forms a loop and changes differently in the accelerating and decelerating flow ranges. Friction velocity \( u^* \) does not return to the initial value of the base flow after the decelerating ranges, because water depth continues to slowly decrease past the end of the decelerating ranges and reaches base flow depth much later (Figure 4). This was already seen in the velocity profiles above. It decreased linearly in the decelerating flow range and is similar for the 30 s and 60 s hydrographs. However, it shows a more complex relationship in the accelerating flow. The large difference between the two hydrographs in the unsteady accelerating ranges shows
the effect of the change in unsteadiness. For comparable mean velocities in the accelerating and decelerating flow ranges, friction velocities are different. Even though flow velocities come to the same value at the peak flow end of the unsteady flow ranges as seen in Figures 2 and 3, friction velocities at the end of the unsteady flow range in the 30 s hydrograph are smaller than those in the 60 s one. This shows that mean flow adjustment during the peak flow phase is different in the two hydrographs.

Figure 2. Longitudinal velocity at different depths for accelerating and decelerating time = 30 s

Figure 3. Longitudinal velocity at different depths for accelerating and decelerating time = 60 s

Figure 4. Friction velocity $u^*$ distribution for the unsteady ranges of 30 s and 60 s hydrographs
3.2. Sediment suspension

For the present analysis, the same 30 s hydrograph was repeated six times and the data from the six experiments were superimposed for all time slices in order to generate an average data set. Note that during this set of experiments no other flow tracers were in the water. Therefore, the data represent only sediment suspension dynamics. Results of the particle velocity profiles covering the accelerating range and the steady peak flow range are presented in Figure 5. No data were obtained with the ADVP during the base flow and the initial accelerating flow, because no particles were suspended and therefore no flow tracers were in the water. Figure 5 shows a rapid increase in the velocity profile near the bottom all along this section of the hydrograph. In the upper part of the water column, particle velocity rapidly falls to zero.

![Figure 5. Mean particle velocities during the unsteady flow range](image)

Figure 5 presents maximum particle velocities in each time slice profile against the depth variation, covering the whole range of this part of the hydrograph. They were extracted from the above figure in order to present the suspension dynamics during the accelerating and peak flow ranges of the hydrograph. This shows that initially particle velocity slowly increases until “a” (corresponding to the 15 s in Figure 5) and then rapidly until “b” (corresponding to 40 s in Figure 5). Thereafter, it remains nearly constant. A comparison of the results in Figures 2 and 6 shows that the rate of change of flow velocities is quite different from that of particle velocities, particularly in the accelerating ranges, but also in the peak steady range of the hydrograph.

![Figure 6. Maximum particle velocities during the accelerating flow range](image)

3.3 Video imaging

In low sediment concentration flows which typically occur during the beginning of accelerating flow, acoustic methods may have difficulty determining the sediment particle concentration correctly, due to
the relatively low number of particles inside the acoustic beam (Bagherimiyab et al. 2009). Therefore, in this study, video image recording was synchronized with the ADVP measurements in order to visualize the sediment suspension process during the hydrograph and thereby confirm the above ADVP measurements. Previously (Bagherimiyab et al. 2010), we had shown from video images that sediment transport is initially limited to saltating particles in the near bottom layer in accelerating flow. In the later phase of the accelerating range and during peak flow, sediment transport near the bed increased and particles were also carried higher into the water column.

During the late phase of the accelerating range of the hydrograph, ripples formed rapidly on the bed. The ripples influenced the sediment suspension dynamics. These bed forms grew within a few seconds to a length of about 0.6 water depth and to a height of about 5 to 10 mm. Sediment particles rolled up the ramp of the ripple and were ejected into the water column by vortex shedding from the ripple crest. They then propagated in the form of a burst, as seen in Figure 7. Ripples remained in place when the flow was decelerated down to base flow. Thus, ripples control sediment suspension into the water column over an extended period of the hydrograph.

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**Figure 7.** Example of PTV results during the final phase of the accelerating flow range. Arrows indicate particle velocity vectors

In this study, the Particle Tracing Velocimetry (PTV) technique (Muste et al. 2008) was used to calculate particle velocity and analyze the dynamics of suspended sediment. In Figure 7, two images of velocity vectors are shown which were taken at a 80 Hz frame rate during the end part of accelerating flow range. The time interval between these two images is 0.05 s. As seen in Figure 7, suspension is nearly uniform in a shallow layer above the bed (about 2 cm high). Particle transport remained strong in the near bottom layer, in agreement with the ADVP observations shown in Figure 5. Suspension into the water column above occurs in burst-like events. In this flow, turbulence intensity and the strength of the burst events are not sufficient to suspend these particles over the full water depth. Several bursts can be identified in Figure 7a and bursts are strongest just behind the ripple crest on the left.

**Figure 8.** Mean particle velocities in six positions of images
Figure 8 shows the mean particle velocities in six representative positions in the horizontal direction of the images. These profiles are the average of over 2000 images. The profile form is similar to that measured by the ADVP (Bagherimiyab et al. 2010). Velocities are similar in all positions with a slight trend of increase from right (above the ripple) to left (in the trough).

In Figure 9 are shown the sediment concentration profiles at the same positions, calculated from the averaged particle density for those positions. The highest concentration is found in the position where ripples are formed (x = 10.2 cm) with a strong gradient towards the trough. This confirms the burst structure pattern seen in Figure 7 with strongest bursts near the ripple crests. The mean backscattering profiles recorded with the ADVP for the same section of the hydrograph are similar to the one at x = 10.2 cm (Bagherimiyab et al. 2010). However, the ADVP cannot reproduce the details seen in the analysis of the video images. Therefore, a combination of the two methods greatly enhances the understanding of the underlying processes.

Figure 9. Particle concentrations in the same position as Figure 8

Figure 10. Bed form formation during the final phase of the accelerating flow range indicating the positions shown in Figs. 8 and 9

4. CONCLUSION

Accelerating and decelerating flow over a rough bottom was investigated experimentally. Even though the discharge was changed linearly at the same rate in both unsteady flow ranges, the change of relative submergence was not linear and it was different in the two flow ranges, resulting in considerable differences in the flow dynamics. During the accelerating range, both mean velocity and friction velocity initially increased strongly and less thereafter. Unsteadiness in the accelerating stage for accelerating and decelerating ranges in the 30 s hydrograph is greater than in the 60 s one. During decelerating flow, only one slope and thus one relationship between bed shear velocity and mean flow velocity was found throughout the unsteady flow range. Furthermore, systematically higher friction velocities were observed in accelerating flow than in decelerating flow for comparable mean flow velocities. This indicates that the same change of relative submergence generates different flow dynamics during the accelerating and decelerating flow ranges. The hysteresis loop found by Nezu et al. (1997) was confirmed.

The investigation of unsteady open-channel flow over a coarse bed with a fine sediment layer was limited to the observation of dynamics in velocities produced by suspended sediment particles serving as a tracer. No fine particle transport occurred during the initial phase of the unsteady flow, and particle suspension was progressively intensified during the unsteady flow range. The ADVP is sensitive enough to capture clean signals for the time history of sediment suspension. Optical methods which were applied simultaneously helped to verify and to interpret the ADVP data and to visualize the
physical processes leading to suspension. The combination of acoustical and optical methods provides for an ideal approach to study suspension in unsteady flow. An event structure in particle suspension is seen by both methods. When the flow had sufficiently accelerated, fine sediment was suspended in bursts into the intermediate layers of the water column and at the same time, rapidly created nearly stationary ripples during the final phase of the accelerating flow range. Sediment particles were not suspended into the upper 40% of the water column. Vortices shedding from the ripple crests produced most of the sediment suspension in the form of events, making suspension intermittent. High sediment suspension continued to occur during the decelerating flow even though the flow velocity decreased. This phenomenon is attributed to the presence of ripples which remained in place during this phase of the hydrograph. Hydraulic parameters, such as water depth, mean velocity time development and profile form were not affected by the presence of fine sediment particles. The results indicate that sediment suspension in unsteady flow is controlled by the same large scale turbulence processes as in steady flow as was discussed in the introduction.

The results of this study have verified existing concepts of unsteady flow. However, new and detailed results made possible by combining the ADVP and imaging techniques provide valuable insight into the dynamics of unsteady flow and of fine sediment suspension under unsteady flow conditions which were previously not possible.

5. ACKNOWLEDGMENTS

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6. REFERENCES


