On using acoustic profiling to study bottom boundary layer dynamics in unsteady sediment-laden open-channel flow

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Abstract: *Sediment transport dynamics in the bottom boundary layer of unsteady open-channel flows directly impacts on processes in the water column. To study the bottom boundary layer interactions requires observations of the bed, flow and sediment movement. Recently developed acoustic techniques can provide measurements of these three parameters at high temporal-spatial resolution. Here we employ acoustics to provide quasi-instantaneous simultaneous and collocated profile measurements of (i) the three orthogonal components of flow using phase coherent techniques, and (ii) suspended sediment particles using acoustic backscatter. This allows for an in depth investigation of bottom boundary layer physics in unsteady sediment-laden flow.*

Keywords: *unsteady flow, fine sediment, resuspension, ADVP.*

1. INTRODUCTION

Suspended sediment transport in rivers directly impacts on the physical and biogeochemical processes in the water column. While some progress in understanding sediment fluxes has been made under uniform flow conditions [1], [2], much less is known about unsteady flows, even though flows in rivers and open channels are unsteady most of the time. Unsteady flows may lead to initiation of sediment resuspension, generate bedforms and bed topography changes. Therefore, in order to capture the essential dynamics of unsteady flow, instrumentation is required which can simultaneously measure hydrodynamics, sediment concentration in the whole water column and bed morphology with sufficient spatial and temporal resolution to resolve turbulent scales. Acoustic methods are well suited to fulfilling these requirements.

Acoustic Backscattering Systems (ABS) allow capturing the Doppler phase angle and the intensity of the backscattered signal. The phase angle has been used in Acoustic Doppler Velocity Profilers (ADVP; [3]) and was extended to full 3 velocity component instruments [4], capable of resolving turbulence scales in space and time. They were further improved in the hardware [5] and software [6], [7], [8] domain and are today reliable instruments.

Backscattered intensity can be inverted into particle size and concentration after calibration [9], [10]. An iterative inversion method has been proposed [11] and an explicit inversion method is also available [12]. However both methods suffer from errors propagating through the profile.

This problem was overcome by using backscattered and forward scattered profile signals, thus providing attenuation compensation even in high particle concentrations as long as multiple scattering is avoided. Integrating this approach into the existing ADVP, a particle flux profiler was developed [13] which simultaneously determined the 3-axis velocity field and the suspended particle concentration field in the same scattering volumes of the profile.

The inconvenience of this solution (requiring forward scattering measurements) for field applications of the system was overcome by a new approach based on the exploitation of backscattering intensity at two (or more) emitted frequencies [14], [15]. The advantage of this solution is that two relatively close frequencies (such as 1.25 Mhz and 2 Mhz) completely resolve the concentration field of fine particles typically found in hydraulic applications. This frequency range can easily be handled by a single transducer. Therefore, a two frequency backscattering intensity profiler can be integrated in the existing ADVP and provides a particle flux profiler which is unlimited in its application in laboratory and field studies in rivers, open channels, oceans and lakes. Again, 3-axis velocity and particle concentration profile information can be obtained simultaneously, co-located in the same scattering volumes within the profile, resolving turbulence scales in time and space.

The location of the bed is easily extracted from ADVP or particle flux profilers by the strong echo of the backscattering intensity or from the zero velocity in the Doppler phase.

In the present study, the acoustic two-frequency particle flux profiler has been applied to unsteady turbulent open-channel flow. The objective is to determine whether the instrument is capable of detecting the onset of fine sediment resuspension.

2. EXPERIMENTAL SET-UP AND PROCEDURE

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 was covered with a 0.1 m thick gravel layer (D_{50} = 5.5 mm). ADVP profiling was carried out on the centerline of the channel about 15 m. A bifrequency (1.25 Mhz and 2 Mhz) system was used.

The hydrograph for the experiment consisted of a base discharge, followed by the rising stage of the unsteady flow where the discharge was linearly increased over a period of 30 s. Table 1 gives the hydraulic parameters at the beginning and the end of the hydrograph. No sediment resuspension occurred during the initial phase of the unsteady flow.

In order to investigate resuspension of fine sediments, the coarse bed was covered with an about 2 mm thick layer of sand with D_{50} = 0.16 mm on a surface area extending about 1m upstream from the location of the ADVP. The acoustic measurements were complemented by simultaneously collected high-speed videos in the center of the channel, just upstream of the ADVP location. Only a narrow slot (about 1 cm in transversal depth) of the flow in the center of the channel was illuminated.

Table 1 Range of variation of hydraulic parameters at the beginning and the end of the unsteady flow range

		Beginning	End
Pump discharge Q	(l $\sec^{-1}$)	16	40
Water depth	(cm)	10.6	15
Mean velocity	(cm $\sec^{-1}$)	35.8	58.46
Reynolds Number		8.20×10^4	2.038×10^4

RESULTS

The water level change in the unsteady range is not linear, even though the discharge increased linearly. This indicates a deformation of the wave progressing through the channel. The unsteady flow range was divided into a sequence of 100 mean profiles. During the unsteady flow, all profiles followed a logarithmic law in the inner layer, documented by examples in Fig. 1 where data values up to the velocity maximum are included. Therefore mean flow dynamics of unsteady flow are comparable to steady flow conditions.

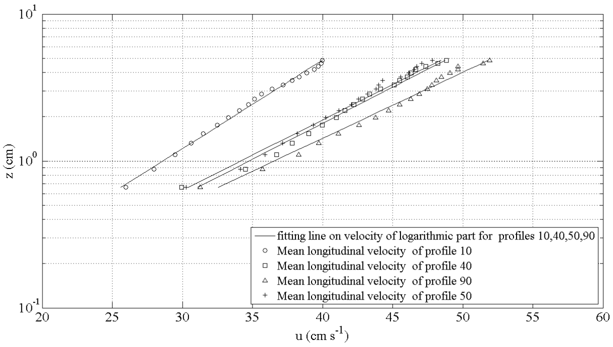

Fig. 1 Examples of mean longitudinal velocity profiles for the unsteady range of the hydrograph.

Backscattered intensity was extracted from the same data from which the velocity components discussed above were obtained. Results are plotted in Fig. 2 for the unsteady flow range. Initially, no particle transport occurred. Video images indicate that saltation starts around profile 30, followed by ejection events around profile 50 and more general resuspension after profile 70. The ADVP detects the different resuspension phases and shows that during the unsteady flow range, particles are progressively resuspended to greater height which reaches up to about $0.3h$ (h = waterdepth). Note that resuspension occurs in individual events even during the final phase of the unsteady flow. This agrees with the video images (Fig. 3). From Fig. 3 it can be seen that even at the end of the unsteady flow range, the particle concentration in suspension is low. The ADVP can track these low concentrations.

Total velocity vectors, combining the horizontal, u, and the vertical, w, velocity vectors for the range of profiles 80 to 90 (Fig. 2) were plotted in Fig. 4. The range of profiles 80 to 90 is characterized by two events of strong backscattering intensity. In the near bottom boundary layer, velocity vectors are mainly upwards oriented which can explain the resuspension of fine sediment during this period.

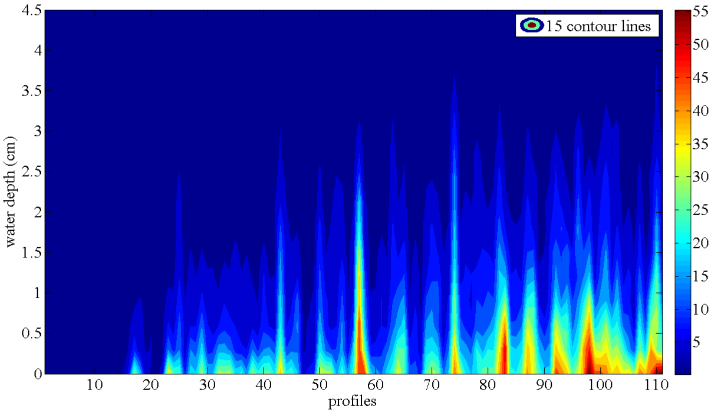

Figure 2 Backscattering intensity during the unsteady flow range

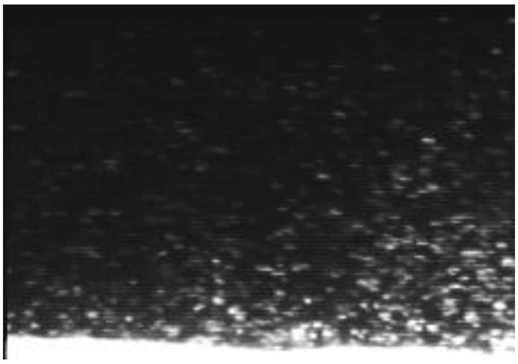

Fig. 3 Video image during the final phase of the unsteady flow. Image height is 5 cm

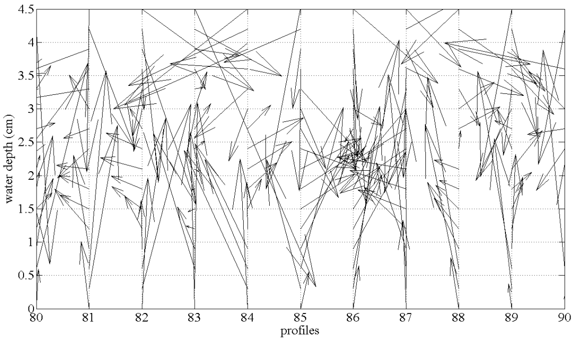

Fig. 4 Total velocity vectors in the near bottom boundary layer for the range of profiles 80 to 90 shown in Fig. 2.

4. CONCLUSIONS

In this study, unsteady open-channel flow over a coarse bed with a fine sediment layer was investigated. Acoustic techniques were successfully applied to determine detailed current velocity and backscatter intensity profiles. Particle resuspension progressively intensified during the unsteady flow range. Even though the concentration of suspended particles was too low to reliably invert the backscattered intensity signal into particle concentration, the ADVP is sensitive enough to capture clean signals for the time history of the initial phase of sediment resuspension.

The combination of acoustical and optical methods provides for an ideal approach in studying resuspension in unsteady flow. An event structure in resuspension is seen by both methods. These results and further experiments which will be carried out refining the approach outlined in this paper provide valuable insight into the dynamics of fine sediment resuspension under unsteady flow conditions.

5. ACKNOWLEDGEMENT

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