ULTRASONIC MEASUREMENTS OF INSTANTANEOUS VELOCITY AND SUSPENDED CONCENTRATION IN OPEN-CHANNEL FLOW

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Keywords: open-channel flow, sediment transport, velocity measurement, concentration measurement, burst cycle

ABSTRACT

The Acoustic Particle Flux Profiler (APFP) was developed and assembled at the Laboratoire de Recherches Hydrauliques (LRH) at the Polytechnic School of Lausanne (EPFL), Switzerland.

This non-intrusive instrument permits to measure simultaneously the instantaneous 2-dimensional velocity and the suspended concentration in experimental suspension flows in open channels.

The 2-dimensional velocity was obtained by measuring the Doppler frequency of the backscattered echo. On the same time, by measuring the back-scattered and forward-scattered echo intensity, the instantaneous suspended concentration was also obtained. For the velocity measurement a calibration was not necessary whereas for the concentration a mean suspended concentration measurement by suction had to be performed.

The visual comparison between the instantaneous velocity and suspended concentration shows a strong correlation. The vertical fluctuating velocity seems to be responsible of both erosion and deposition. To try to quantify this phenomenon, the APFP instrument was applied to the analysis of the mutual influence between suspended sediments and coherent flow structures. These structures were studied by using the 4-quadrant analysis. The measurements were carried out in particle laden, open-channel flows. They clearly show the predominance of the ejection and sweep phases that are part of a burst cycle.

The analysis further demonstrates the importance of the ejection and sweep phases in sediment resuspension and transport. Ejections pick up the sediment at the bed and carry it up through the water column close to the surface. It is shown that while ejections and sweeps are in near equilibrium in the near bottom layer, ejections clearly dominate in the remaining water column. The implications of these results for sediment transport dynamics are discussed.

1. THE APFP INSTRUMENT

The APFP (Acoustic Particle Flux Profiler) instrument was developed at the Hydraulic Laboratory of the Ecole Polytechnique Fédérale de Lausanne (Switzerland) by Dr. U. Lemmin (*Lhermitte* and *Lemmin*, 1994, *Lemmin* and *Rolland*, 1997, *Rolland* and *Lemmin*, 1997), Dr. T. Rolland (*Rolland*, 1994) and W.C. Shen (*Shen*, 1997).

This instrument has been set up to measure simultaneously the velocity and the suspended sediment concentration profiles (see *Shen*, 1997). The transducer below the bed and the tilted transducer measure the instantaneous velocity profiles in the same manner than the classical ultrasonic profiler (for example ADVP, *Rolland*, 1994). To measure the instantaneous suspended sediment concentration profiles the vertical transducers record alternatively the intensity of the ultrasonic echo coming from the targets in the water columns ensonified. *Shen* and *Lemmin*, 1996, showed that the local sediment concentration is proportional to the intensity of the ultrasonic echo.

2. THE EXPERIMENTS

Experiments were carried out in a highly turbulent subcritical flow. Details of the hydraulic conditions and the sediment characteristics for all three runs are given in Table 1. For the investigations into suspension flow, quartz-like sediment particles were gradually added to the flow until a thin (~3 mm of thickness) layer of sediments, remaining stable during the time of the experiments appeared on the bed of the channel. No bed forms were observed. The thickness of the bed sediment layer was sufficient to ensure particle deposition and resuspension at all times without completely eroding the sediment bed layer. No more sediment was added from this moment onward because the capacity charge equilibrium condition was reached and the bottom roughness elements were completely covered with the sediments. The reference concentration c_{sa} was measured by a suction device under isokinetical conditions at the water depth y/h=0.05.

The instantaneous velocity and concentration profiles measured with the APFP instrument which will be discussed here, have been correlated and conditionally averaged to obtain information about ejection and sweep events. Even though ejection and sweep events are defined in the generation region, $5 < yu_* / \nu < 70$, the same conditional averaging technique will be applied over the whole water depth.

run	sand	Q	h	u_c	U	S_b	$Re*10^5$	u_*
		m^3/s	m	m/s	m/s	%	--	m/s
Q50S01	I	0.057	0.12	0.930	0.792	0.100	2.712	0.039
Q50S01	II	0.058	0.12	0.916	0.801	0.100	2.743	0.039

run	sand	ρ_s	d_{50}	v_{ss}	C_s	c_{sa}
		kg/m^3	mm	mm/s	kg/m^3	kg/m^3
Q50S01	I	2650	0.135	12.0	3.61	39.33
Q50S01	II	2650	0.230	21.0	1.57	21.31

Table 1: Summary of experimental conditions

run: name of the run; sand: name of the sand; Q: flow discharge
B: 0.60 m width; h: flow depth; u_c: maximum velocity
U: depth-averaged velocity; S_b: bed slope
Re: Reynolds number; u_*: shear velocity; ρ_s: sediment density (quartz sand)
d_{50}: nominal particle diameter; v_{ss}: settling velocity
C_s: depth-averaged concentration; c_{sa}: reference concentration at $y = a = 0.05h$

From the parameters given in Table 1, the sediment laden flows are in the lower range of transition flows. A value of $y^+ = 100$ corresponds to $y \approx 2.5\,mm$. Only the lowest points of our measured profiles fall into this range. From *Nakagawa* and *Nezu* (Fig. 8.12; 1993) it is obvious that the roughness effect on the coherent structure dynamics is already diminished above that height. Due to the noise constraints mentioned above, these lowest points have to be interpreted with some caution.

3. VISUAL CORRELATION BETWEEN VELOCITY AND SUSPENDED CONCENTRATION

The APFP instrument measures simultaneously, and continuously, the velocity and the suspended concentration of the flow at the centerline of the measuring section. Interesting observations can already be made by visually comparing the instantaneous profiles of velocity and concentration (Fig. 1). In fact, if these profiles are plotted against time, it becomes possible to observe the temporal evolution of the measured velocity and concentration and particularly their correlation.

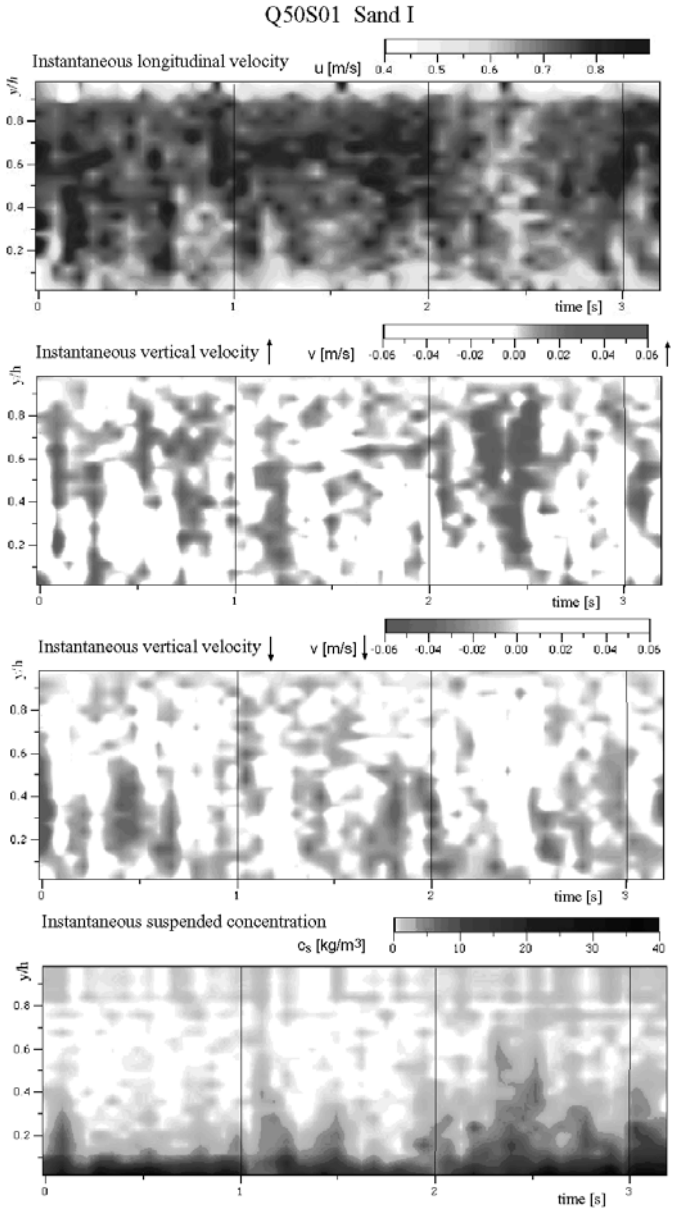

Fig. 1 Instantaneous velocity and concentration profiles

In Fig. 1, an example of the velocity and concentration profiles measured for run Q50S01 (with sand I) is plotted. In order to present sufficient detail, a typical segment measured during three seconds has been presented. Both the longitudinal and vertical velocities are given with the local long-term mean values being subtracted. Note that the flow field is essentially composed of a sequence of correlated high and low longitudinal and vertical velocities showing a certain regularity of the motion of the flow. Superimposed on the velocity pattern, the simultaneously measured instantaneous suspended concentration is shown.

Close to the bed, *y/h*<0.2, the high concentration layer is particularly evident. Although this region is thin and always located close to the bed, in certain cases its thickness approaches and temporarily exceeds *y/h*≈0.3. Several events in Fig. 1 make evident that a sediment “cloud” is generated very close to the bed and is subsequently carried into the outer layer, even up to the surface layer with little change in particle concentration. During these events, the existence of a correlation between the sediment clouds and events of strong instantaneous velocity is already obvious by comparing the two series in this example. Note that the instantaneous velocity vector in these events is always composed of the two components. In the following we will quantify aspects of the statistical correlation between the two signals.

4. RESULTS OF THE 4-QUADRANT ANALYSIS

4.1 FILTRATION OF THE INSTANTANEOUS VELOCITY

The instantaneous (horizontal *u*, vertical *v*) as well as the Reynolds stress ($u'v'$) and the sediment flux ($c_s'v'$) have been filtered to compute the contribution coming from each of the four quadrants, (Fig. 2). The filtration has been performed by introducing the discriminating variable, $I_H^i(y,t)$, defined as follows:

$$I_H^i(y,t) = \begin{cases} 1, \text{ if } \left[u'(y,t),\ v'(y,t)\right] \text{ is in quadrant i and if } \left|u'(y,t)\cdot v'(y,t)\right| > H\sqrt{\overline{u'^2}}\sqrt{\overline{v'^2}} \\ 0, \text{ otherwise} \end{cases} \quad (1)$$

where H is called the hole size and it is used as a threshold for weakest velocities.

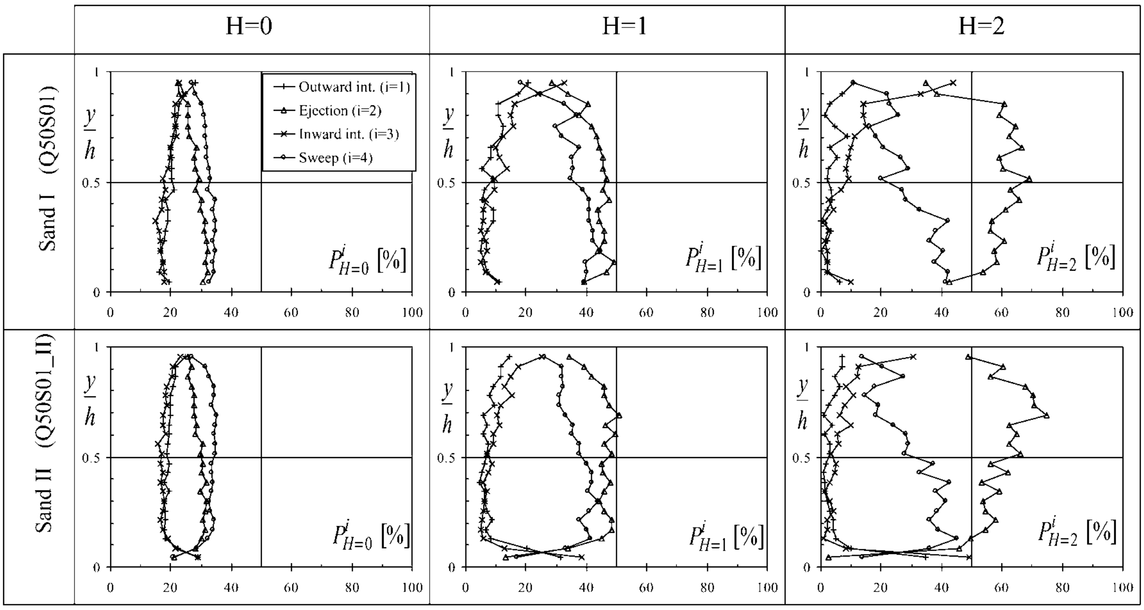

Fig. 2: Event occurrence probability for clear-water and suspension flows (sand I and sand II) for different hole sizes, *H*.

The computation of the occurrence probability of each quadrant has been performed three times by first taking all the events (*H*=0), and then progressively eliminating the weaker ones (*H*=1,2) respectively. For *H*=0, the highest probabilities are found for the sweep events, $P_{H=0}^{i=4}$, followed by the ejection ones, $P_{H=0}^{i=2}$. The other events, namely the outward, $P_{H=0}^{i=1}$, and the inward, $P^{i=3}_{H=0}$ interactions, have the same but rather small occurrence probability. By increasing the hole size value, *H*=1, i.e. eliminating the weakest events, the probability of observing an ejection, $P^{i=2}_{H=1}$, increases rapidly, becoming slightly larger than that of the sweep one, $P^{i=4}_{H=1}$.

For *H*=2, i.e. taking into account only strong events, the ejection occurrence probability dominates the profile and increases towards the surface with a maximum value near the surface. The highest sweep occurrence probability has been detected close to the bed at *y/h*≈0.1; at that level, its value is identical to that of the ejection probability but then it decreases rapidly towards the water surface. The probability of observing outward and inward interactions rapidly becomes negligible with increasing the hole-size value.

4.2 FILTRATION OF THE REYNOLDS STRESS

The filtration of the Reynolds-stress profiles, $\overline{u'v'}(y)$, into the four quadrants provides information about the contribution coming from each event. This is particularly interesting because the Reynolds stress is directly related to the beginning of the motion of sediment particles on the bed and their subsequent suspension in the flow. In Fig. 3 the filtered and the unfiltered Reynolds-stress profiles are shown. Again, the contribution to the Reynolds stress coming from the ejection event, $\overline{u'v'}^{i=2}_{H=0}(y)$, is the most important one for both suspension flows. The second most important contribution comes from the sweep event, $\overline{u'v'}^{i=4}_{H=0}(y)$. The outward (i=1) and the inward interaction (i=3) make similar but small negative contributions.

The contribution coming from the ejection event, i=2, is about 80%, while the sweep-event one is about 60% for both suspension flows. *Nakagawa* and *Nezu*, 1977, p. 120, *Nakagawa* and *Nezu*, 1981 and *Lu* and *Willmarth*, 1973, p. 497 obtained similar results investigating the contribution to the Reynolds stress in clear water flows close to the bed. The largest contribution comes from the ejections and sweeps, showing again the importance of these events also in suspension flows. The strong influence of these events on the erosion, deposition and suspension of sediments is confirmed.

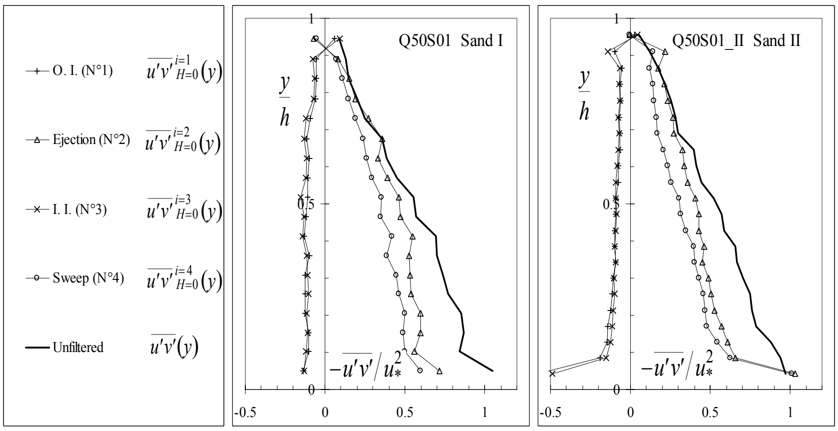

Fig. 3: Filtered Reynolds-stress profiles

4.3 FILTRATION OF THE SEDIMENT FLUX

The sediment flux, $\overline{c_s'v'}$, represents the upward flux of sediment generated by the fluctuating vertical velocity which compensates the downward flux of sediment caused by the gravitational settling, $\overline{c_s} \cdot v_{ss}$, where v_{ss} is the settling velocity. The solution of the equation obtained by imposing the equilibrium of these two fluxes leads to the Rouse equation expressing the vertical mean concentration distribution.

If the ejection event is the principal contributor to the upward fluctuating velocities and to the Reynolds stress, as was shown by the filtration of velocities, then the sediment flux should also be primarily generated by the ejection event. To verify this hypothesis, the filtration of the sediment flux into the $u'v'$-plane has been performed. In Fig. 4, the filtered and the unfiltered sediment-flux profiles are shown. As expected, the largest contribution to the sediment flux comes from the ejection events, $\overline{c_s'v'}_{H=0}^{i=2}(y)$. The second largest contribution comes from the sweep event, $\overline{c_s'v'}_{H=0}^{i=4}(y)$. In this case the sediment flux is directed towards the bed. The contributions coming from the outward (i=1) and inward (i=3) interactions are once again negligible.

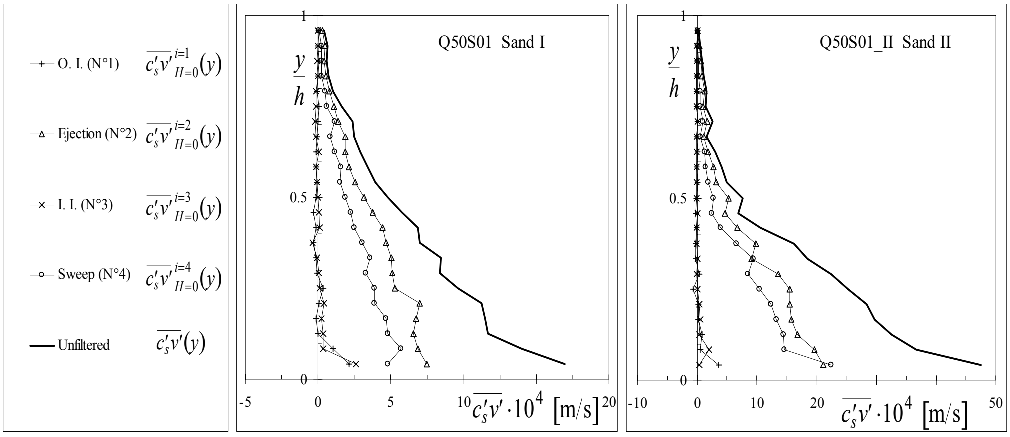

Fig. 4: Filtered sediment-flux profiles

5. CONCLUSIONS

The analysis of this study has been carried out by filtering the instantaneous longitudinal and vertical velocity profiles as well as the suspended concentration profiles according to the well-known four quadrant $u'v'$-plane decomposition.

For all parameters investigated, the ejection events are observed most frequently always followed by the sweep events. The contributions by the remaining two events, namely the outward and the inward interactions are insignificant and can be ignored in the analysis. This discrepancy becomes even more pronounced when the weakest events are filtered out. It is seen that the further one moves up in the water column the more important become strong ejection events. The occurrence probability profiles of each event measured in the two suspension flows are similar. This means that the statistical distribution of the events in the suspension flow is not affected by the size range of the suspended sediments used in the present study. We have also investigated clear water flow under the same hydraulic conditions and found very similar results as for the suspension flows (*Cellino*, 1998). Obviously, the presence of particles in suspension does not alter the dynamics of coherent structures.

For the Reynolds stress, $\overline{u'v'}$, it is evident that the ejection event contributes the most to the unfiltered Reynolds stress. The second most important contribution comes from the sweep event. Thus, the critical Reynolds stress, normally used as a threshold level for the motion of the particles on the bed, could be effectively replaced by an equivalent critical ejection level.

The sediment flux, $\overline{c_s'v'}$, (representing the upward flux of sediment that compensates the downward one, $\overline{c}_s v_{ss}$, due to the gravitational settling), is mainly generated by the ejection events. The contribution of the sweep events, directed towards the bed and always smaller than the ejection ones, can not be neglected.

Visual inspection of simultaneous time series of the instantaneous velocities and suspended concentration profiles confirms the importance of the ejection and sweep events on the suspended transport mechanics (*Cellino*, 1998). The appearance of sediment clouds in the upper water column, eroded from the bed is always found to be directly correlated to a strong upward vertical fluctuating velocity and a strong ejection event in particular. On the other hand, these sediment clouds disappear in the presence of a vertical downward fluctuating velocity or a sweep event.

In summary, our analysis has clearly shown that the burst cycle plays an important role in sediment suspension mechanics. In particular, the ejection event represents the main cause for the erosion and/or the suspension of particles, whereas the sweep event can be associated with the sediment deposition.

ACKNOWLEDGMENTS

This research was funded by the Swiss National Science Foundation grant 20-39495.93. We are grateful for the support.

REFERENCES

Cellino, M. (1998). *Experimental Study of Suspension Flow in Open Channel*, Doctoral dissertation No. 1824, Ecole Polytechnique Fédérale, Lausanne, Suisse.

Lemmin, U. and **Rolland, T.** (1997). *Acoustic Velocity Profiler for Laboratory and Field Studies*, J. Hydr. Engr., vol. 123, N°. 12.

Lhermitte, R. and **Lemmin, U.** (1994). *Open-Channel Flow and Turbulence Measurements by High-Resolution Doppler Sonar*, J. Atm. Oceanic Tech., vol. 11, N°5, pp. 1295-1308.

Lu, S. S. and **Willmarth, W. W.** (1973). *Measurements of the structure of the Reynolds stress in a turbulent boundary layer*, J. Fluid Mech., vol. 60, part 3, pp. 481-511.

Nakagawa, H. and **Nezu, I.** (1977). *Prediction of the contributions to the Reynolds stress from bursting events in open-channel flows*, J. Fluid Mech., vol. 80, part 1, pp. 99-128.

Nakagawa, H. and **Nezu, I.** (1981). *Structure of space-time correlations of bursting phenomena in an open-channel flow*, J. Fluid Mech., vol. 104, pp. 1-43.

Nakagawa, H. and **Nezu, I.** (1993). *Turbulence in open-channel flows*, IAHR Monograph. A.A. Balkema, Rotterdam, the Netherlands.

Rolland, T. (1994). *Developpement d'une instrumentation Doppler ultrasonore adaptée a l'étude hydraulique de la turbulence dans les canaux*, These de doctorat N° 1281, Ecole Polytechnique Fédérale, Lausanne.

Rolland, T. and **Lemmin, U.** (1997). *A two-component acoustic velocity profiles for use in turbulent open-channel flow*. J. Hydr. Res., vol. 35, N°4.

Shen, C. (1997). *An acoustic instantaneous particle flux profiler for turbulent flow*, These de doctorat N°1630, Ecole Polytechnique Fédérale, Lausanne

Shen, W. and **Lemmin, U.** (1996). "Ultrasonic measurements of suspended sediments. A concentration profiling system with attenuation compensation." Meas. Sci. Tech., vol. 7, pp. 1191-1194.