Coupling acoustic devices for monitoring combined sewer network sediment deposits

I. Carnacina and F. Larrarte

ABSTRACT

Combined sewer networks display some unique features that are not easily reproducible in the laboratory and have yet to be well understood. The transport of organic and mobile sediments, present in large quantities despite the use of optimal design practices, dramatically changes sewer flow patterns and the interaction between flow and sediment. To understand both the flow patterns and transport features of these complex environments, it is therefore necessary to install instrumentation *in situ*. For this paper, two distinct acoustic techniques were coupled in order to measure both the sediment interface and velocity. For this purpose, a 2 MHz rotating head acoustic profiler and a 10 MHz acoustic Doppler velocimeter (ADV) were jointly installed to survey the position of sediment deposits and measure velocity patterns. Results were compared with measurements recorded in different environments, where both coarser and finer soft deposits were present. These results typically showed good agreement between the interfaces detected using velocity measurements on coarse deposits, while the presence of soft deposits demonstrated the need for coupling measurements techniques that can correctly assess the sediment interface.

Key words | acoustic Doppler velocimeter, acoustic profiler, coupled measurements, sediment interface

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INTRODUCTION

Sediment transport processes over an urban drainage basin result in large quantities of sediment deposits accumulating within the connected combined sewer network. These deposits are responsible for changes in flow patterns and large pollutant loads entering water bodies. Due to the environmental constraints typical of combined sewer networks, the type and characteristics of such deposits remain uncertain and are topics of continuous study and analysis. As an example, Crabtree (1989) proposed a classification system for combined sewer sediment deposits (based on particle size properties, origin, nature, and location within the sewer network) referred to as A to E deposits. According to this system, type A deposits are characterized by a large amount of mineral particles of a coarser size that typically form a compact layer. As types A and B are characterized by similar properties they will be referred to as a single type (A) for the sake of simplicity. In contrast, type C deposits are characterized by a higher organic content and finer particle sizes; they tend to form a soft unstructured layer on top of type A deposits; this layer can be easily eroded by a relatively low shear stress compared to type A deposits. Owing to the heterogeneity of particle size, density and organic content, particles may be transported as either bed load or suspended sediment. When coarser, type A sediment deposits are the only ones observed along the bottom invert, suspended sediment concentrations C are indicated by a slight vertical gradient trough the column, shown in Figure 1(a), and driven by the three-dimensional flow pattern typical of narrow channels (Larrarte 2008). In a site 500 m upstream of the site DA, analysis carried out by Larrarte (2013) also shows that the vertical gradient of total suspended solid concentration is almost negligible, when sediment deposits are not present, on the bottom. In this figure, z is the vertical axis from the bottom invert and u the longitudinal flow direction.

Under certain conditions however, *in situ* observations have revealed high suspended sediment concentrations on the top of type C sediment (Wohrle & Brombach 1991), which are often followed by a spike in concentration (Ahyerre *et al.* 2001). This distinct transition is typical of

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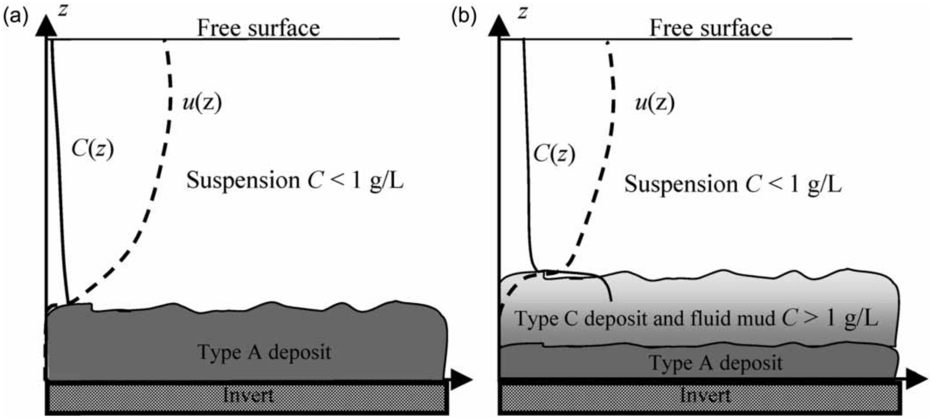

Figure 1 | Typical total suspended solid patterns observed within combined sewer networks: (a) coarse sediment deposits (type A); (b) presence of a high concentration layer (type C) and the lutocline definition.

the presence of a lutocline (McAnally *et al.* 2007a, b) and may be regarded as the interface of a highly concentrated mud and a less concentrated, mainly fluid mud; see Figure 1(b). These types of muddy sediment deposits are characterized by a weak interface (Ashley & Verbanck 1996), flocculation processes and a fine particle size. However, these types of deposits present characteristics that are far from being understood and still necessitate further analysis. In fact, these deposits cannot be detected on a point gauge without altering their structure and morphology and without changing the conditions under which concentration and velocity measurements are performed.

The complexity of processes occurring in combined sewer networks has led to the successful development and adaption of instrumentation typically used in rivers and marine environments, for example, acoustic Doppler velocimeters (ADV) and acoustic Doppler profilers (Le Barbu & Larrarte 2010). Among the other devices, acoustic instrumentation is well suited to working in high-turbidity and confined environments (Bertrand-Krajewski & Gibello 2008; Romanova *et al.* 2012).

For this paper, we conducted experiments in order to improve the knowledge of deposits present within sewer networks. A new ultrasonic surveying technique, based on an acoustic profiler bathymetry, was introduced, in addition to developing a new data algorithm. To understand the potential stratification of solids and their interfaces, an accurate flow assessment is critical. A simultaneous measurement of both the flow velocity and turbulence was conducted with an ADV. This paper will present the experimental sites and set-up used to carry out this experimental research. The data analysis process will be explained and the experimental results discussed. Afterwards, the sediment interface position will be assessed by means of acoustic measurements. We will also show how different types of deposits and their various characteristics can affect the signal detected by acoustic instrumentation. The interface location, as detected with an acoustic profiler, will be compared with the ADV acoustic response in distinct environments: laboratory, sandy and muddy sediments.

EXPERIMENTAL FRAMEWORK

Experimental sites

Surveys have been conducted as part of an extensive collaborative program involving both the Geotechnical, Water and Risk Department of the French Institute of Sciences and Technology for Transport, Development and Networks (IFSTTAR) and the Nantes Metropolitan government.

Laboratory tests were performed at IFSTTAR's hydraulic facility. A rectangular recirculating hydraulic channel was used to test the devices. This testing facility is 40 cm wide, 3 m long, 40 cm deep and composed of Plexiglas. *In situ* experiments were carried out in Nantes' municipal combined sewer network. Two experimental sites were distinguished, namely the Allée de l'Erdre combined sewer (AE in Figure 2) and the Duchesse Anne combined sewer (DA in Figure 2).

Both sites have a composite egg-shaped cross-section with a single lateral sidewalk. The DA site has a total catchment area of 4.11 km^2, a population equivalent of 200,000 equivalent inhabitants (Eq/Ab), 60 km of combined sewer network length and an estimated permeable area equal to 30% of the total land area. Average slope in the invert

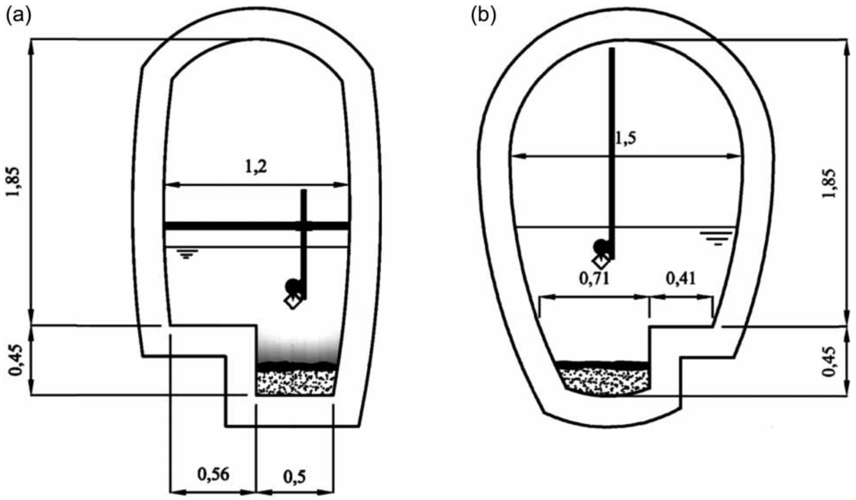

Figure 2 | Invert diagram with notation: (a) 'AE' and (b) 'DA' (dimensions shown in meters).

cross-section where measurements were taken is $S = 0.0003$. The AE site has a catchment area of 1.41 km^2, a population equivalent of 15,000 Eq/Ab, 20 km of combined sewer length and an estimated permeable area of also 30%. In the section where measurements took place, the average slope is $S = 0.0012$.The choice of these two sites was based on various flow characteristics, as well as on sediment deposit typologies and the suspended sediment characteristics. Besides the acoustic instrumentation used for these experiments, most experimental equipment was produced by the IFSTTAR Laboratory and Nantes metropolitan offices.

Apparatus and measurement execution

Marine Electronics pipe profiler 1512 USB emitting a signal frequency of 2 MHz was used to survey the sewer invert. This profiler records the intensity of the backscattered signal at a 1 Hz frequency. The backscattered signal intensity depends on particle size, particle distribution and the vertical suspended solid concentration profile. The acoustic profiler is delivered with two sensors that measure probe pitch and roll to an accuracy of 0.1°. A side-looking Sontek ADV was attached directly below the acoustic profiler; see Figures 3(a) and 3(b). The ADV emits a 10 MHz signal at a sampling frequency of 25 Hz and a control volume of 0.5 cm^3. The distance to the control volume from the central emitter was approximately 10 cm. The ADV orientation was adjusted in accordance with the profiler sensors; however, before each measurement, the operator reduced both tilt and rolling angles to $<1°$. Figure 3 provides a detailed view of the acoustic profiler and ADV in their working configuration. In this figure, z_r is the distance

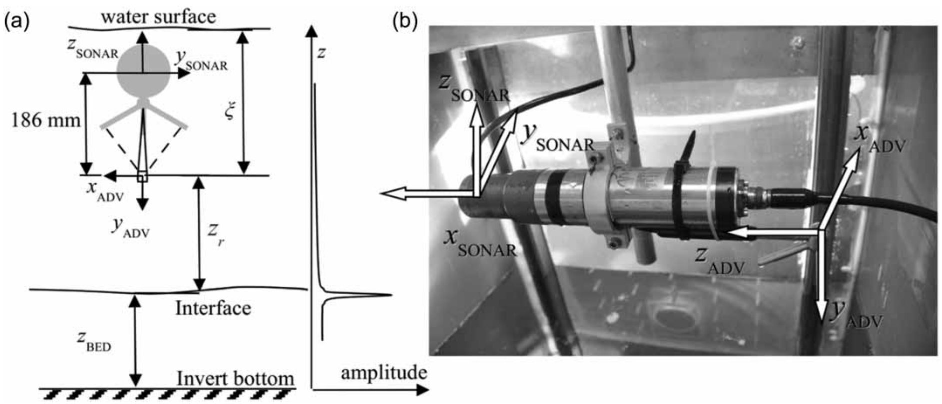

Figure 3 | (a) ADV and acoustic profiler diagram (note that the ADV is attached under the cylindrical body of the acoustic profiler in order to reduce its disturbance) and (b) close-up of the acoustic profiler and ADV installation under laboratory conditions.

from the center of the ADV control volume to the sediment interface, as detected with the profiler; ξ is the distance between the center of the ADV control volume and the free surface, z_{BED} is the position of the sediment detected with the profiler from the invert; and x_{ADV} and y_{ADV} are the longitudinal and transverse axes respectively, in reference to the original ADV configuration, z_{SONAR} and y_{SONAR} are the vertical and transverse distances from the center of the acoustic profiler. The distance between the center of the acoustic profiler reference and the center of the ADV control volume was carefully measured in the laboratory by comparing both the acoustic profiler and ADV backscattered signal. In this particular set-up, the distance between the two centers is 186 mm.

To prevent clogging and signal disturbance, the side-looking ADV was positioned with its y-axis pointing downward, as shown in Figures 3(a) and 3(b), and the axes were successively rotated according to information provided by the profiler tilt and rotation sensors. The z_{ADV} axis corresponds to the x-axis of the rotated configuration, hence the vertical velocity w_{ADV} corresponds to the longitudinal channel velocity u.

Moreover, for each experimental run, the head of the ADV was fixed downstream of the acoustic profiler head, so as to minimize any disturbance of the acoustic profiler head on flow measurements, whereas the influence of the ADV body on sediment measurements was negligible. For each transverse section, the probe center was set at the free surface over the invert center, as shown in Figures 2(a) and 2(b), in order to minimize flow and sediment morphology disturbance as well as to reduce the effect of secondary currents on flow measurements. The acoustic profiler backscattered signal was recorded for each sampled section: velocity measurements were successively carried out for 180 seconds with a 25 Hz sampling frequency. After each acoustic profiler and ADV measurement sequence, the probes were lowered by 5–10 cm and the same steps were repeated until the ADV control volume was sufficiently immersed in the sediments. The instrumentation was gradually moved downstream along the rails installed in the network and each new section was then surveyed again using the same steps.

Data treatment

The responses of both the ADV and acoustic profiler are expected to differ between the two sites and should be affected by the differences in suspended sediment concentration and typology. The algorithms produced by Marine Electronics effectively capture the rectangular channel geometry under laboratory conditions and, more generally, in the presence of compacted material, i.e. the concrete surface of the invert and sand, whether tested or observed under both laboratory and *in situ* conditions. Figure 3(a) also shows the typical signal recorded by the acoustic profiler for compacted and sandy sediment. The signal travels through the water column without reflection. When the signal emitted by the acoustic profiler hits an interface, that is, steep change in water density (lutocline) or sediment deposits, most of the signal is reflected back to the acoustic profiler, showing a large peak in the backscattered signal.

This set of algorithms was unable, however, to unequivocally detect the interface of soft deposits and lutocline; hence it was necessary to introduce an alternative procedure to treat the raw backscattered signal. Different definitions of the interface, detected by acoustic altimeters, have been introduced by Bell & Thorne (1997), Gallagher *et al.* (1996) and Webb & Vincent (1999). Using an approach similar to that introduced by Green & Black (1999), the sediment interface detected by the acoustic profiler was defined as the distance from the probe where the backscatter signal shows the highest gradient.

To reduce the possible noise generated by the presence of a large backscatter present in the flow and improve interface detection, a Gaussian filter with a 5 mm variance (equal to the instrument variance) along with a unitary norm were used to filter each beam at different angles

$$f'(R) = f{*}g(R) = \int_{r=0}^{r=R} f(R)\cdot g(\varsigma - R)\,\mathrm{d}R \tag{1}$$

where f is the original signal, g a kernel function, ς the lag variable, and f' the filtered signal. This digital filtration seeks to remove the spikes from the original signal as they may trigger false detections. The interface was then calculated using Equation (2)

$$R^{j}_{\mathrm{int}} = \max\left[\frac{\mathrm{d}f'(R^{j})}{\mathrm{d}z_{\mathrm{SONAR}}}\right] \quad \text{for} \quad 0 < j < 400 \tag{2}$$

in which j represents the jth beam of 0.9° width detected by the acoustic profiler, and R the distance from the center of the profiler.

Applying results obtained from the previous processing step, the position h of the ADV control volume was measured from the interface defined by R_{int} in Equation (2), measured at $j = 200$, i.e. the vertical distance from the control volume to the interface.

RESULTS

Interface definition and detection

During dry weather periods, DA sewer sediment deposits are mainly composed of sandy (type A) deposits. Dry weather conditions correspond herein to the time period during which cumulative precipitation per day is <0.25 mm for at least 7 consecutive days. On the other hand, the AE site typically shows, starting from the bottom, an initial sand layer, a concentrated mud layer, and in general a soft mud or highly concentrated suspension whose thickness can broadly vary with the channel's longitudinal direction. Despite the higher slope observed in AE, dry weather period speeds are comparably slower than those observed in DA, as will be discussed in the next section.

The signal emitted by the acoustic profiler was recorded and filtered according to Equations (1) and (2). Figure 4 presents the survey results obtained with the profiler.

In Figure 4, the dots show the actual surveyed sections, while the surface was obtained by interpolating the points detected with the profiler. The figure also shows the egg-shaped cross-section for reference. The first site, AE, shown in Figure 4(a), is characterized by a large amount of sediment deposits ($z_{\text{BED}} > 400$ mm). The three-dimensional sediment deposit morphology increases when traveling upstream and covers the sidewalk (located at $z_{\text{BED}} = 450$ mm) after $x < -150$ cm. Not surprisingly, the operator literally felt the presence of soft deposits on the sidewalk while moving the equipment. In general, the deposits were more substantial further from the sidewalk, owing to both the three-dimensional flow field typical of the sewer section (Larrarte 2006) and the additional turbulence generated by the sidewalk corner. On the other hand, site DA, shown in Figure 4(b), exhibits total deposits from a few centimeters to a total absence, as observed in the middle of the three surveyed sections.

Figure 5 shows the backscattered amplitude for the two sites at the various surveyed sections. This figure indicates the signal measured vertically under the acoustic profiler (i.e. $y_{\text{SONAR}} = 0$ mm). Whenever the acoustic signal hits a sediment particle, part of it is reflected, another part absorbed, and yet another part keeps traveling through the sediments. On the whole, the signal presents an initial section, as represented by the water phase with low sediment concentration, in which the amplitude is nearly constant. As the acoustic signal approaches the sediment interface, it is reflected backwards and the backscattered signal amplitude increases with a steeper gradient. As part of the signal travels through the sediment, the backscattered signal amplitude is damped and the gradient yields negative values until most of the signal is absorbed by the rest of the sediment deposit. A first major feature distinguishing the two types of sediment can also be observed. The amplitude gradient signature typical of sand deposits is always characterized by the presence of a single peak, after which the signal is totally absorbed and dissipated; see Figure 5(b). In contrast, the mud displays multiple gradient peaks, which seem to reveal the presence of a softer layer near the interface with the flow of purely suspended solids. This layer might be sufficiently consolidated to reflect part of the signal but not so consolidated that it completely absorbs the signal emitted by the acoustic profiler.

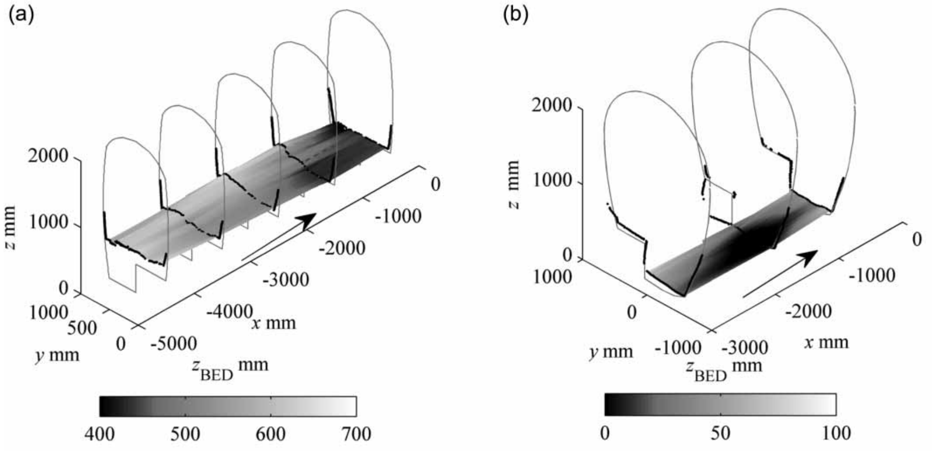

Figure 4 | Acoustic profiler sediment deposits from the invert bottom ($z_{\text{BED}} = 0$ mm) for (a) AE and (b) DA. The dotted lines represent the actual surveyed section and the arrows indicate the flow direction. Gray shapes indicate the site's composite cross-section.

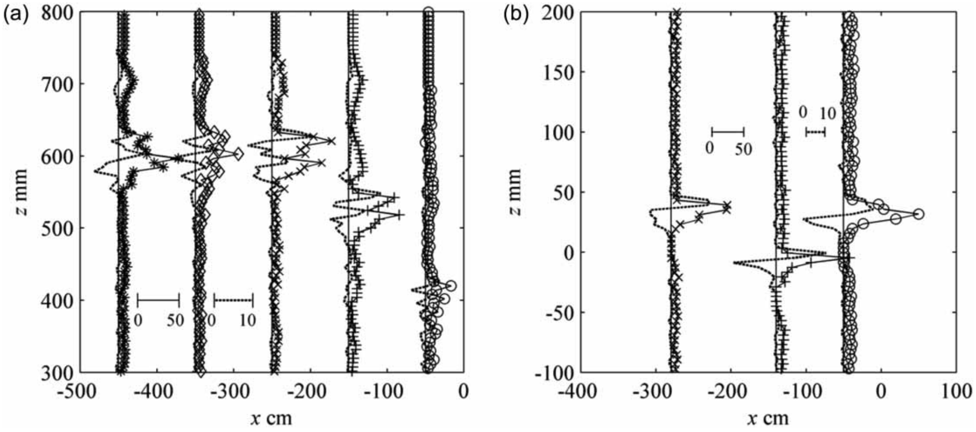

Figure 5 | Acoustic profiler backscattered signal (black lines, with counts) and signal gradient (dotted lines, counts/mm) for: (a) AE at $x = -50$ cm (o), $x = -150$ cm (+), $x = -250$ cm (×), $x = -350$ cm (◊), $x = -450$ cm (*); (b) DA at $x = -50$ cm (o), $x = -140$ cm (+); x) $x = -280$ cm (×).

The first two sections between $-100\text{ cm} < x < -150\text{ cm}$ of the AE site in Figure 5(a), where the sediment deposit is thinnest, are characterized by a low backscattered intensity that might reveal the presence of soft deposits. On the other hand, for $x = -250$ cm, i.e. on top of the dune, the backscattered signal is relatively more intense. These results are consistent with what was observed by Oms (2003) and demonstrate how troughs might be filled by soft unconsolidated type C deposits, while dune tops eroded and revealed more consolidated surfaces. Interface detection with just the maximum amplitude may indeed lead to an incorrect estimation, since two peaks may occur, as observed in the $x = -150$ mm case. In this instance, interface detection based on the steepest gradient recorded in the backscattered signal amplitude is used to highlight the sediment concentration spike observed in the lutocline and define a single interface above the two peaks. As opposed to the upstream deposits, the dune seems to be more consolidated with a more intense backscattered signal, as soft sediments might be removed from the dune. On the contrary, the DA site, in Figure 5(a), presents higher maximum backscattered intensities due to the coarser and more consolidated nature of deposits observed on the invert, i.e. type A. The maximum gradient at which the interface is detected exhibits a behavior comparable to that determined by the maximum backscattered amplitude. For instance, a solid and flat PVC tested under laboratory conditions results in a scaled backscattered signal amplitude gradient of 25 counts/mm. The maximum gradients recorded on coarser sediment deposits once again show higher values at the top of the dune for the AE site. The signal generally presents a steep jump in backscattered amplitude for the DA site, which facilitates distinguishing the solid deposit interface. These types of deposits also tend to be easily detected during manual surveys performed with a point gauge.

Comparison with ADV results

The ADV records a reflected signal, whose amplitude is proportional to sediment concentration. It is widely known in the literature that a minimum amount of particles needs to be detected by the probe in order to generate correct flow velocity measurements. Efforts have been made, however, to correlate the amplitude intensity with sediment concentration (Ha *et al.* 2009). Figure 6 shows the results obtained in three different environments: laboratory conditions, AE site, and DA site.

In Figure 6, only the longitudinal velocity u has been plotted. The signal amplitude S_{ADV} indicated herein corresponds to the amplitude recorded by beam 0, i.e. the one facing the current during the measurement sequence. Laboratory experiments were carried out to accurately calibrate the distance between the center of the ADV control volume and the center of the acoustic profiler, as well as to determine the ADV signal response when the control volume hits a solid boundary.

Laboratory experiments also show an average signal amplitude of 120 counts throughout the water column, with values that tend to drop from the free surface towards the bottom. The flow displayed small air bubbles generated by the pump systems. The ADV detects these small bubbles as backscatters instead of particles that are usually introduced to perform laboratory experiments with tap water. Due to the bubble buoyancy, a higher bubble concentration occurs near the water surface. A sudden jump at $h = 75$ mm

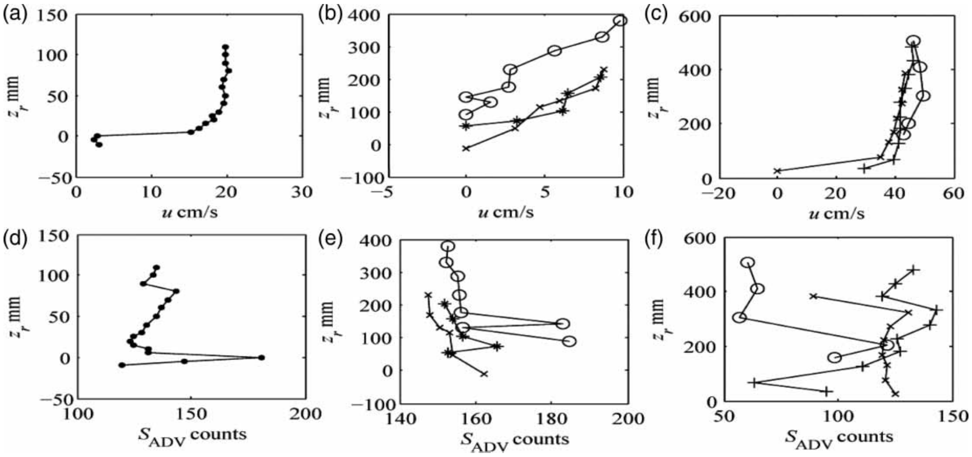

Figure 6 | Longitudinal velocity *u* recorded with the ADV for (a) laboratory conditions (•), (b) the AE site, and (c) the DA site; and an ADV single-beam recorded amplitude (counts) for (d) laboratory, (e) the AE site, and (f) the DA site (the ADV probe is located at different positions along the invert; see Figure 4 for symbol definition).

in signal amplitude, shown in Figure 5(d), is mainly due to bubble cleaning from the ADV probe. As the ADV control volume enters the bottom surface, the amplitude of the detected signal increases to a peak of 180 counts, which corresponds to the bottom surface. The longitudinal velocity profile follows the typical shape observed for narrow channels, with velocity damping near the free surface. It is important to note that the minimum velocity detected corresponds to the PVC bottom. Near the bottom however, interaction with the PVC surface creates a high level of noise, as reflected by the fact that part of the control volume lies inside the PVC bottom and the probe records more noise compared to the original signal.

The profile obtained by coupling the ADV with the profiler measurement suggests how the presence of soft deposits may affect the velocity recorded with the ADV. The DA site, shown in Figures 5(c) and 5(f), actually shows for the three surveyed sections a velocity profile similar to that observed in an open channel of similar shape (Larrarte 2006), where the maximum velocity sinks due to a secondary flow momentum exchange, which is typical of the three-dimensional nature of flow observed in a narrow channel. Signal amplitude is lower than that of the laboratory signal, most likely as a result of the low sediment concentration (around $C = 150$ mg/L) observed during the survey. For all three surveyed sections, the amplitude and velocity recorded seem to indicate that the ADV control volume never interacted with the sediment deposits. The AE site, on the other hand, is characterized by lower velocities, thus allowing for the presence of large sediment deposits ($u < 0.10$ m/s). Over the same section with observations of a more intense acoustic profiler backscattered signal and higher gradient ($x < -250$ cm), the velocity profiles show higher velocity adjacent to the interface and roughly constant amplitude values through the water column, thus indicating the near absence of interaction between the control volume and the sediments. The amplitude observed in this case reveals how a higher suspended solid concentration (around $C = 500$ mg/L) is detected by the backscattered amplitude, with relatively high values compared to DA. For the last upstream section, the amplitude registers two peaks quite far from the interface distinguished with the acoustic profiler. This finding also corresponds to a near-zero longitudinal velocity, underscoring the strong disturbance generated by the soft sediment deposits observed in this section. Moreover, concentration values above $C > 2{,}000$ mg/L were measured from vacuum-sampled wastewater (see Jaumouillie *et al.* (2002) for references to vacuum sampling operations) extracted at these depths. However, when the backscatter amplitude produced values comparable to those observed for $h > 200$ mm, the ADV was able to detect a longitudinal velocity of 3 cm/s; this observation indicates how the upper portion of the hyper-concentrated layer might be in motion and should therefore not be considered as part of sediment deposits, as detected according to the interface definition algorithm.

CONCLUSION

This paper has discussed the potential of an acoustic measurement that couples two distinct systems: an acoustic profiler and an ADV. Results have highlighted how the type of sediment can affect measurement quality and necessitate a new definition of the interface between sediment and flow, especially in the presence of type C deposits observed during *in situ* conditions. The comparison drawn between the signal observed with the profiler and with ADV confirms the presence of more highly unconsolidated deposits. These types of deposit clearly affect the responses of both the ADV and profiler signal compared to more consolidated sediment deposits. The velocity and signal amplitudes measured in soft deposit clearly indicate that the presence of a mud layer is characterized by extremely low velocity. However, the disturbance of soft deposits and fluid mud on the signal can be relatively high and further analysis is needed to understand the effects on acoustic measurements and their hydrodynamics.

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