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UNSTEADY TURBULENT VELOCITY PROFILING USING AN ARRAY OF TWO VECTRINO II PROFILERS IN TIDAL BORES AND OPEN CHANNEL FLOWS

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ABSTRACT

The propagation of positive surges in rivers and open channels is a highly unsteady turbulent process, with intensive sediment scouring and mixing. Despite its ecological and engineering significance, systematic physical studies of the unsteady turbulent characteristics of tidal bores remain limited. The present investigation performs ensemble-averaged velocity measurements using an array of two Vectrino II Profilers to investigate the vertical and transverse variability of the instantaneous velocity field during the propagation of breaking bores in open channel flows. Results highlight satisfactory performances of Vectrino II Profilers in highly unsteady turbulent open channel flows. Rapid longitudinal deceleration, transient recirculation and large velocity fluctuations in all directions are observed with the bore passage. The vertical velocity increased then decreased with the sharp free-surface rise. The transverse velocity data highlighted drastic transverse motions of bores and existence of large vortical structures in the flow. Overall, the results suggest that the propagation of tidal bore is a highly unsteady turbulent process, and a three-dimensional phenomenon. The process is associated with large fluctuations in all velocity components, as well as formation of large vortical structures and intense turbulent mixing in the wake of the surge.

Keywords: Open channel flow; turbulence; velocity profiling; unsteady flows.

1 INTRODUCTION

A sudden rise of water depth in open channel flows induced by the rapid closure of a downstream regulation gate is called a positive surge. In nature, a positive surge could occur during spring tide period in a funnel-shaped estuary with large tidal range and low freshwater level. This phenomenon is also called a compression wave or a tidal bore. Figure 1 illustrates the breaking tidal bore in the Qiantang River (China). To date, there are estimated to be over 400 rivers and estuaries where tidal bores were found, including all continents except for Antarctica (Chanson, 2011). The propagation of a tidal bore is an unsteady turbulent process, with intense shear and mixing underneath. The strength and shape of a bore is characterized by its Froude number Fr_1 defined as:

$$Fr_1 = \frac{V_1 + U}{\sqrt{g \times d_1}} \qquad [1]$$

where V_1 is the initial flow velocity positive downstream, U is the bore celerity positive upstream, g is the gravitational acceleration (equals to 9.80 m/s^2 as in Brisbane, Australia), d_1 is the initial water depth. When $Fr_1 < 1$, a tidal bore cannot form. When $1 < Fr_1 <$ 1.3-1.4, the bore is undular, characterized by a smooth free-surface rise and a train of secondary quasi-periodic waves (Treske, 1994; Koch and Chanson, 2008; Leng and Chanson, 2017a; 2017b). When $Fr_1 >$ 1.5-1.6, the bore is fully breaking, with a turbulent breaking roller and energetic white water splashes (Hornung et al., 1995; Leng and Chanson, 2017a; 2017b).

Herein, new experiments were conducted to study the unsteady turbulent characteristics of breaking bores in a systematic manner under controlled flow conditions. The experimental channel was a relactively large rectangular tilting flume. The breaking bores were generated by rapidly and fully closing a downstream Tainter gate and propagated upstream. An array of two Nortek™ Vectrino II Profilers were mounted side-by-side at mid-channel for velocity measurements. The two Profilers were equipped respectively with a fixed down-looking probe and a flexible probe mounted in a side-looking fashion. The present physical study aims to: (1) validate the performances of two Vectrino II Profilers when conducting velocity measurements simultaneously in an array under highly unsteady turbulent flow conditions; and (2) study the vertical and transverse distributions of the three-dimensional velocity characteristics associated with propagations of breaking bores.

Figure 1. Photographs of tidal bores in natural rivers: breaking bore in Qiantang River, Jiuxi, China (20/09/2016) – Bore propagation from left to right.

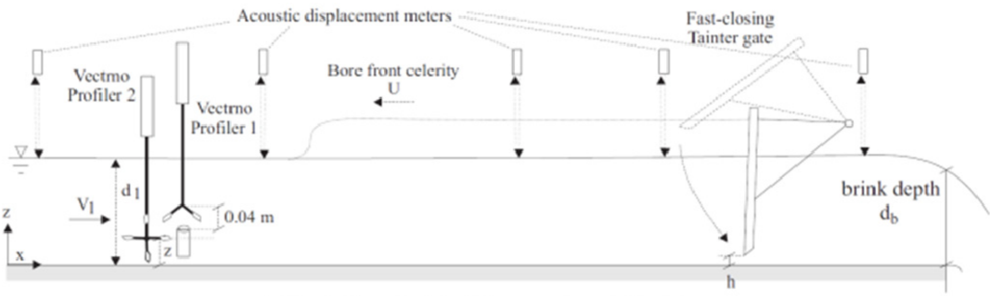
2 EXPERIMENTAL FACILITY AND INSTRUMENTATIONS

2.1 Experimental flume and instrumentations setup

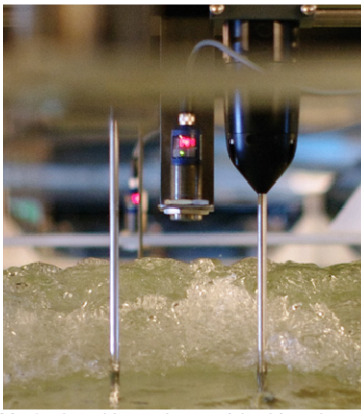
The flume was 19 m long and 0.7 m wide rectangular prismatic, with glass sidewalls, a smooth PVC invert and an adjustable bed slope. Water was supplied by an upstream water tank through a smooth convergent intake into the test section. The discharge was measured by a magneto flow meter with an accuracy of 10^{-5} m^3/s. The measured discharge was frequently checked against the brink depth d_b at the end of flume. A fast-closing Tainter gate was located near the downstream end at x = 18.1 m, where x was measured from the upstream end. The gate closure time was within 0.2 s, so that no effect would be caused by the closing mechanism on the bore properties. Figure 2a shows a sketch of the flume with all experimental apertures and instrument mountings.

During the steady flow period before the gate closure, the water depths were measured using point gauges with an accuracy of 0.001 m. In unsteady flows, water depths were recorded using a series of acoustic displacement meters (ADMs) (Fig. 2b). A Microsonic^{TM} Mic+35/IU/TC unit was located at x = 18.17 m immediately downstream of the Tainter gate. Further nine Microsonic^{TM} Mic+25/IU/TC units were spaced along the channel from x = 17.81 m to 1.96 m. All ADMs were calibrated against point gauge measurements and the sensors were sampled at 100 Hz on the channel centerline.

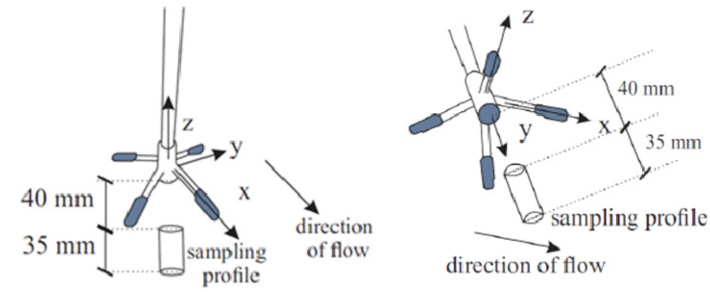
The velocity measurements were performed using an array of two Nortek^{TM} acoustic Doppler velocimeter Vectrino II Profilers. The fixed-head Profilers (Hardware ID VNO 1366, firmware ID 1950, referred to as Profiler 1) was validated and used previously by Leng and Chanson (2017a,b). Herein, it was used to measure velocity at the same time as a validating reference of the newly introduced Profiler, called Profiler 2. The Profiler 2 (Hardware ID VNO 1436, firmware ID 1950) was equipped with a flexible head, mounted in a side-looking fashion. Both Profilers used coherent Doppler processing technology, and had a three-dimensional head, which is able to record velocity in the longitudinal, transverse and vertical directions. Both Profilers were configured to quasi-simultaneously sample the velocity at 100 Hz for 35 sampling points in 35 mm profiles (Note that the physical experiments were conducted prior to the introduction of any manufacturer's re-calibration and probe upgrade). The sampling profile of Profiler 1 was arranged in the vertical direction, and in the transverse direction for Profiler 2. The first point of each sampling profile was located 40 mm from the probe central emitter. Figure 2c shows dimensioned sketches of the two Profilers and the arrangement of their sampling profiles.



(a) Definition sketch of the experimental facility



(b) Mounting of the ADMs (pointed by red arrow) looking downstream at an incoming bore



(c) Coordinated sketch of Profiler 1 (left) and 2 (right).

Figure 2. Definition sketch of the experimental facility.

The two Profilers, 1 and 2, were mounted at x = 8.5 m and 8.425 m respectively. The velocity range was set to ± 1 to ± 1.5 m/s, and the sampling frequency was 100 Hz. Figure 3 shows the setup of the two Profilers during unsteady turbulent velocity measurements. At the lowest vertical elevation, the sampling profile of Profiler 1 covers z = 1 – 35 mm with z = 0 at the channel bed. Whereas the sampling profile of Profiler 2 was arranged to be orthogonal to that of Profiler 1, located at z = 30 mm, which was the lowest possible elevation with this setup. During the present study, the relative distance between the two Profilers' sampling profiles remained constant longitudinally, transversely and vertically. This setup was tested and chosen based upon a series of systematic experiments to ensure minimum interactions between instruments and adequate correlations between two sets of velocity signals. Both Profilers were synchronised together with all 10 ADMs. The synchronization between instruments was within ± 1ms.

The steady flow data of both Profiler signals were post-processed by the MATLAB program VTMT version 1.1, designed and written by Becker (2014). In steady flows, the post-processing included removing data with averaged correlation values less than 60% and averaged signal to noise ratio less than 5 dB. The phase-space thresholding technique developed by Goring and Nikora (2002) was applied to remove spurious points. In unsteady flows, the above post-processing technique was not applicable (Nikora, 2004; Person. Comm.; Chanson, 2008; 2010; Koch and Chanson, 2009) and raw data was used directly for analysis.

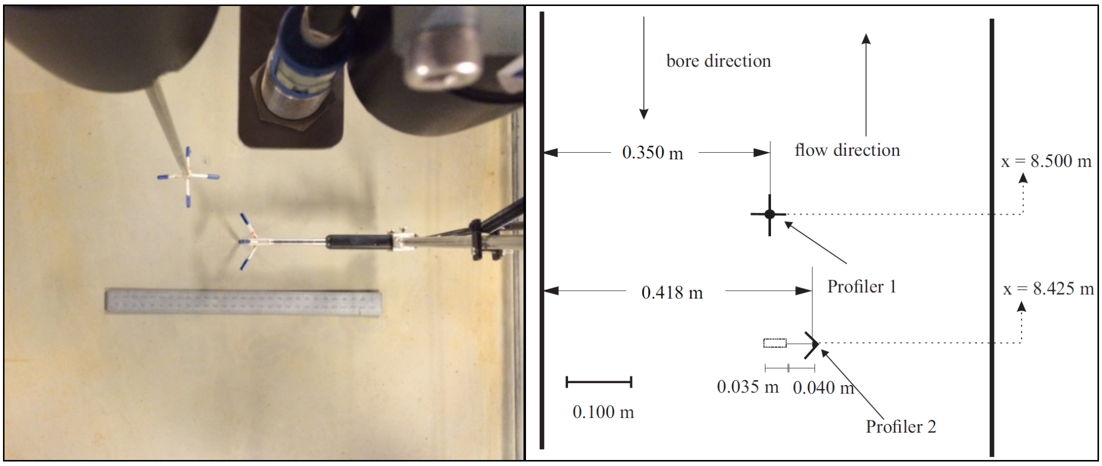


Figure 3. Photograph and dimensioned sketch of the profilers setup viewed in elevation.

2.2 Experimental flow conditions

Since the propagation of tidal bores is a highly unsteady turbulent process, a time-averaging technique would not be meaningful. Hence, ensemble-averaged measurements were necessary, where experiments were repeated 25 times for each controlled flow condition and the results were ensemble-averaged. Table 1 summarises the experimental flow conditions for ensemble-averaged measurements conducted with an array of two Profilers. In Table 1, S_o is the bed slope, Q is the initially steady water discharge, d_1 is the initial water depth at x = 8.5 m before the bore arrival, h is the gate opening after the rapid closure, y is the distance measured from the right side wall, B is the channel width which equals to 0.7 m, throughout and U was the bore celerity.

Table 1. Experimental flow conditions for velocity measurements using an array of two profilers.

	o	Q (m^3/s)	d_1 (m)	h (m)	z/d_1 Profiler 1	z/d_1 Profiler 2	y/B Profiler 1	y/B Profiler 2	U (m/s)	Fr_1
Present		0.101	0.174	0	0.01-0.20	0.17	0.5	0.46-0.51	1.15	1.52
Study		0.101	0.176	0	0.09-0.28	0.26	0.5	0.46-0.51	1.11	1.50
		0.101	0.176	0	0.23-0.43	0.40	0.5	0.46-0.51	1.18	1.55

3 VELOCITY MEASUREMENTS IN THE INITIALLY STEADY FLOW

3.1 Presentation

A Nortek^{TM} Vectrino II profiling velocimeter is a relatively newly developed instrument which is more and more broadly in the laboratory and field. Compared to traditional Nortek^{TM} Vectrino+ acoustic Doppler velocimeter (ADV), the advantage of a Vectrino II Profiler is its ability to simultaneously measure the instantaneous velocity in a profile, containing up to 35 sampling points with a minimum size of 1 mm. The performance of a Vetcrino II Profiler in steady and unsteady flows were previously documented by Craig et al. (2011), Zedel and Hay (2011), MacVicar et al. (2014), Dilling and MacVicar (2017), Leng and Chanson (2017a; 2017b). Leng and Chanson (2017b) found satisfactory performances of the Vectrino II Profiler in highly-fluctuating turbulent steady and unsteady flows, and was relatively accurate in estimating the time-averaged instantaneous velocity at high frequency (up to 100 Hz). Issues with the Profiler included erroneous points (weak spots) at certain positions beneath the flow, where velocity data were not meaningful. Other issues included wrong estimation of velocity variances and Reynolds stresses except at the sample “sweet spot”. Overall, previous experimental results for application of a Vectrino II Profiler in turbulent flows were encouraging, while careful post-processing and validation were required.

Steady flow measurements were herein performed under controlled flow conditions to test the performance and data quality of the newly introduced Profiler 2. The same methodology was used to check and validate the performance of Profiler 1, and was documented in Leng and Chanson (2017b). Steady flow experiments were conducted using Profiler 2 at a range of vertical elevations (z/d_1 = 0.17 – 0.86) and transverse locations (y/B = 0.22 to 1.00) under the same flow conditions as in Table 1. The results were compared to previous measurements using ADV - an instrument which has been carefully validated against Pitot tube and proven to be accurate in steady and unsteady turbulent flows (Koch and Chanson, 2005; Leng and Chanson, 2017b). Figure 4 shows the comparison between the Profiler 2 results (y/B = 0.48 – 0.52) and previous ADV measurements (Leng and Chanson, 2016a) in steady flows. The ADV data was collected under the same flow conditions at about the same elevations and on the channel centerline. Note that the ADV data was sampled at 200 Hz for 60 s, whereas Profiler 2 was sampled at 100 Hz for 90 s.

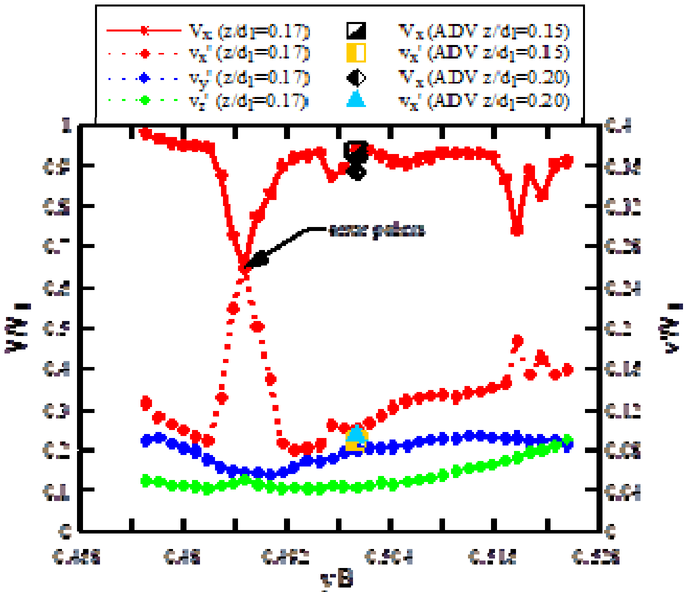


Figure 4. Transverse profile of time-averaged longitudinal velocity, velocity fluctuations with comparison to ADV data (Leng and Chanson, 2016a); ADV data measured at a point on the channel centerline.

3.2 Results

For the tested range of vertical elevations, the Profiler 2 gave good estimation of time-averaged velocity for a majority of sampling points in a transverse profile. The velocity magnitudes agreed well with previous centerline ADV data at similar vertical elevations. A few outliers were observed as marked in Figure 4. These error points were also observed in past studies by Zedel and Hay (2011), MacVicar et al. (2014), Dilling and MacVicar (2017), Leng and Chanson (2017a; 2017b). The number and proportion of these outliers were small, usually less than 5 points for a 35-point sampling profile, and thus can be easily removed before further analysis.

Previous studies highlighted inaccurate estimation of root-mean-square (RMS) of the velocity data using a Vectrino II Profiler (Zedel and Hay, 2011; MacVicar et al., 2014; Dilling and MacVicar, 2017; Leng and Chanson, 2017a; 2017b). The present study found spurious shapes and values in terms of the velocity RMS v' especially for the longitudinal component (Fig. 4). Only a small portion of the transverse profile was associated with meaningful values of velocity RMS close to the ADV data (y/B = 0.48 – 0.50). A few outliers were highlighted between y/B = 0.48 – 0.49 (~ 5 points). The transverse and vertical velocity components were associated with better quality data, however with an unreasonable curvy shape of the profile.

Overall, for the experimental range of vertical and transverse locations, Profiler 2 demonstrated good approximations of time-averaged velocity for the majority of sampling profile, and reasonable velocity RMS at the sampling "sweet spot" (typically at the middle or 1/3 of the sampling profile). The error points, where time-averaged velocity was not well estimated, occurred at different numbers and locations as the sampling location varied. It would be hard to predict the occurrence of these points. However, for a fixed location, the presence of error points were consistent, i.e. always at the same point in a profile with repeating experiments. This important feature enabled fast quality control to be carried out. Namely a wide range of transverse and vertical locations needs to be experimented first to know the number and location of error points, then a location with least number of error points can be selected for further experiments. Herein, the vertical and transverse ranges for ensemble-averaged experiments in Table 1 were selected based upon these steady flow results.

4 ENSEMBLE-AVERAGED MEASUREMENTS USING AN ARRAY OF TWO PROFILERS

4.1 Ensemble-averaged velocity characteristics

Typical ensemble-averaged time-variations of the longitudinal, transverse and vertical velocity components measured by the array of two Profilers are shown in Figure 5. The results of Profiler 1 show data at different vertical elevations in a sampling profile, whereas the results of Profiler 2 show data at different transverse locations. The ensemble-median free-surface elevation is shown in Figure 5 with black diamond symbols to indicate the arrival of the bore. The dimensionless time equals to 0 at the instance of gate closure.

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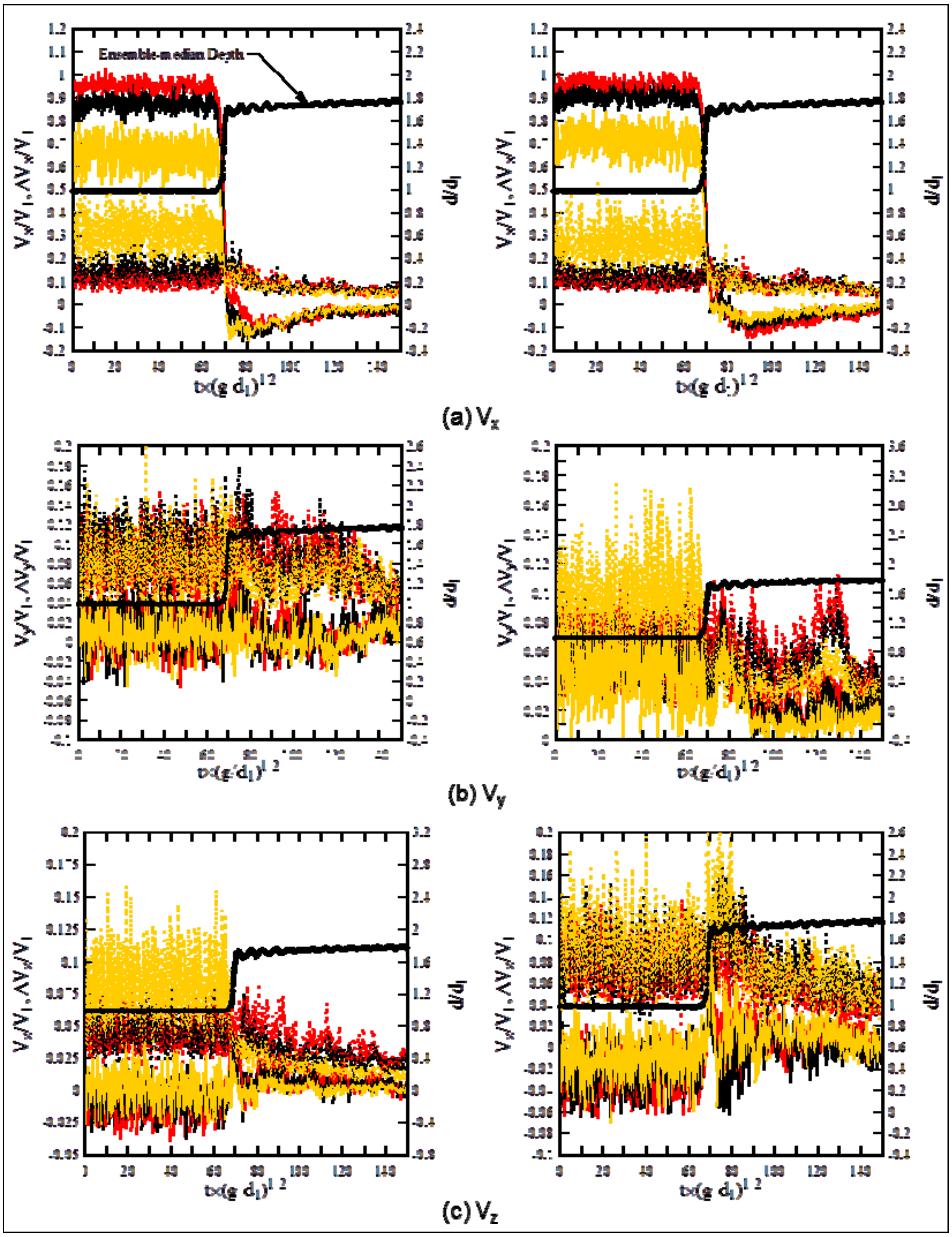

Figure 5. Ensemble-averaged time-variations of the longitudinal V_x, transverse V_y and vertical V_z velocity components measured by Profiler 1 (left) at z/d_1 = 0.17 (red), 0.09 (black) and 0.03 (yellow), and Profiler 2 (right) at y/B = 0.47 (red), 0.48 (black) and 0.50 (yellow); ensemble-median velocity marked by solid lines, velocity fluctuations $\Delta V = (V_{75}-V_{25})$ marked by dotted lines; ensemble-median depth denoted by black rounded symbols.

The velocity data in the initially steady flow prior to the bore arrival highlight clearly the presence of a bottom boundary layer, where the velocity magnitudes increase with higher vertical elevations (Fig. 5). On the other hand, the data of Profiler 2 show decreasing velocity magnitudes with increasing transverse distance from the right side wall in steady flow, indicating the sidewall boundary layer.

Overall, the ensemble-average longitudinal velocity measured by both Profilers shows simultaneous deceleration associated with the rapid increase in water depth, indicating the arrival of the bore. A recirculation velocity is often observed at low vertical elevations (z/d_1 < 0.5 - 0.6) marked by the negative transient longitudinal velocity at the end of declaration during the propagation of breaking bores (Chanson and Toi, 2015; Leng and Chanson, 2016a). Present study highlights longitudinal recirculation velocity measured by both Profilers up to a vertical elevation of z/d_1 = 0.4. This finding is consistent with past studies.

The velocity fluctuations are characterized by the difference between the third and first quartiles (V_{75}-V_{25}), marked by dotted lines in Figure 5. For a dataset with Gaussian distribution, this difference (V_{75}-V_{25}) would be equal to 1.3 of the standard deviation (Spiegel, 1972). The longitudinal velocity fluctuations are associated with sharp increases recorded by both Profilers as the bore passed, except at the end points of a sampling Profiler (z/d_1 = 0.03 and y/B = 0.50), highlighted by the yellow dotted lines. Past experiments documented issues with Profilers in estimating velocity variances at the end points of a sampling profile (Craig et al., 2011; Zedel and Hay, 2011; MacVicar et al., 2014). At the other locations within the profile, the longitudinal velocity fluctuations reach a maxima shortly after the arrival of the bore. This maximum velocity fluctuation and its time lag relative to the bore arrival were previously observed in both ADV and Profiler 1 measurements (Leng and Chanson, 2016a; 2017b). The velocity fluctuations and the associated time lags in the longitudinal directions are very close to past measurements using an ADV or Profiler 1.

The ensemble-averaged transverse velocity measured by both Profilers fluctuates drastically as the tidal bore passes. The data measured by Profiler 2 show an abrupt increase and then decrease shortly after the arrival of the bore. The steady flow transverse velocity shows larger fluctuations and mean values, highlighted by the Profiler 2 data, as compared to Profiler 1 data. The larger mean values could be a result of slight tilt of the probe head due to direct flow impact on the receivers. The comparatively large fluctuations may be caused by some reflection of the acoustic signal on the channel bed, as the receiver associated with the transverse and vertical velocity components was placed very close to the bed. The transverse velocity fluctuations measured by Profiler 1 are larger than the velocity magnitudes, and are comparable to the velocity magnitudes measured by Profiler 2. Some very large oscillations in transverse velocity fluctuations are highlighted at the later stage of the early flood tide phase after the bore passage, with amplitudes twice as large as the velocity magnitudes (Fig. 5, dotted lines). This could be associated with some transverse recirculation and mixing, linked with some large-scale vortical structures.

The vertical velocity components show a rapid acceleration and deceleration associated with the bore arrival, as measured by both Profilers. The data of Profiler 2 is associated with larger fluctuations at all locations, possibly caused by the acoustic reflection near the bed. The vertical acceleration measured by Profiler 2 seems to be more abrupt and sharp. The fluctuations in the early flood tide flow after the bore passage are higher in the measurements of Profiler 2 compared to those of Profiler 1. Both Profilers measured vertical velocity fluctuations twice the magnitudes of the vertical velocity. With Profiler 2, all locations show large increase in fluctuations associated with the passage of the bore. Peak fluctuations are reached shortly after the bore passage.

4.2 Discussion

The ensemble-averaged velocity characteristics measured by the two Profilers at almost the same location were compared (z/d_1 = 0.17, y/B = 0.50 with Δx = 0.075 m). Figure 6 shows one set of the results. The steady longitudinal velocity before the bore arrival shows smaller velocity magnitude measured by Profiler 2, which is 20% lower than that of Profiler 1. This could be caused by the interactions between the two instruments. During the rapidly-varied flow phase with the bore passage, the two Profilers show results which are almost identical, with the same deceleration gradient and almost the same recirculation velocity magnitudes at the end of deceleration. During the early flood tide phase immediately after the bore passage, the ensemble-averaged longitudinal velocity components measured by the two Profilers are very similar, with almost no difference in terms of the magnitudes and variations with time.

The ensemble-median transverse velocity shows some large fluctuations following the arrival of the bore. A peak in transverse velocity was observed for both Profiler measurements. The two peaks of the two instruments has a dimensionless time difference of 2.7, corresponding to a time difference of 0.36 s and a longitudinal distance of 0.41 m (local bore celerity = 1.14 m/s). Hence, this time lag is not caused by the difference in bore arrival times at the two instruments but by the transverse motion of the bore. This could be confirmed by the ensemble-averaged vertical velocity data of the two Profilers. Both Profilers show an abrupt acceleration and deceleration of the vertical velocity with the bore passage. The results of the two Profilers have almost overlapped during the acceleration then deceleration phase, highlighting a maximum vertical velocity nearly at the same time.

The velocity fluctuations show general trends of increase with the bore arrival in all directions measured by the two Profilers. Profiler 1 measurements highlight maximum velocity fluctuations occurred shortly after the bore arrival in the longitudinal, transverse and vertical directions for most of the data sets. Profiler 2 measurements are generally associated with larger velocity fluctuations in all directions compared to Profiler 1 measurements. Some data are associated with peaks in velocity fluctuations, and are more commonly observed in the transverse and vertical components.

To sum up, the array of measurements highlights rapid longitudinal deceleration, transient recirculation and large fluctuations in the transverse and vertical velocity components. The transverse velocity data highlight rapid transverse motion of the bore, possibly linked with large vortical structures near the fluctuating free-surface. The results are combined to show that the propagation of a tidal bore is a three-dimensional process, with turbulent properties rapidly-varied in all three directions.

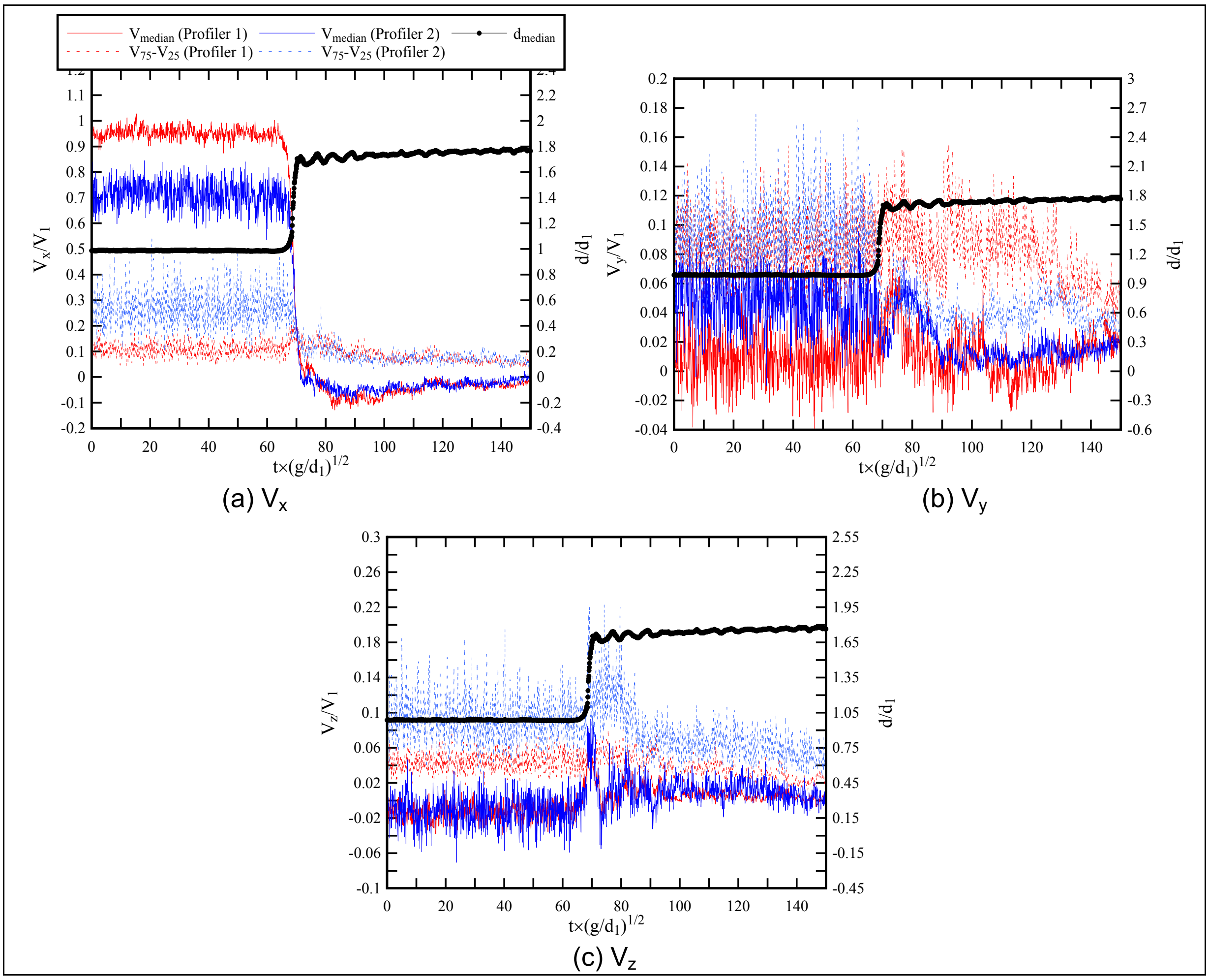

Figure 6. Ensemble-averaged time-variations of the longitudinal (a), transverse (b) and vertical (c) velocity components measured by Profiler 1 and 2 at z/d_1 = 0.17, y/B = 0.50, x = 8.5 m and 8.425 m respectively.

5 CONCLUSION

New experiments were conducted in a relatively large size facility to study the unsteady turbulent properties of tidal bores propagating in open channel flows using an array of two ADV Profilers. Two Nortek^{TM} ADV Vectrino II Profilers were deployed to sample simultaneously at close range the turbulent velocity characteristics in vertical and transverse profiles. Ensemble-averaged measurements were performed, where experiments were repeated 25 times for each controlled flow condition and the results were ensemble-averaged. Present studies demonstrated that both Profilers gave satisfactory performances in highly unsteady turbulent flows when sampled simultaneously and close to each other. Some interactions existed between the two Profilers, causing an underestimation of ensemble-averaged velocity data by Profiler 2 in the initially steady flow. However the interactions did not affect the rapidly-decelerating flow phase and unsteady flow phase after the bore arrival.

The propagation of breaking bores was associated with a rapid longitudinal deceleration, transient recirculation and large velocity fluctuations in all directions. The vertical velocity increased then decreased with the sharp free-surface rise. The transverse velocity data in vertical and transverse profiles highlighted some differences, indicating transverse motions of bores and existence of large vortical structures. Overall, the results suggested that the propagation of tidal bore is a highly unsteady turbulent process, and a three-dimensional phenomenon. The process was associated with large fluctuations in all velocity components, formation of large vortical structures and intense turbulent mixing in the wake of breaking bores.

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DISCLOSURE STATEMENT

The authors have no conflict of interest nor any vested interests. This is not an industry sponsored study.

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