

Steady and Unsteady Turbulent Velocity Profiling in Open Channel Flows Using the ADV Vectrino II Profiler

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ABSTRACT

The Nortek Vectrino II profiler acoustic Doppler velocimeter (ADV) was developed for velocity profiling. Herein, the study aims to 1) demonstrate the applicability of the ADV profiler to steady and rapidly-varied unsteady open channel flows, 2) check the data quality, based upon a new systematically comparative analysis with traditional ADV data, and 3) conduct a sensitivity analysis on ensemble-averaged data collection in a positive surge. This was achieved by systematically performing steady and unsteady velocity measurements under controlled flow conditions in a relatively large laboratory facility. All experiments were repeated 25 to 50 times for each controlled flow condition and the results were ensemble-averaged. Steady and unsteady velocity measurements highlighted a number of instrumental errors using the ADV Profiler. Overall, the study demonstrated that the propagation of positive surges was a highly unsteady turbulent process, and the performance of ADV Profiler in such an unsteady turbulent flow could be satisfactory provided that careful validation was undertaken for all ADV Profiler outputs.

Keywords: ADV Vectrino II profiler, Instrumentation, Steady and unsteady flows, Positive surge, Validation process.

1. INTRODUCTION

In an open channel, steady flow conditions may be achieved when the discharge and boundary conditions remain constant for a reasonable period of time. The operation of any regulation device, such as a gate, is associated with unsteady flow motions: positive and negative surges (Liggett 1994, Chanson 2004). Geophysical applications include tidal bores and tsunami propagating into river systems. Turbulence in open channel flows has been studied for decades (Nakagawa and Nezu 1977, Nezu 2005). Most data were obtained in steady flows: e.g., using laser Doppler anemometry, particle image velocimetry, or acoustic Doppler velocimetry. Measurements in rapidly-varied unsteady flows are less common (Hornung et al. 1995, Koch and Chanson 2009, Leng and Chanson 2015). Herein, new unsteady velocity measurements were performed systematically under controlled flow conditions using a NortekTM acoustic Doppler velocimeter Vectrino II Profiler equipped with a fixed-probe down-looking head. Both steady and unsteady measurements were performed in a relatively large laboratory facility. The quality and accuracy of the present data set obtained using the Profiler were validated against data collected with an NortekTM acoustic Doppler velocimeter Vectrino+.

2. VELOCITY MEASUREMENTS

Two velocimeters were deployed in the present study: a NortekTM acoustic Doppler velocimeter Vectrino II Profiler (Serial number P27338, Hardware ID VNO 1366) and a NortekTM acoustic Doppler velocimeter (ADV) Vectrino+(Serial No. VNO 0436). The latter, referred to as ADV, was used to validate the Profiler data. The Vectrino II Profiler is a high-resolution acoustic Doppler velocimeter used to measure turbulence and three-dimensional water velocity (Nortek 2012). The basic measurement technology is coherent Doppler processing (Zedel and Hay 2011, Nortek 2012). Herein, the Profiler was equipped with a fixed downward-looking head, one central emitter, and four receivers. The Profiler was capable of recording velocity components simultaneously in a vertical profile of up to 35 mm in height (Figure 1-left). The minimum distance from the emitter was 40 mm to the first point of the profile. Two profiling ranges were tested: 30 and 35 mm. The height of each sampling cell was 1 mm: e.g., a profiling range of 35 mm consisted of 35 sampling cells sampled simultaneously. The velocity range was ± 1.0 m/s, and the sampling frequency was 100 Hz. The Profiler was located at $x = 2.0$, 7.87 m, or 8.5 m, where x was the longitudinal distance measured from the channel upstream end. The ADV was

equipped with a three-dimensional side-looking head (Figure 1-right). The ADV was set up with a velocity range ± 1.0 m/s, a transmit length of 0.3 mm, a sampling volume of 1.5 mm height, and power setting High. Two sampling frequencies were used: in the steady flow measurements, the ADV was sampled at 200 Hz; during the unsteady flow experiments, the ADV was sampled at 100 Hz. The Profiler output data were post-processed with the Matlab program VTMT version 1.1 (Becker 2014). In steady flows, the post-processing included the removal of data with average correlation values less than 90% and average signal to noise ratio less than 5 dB. In addition, the phase-space thresholding technique developed by Goring and Nikora (2002) was applied to removal spurious points in the data set. In the unsteady flows, the above post-processing technique was not applicable (Nikora 2004, *Person. Comm.*, Chanson 2008, Koch and Chanson 2009), and raw data was used directly for analysis.

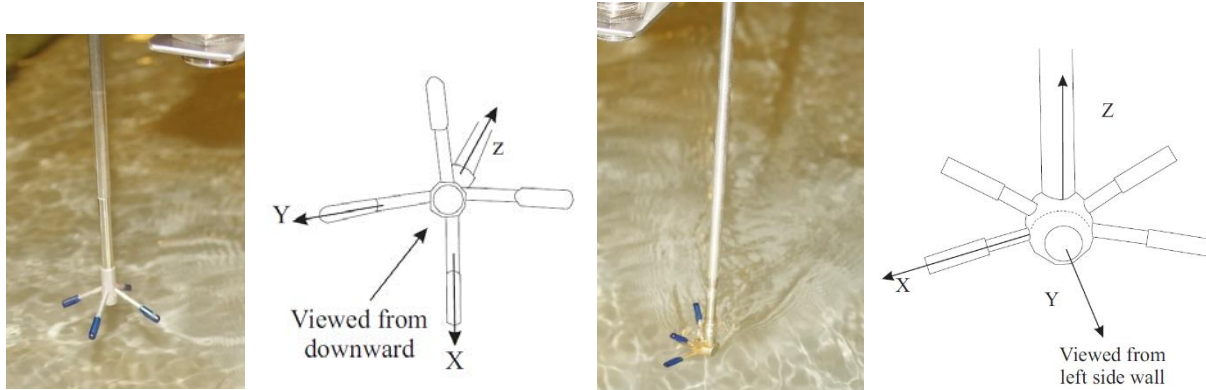


Figure 1. Photographs and coordinated sketches of ADV Vectrino II Profiler and ADV Vectrino+. (Far Left) Profiler photograph; (Left) Profiler definition sketch; (Right) ADV photograph (Far Right) ADV definition sketch.

3. EXPERIMENTAL SETUP AND FLOW CONDITIONS

The experimental channel was 19 m long and 0.7 m wide, made of glass side walls and a smooth PVC horizontal bed. The initially steady flow was supplied by the upstream water tank leading to the glass-sidewall test section through a smooth convergent intake. The discharge provided by the tank was measured by a magneto flowmeter with an accuracy of 10^{-5} m³/s and was checked against the brink depth d_b at the flume's downstream end. A fast-closing Tainter gate was located next to the channel's downstream end at $x = 18.1$ m. The positive surges were generated by rapidly closing the Tainter gate and the bore propagated upstream. A radial gate was located at $x = 18.88$ m to control the initial water depth. Unsteady free-surface measurements were performed using a series of acoustic displacements meters (ADMs) located at various positions, most importantly at $x = 18.17$ m, 8.5 m and 7.93 m. All ADMs were calibrated against point gauge measurements in steady flows and sampled at 200 Hz on the channel centerline. The ADMs and were synchronized within 1 ms with the ADV and Profiler.

First, steady flow velocity measurements were performed using the Profiler over a wide range of flow conditions (Table 1). The data was compared to measurements using the ADV sampled simultaneously. Both ADV and Profiler were located at $x = 7.87$ m. The Profiling range was 30 mm, and the ADV control volume was located at the centre of the Profiling range. Figure 2 presents an overview of the experimental channel and instrumental setup. Second, unsteady ensemble-averaged velocity measurements were performed using the Profiler, with validation against ADV data (Table 1). In the unsteady flow, the experiments were repeated 50 times to obtain the ensemble-averaged median velocity properties. A sensitivity analysis was performed to find the appropriate number of repeats (less than or equal to 50) to characterise accurately the rapidly-fluctuating velocity characteristics. Two instrumental setups were used during the ensemble-averaged measurements (Figure 3) to minimise instrument interferences between Profiler and ADV. In Setup 1, the Profiler was sampled alone at $x = 8.5$ m, with a profiling range of 35 mm. In Setup 2, the Profiler was located at $x = 8.5$ m, sampled simultaneously with an ADV located 0.57 m upstream. The control volume of the ADV was placed at the bottom of the profiling range.

The experimental flow conditions were summarized in Table 1, where Q is flow discharge, d_i is the initial steady flow depth at the velocity sampling location, x is the location of the Profiler measured from the upstream end of the flume, Fr_o and Fr_i are the Froude numbers for the initially steady flow and of the positive surge, respectively, h is the Tainter gate opening after closure, and z/d_i is the dimensionless vertical elevation where velocity measurements were conducted, with z being the sampling volume elevation above the invert. The radial gate opening height is denoted N/A when it is fully opened. Table 2 lists the setup, used to test the combinations of Profiler and ADV. Herein, Brisbane tap water was used, and no seeding was applied. Further details were reported by Leng and Chanson (2016a).

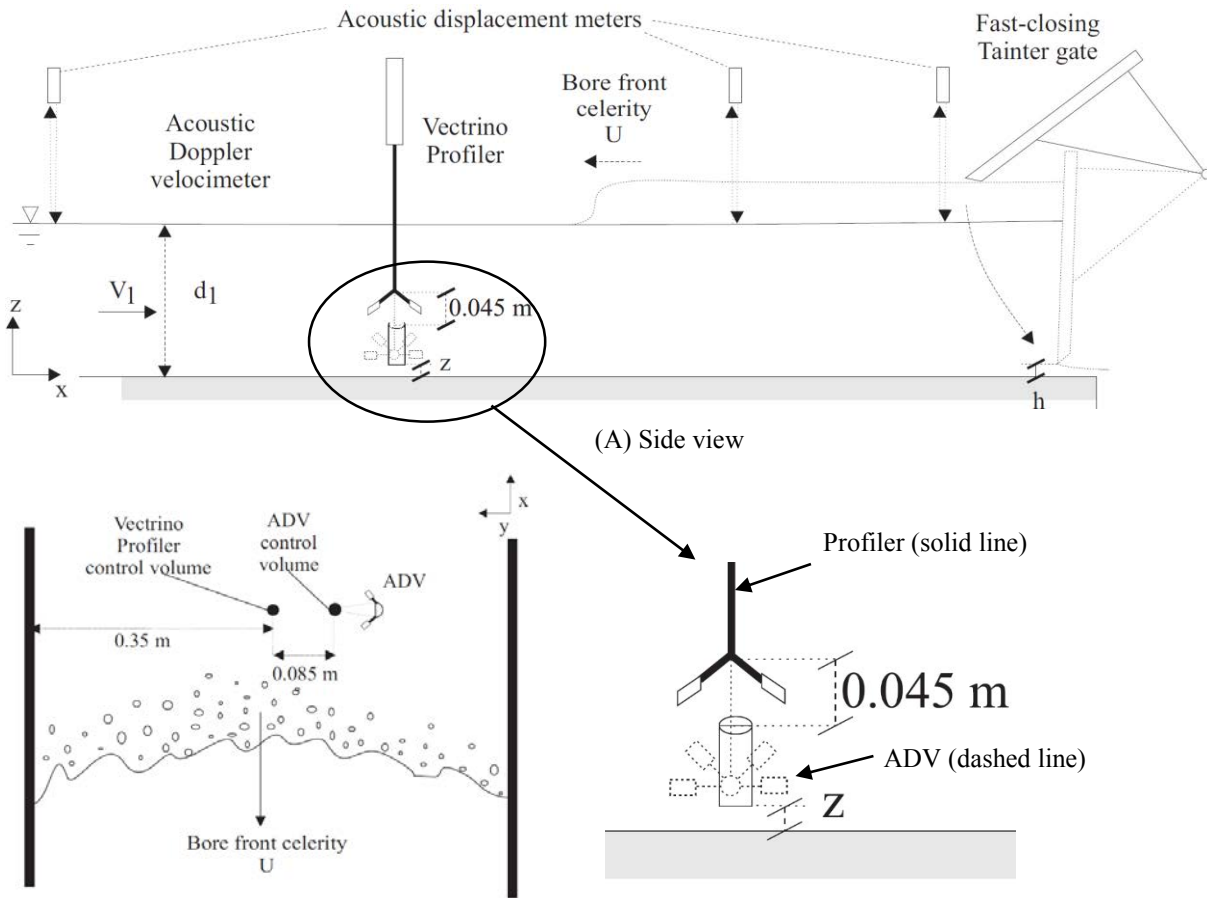


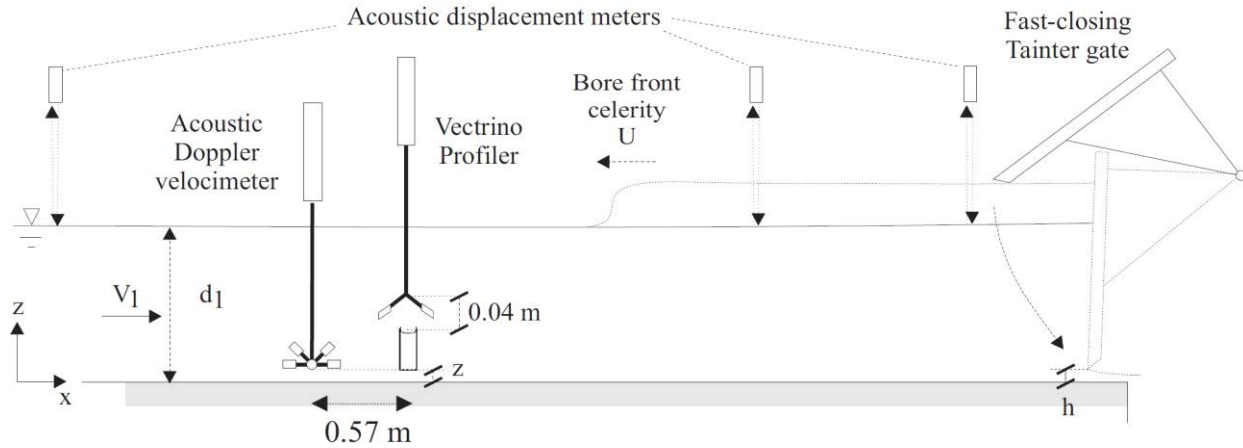
Figure 2. Sketches of the experimental channel and instrument setup (thick black line indicates channel side walls) during the preliminary velocity measurements.

Table 1. Experimental flow conditions.

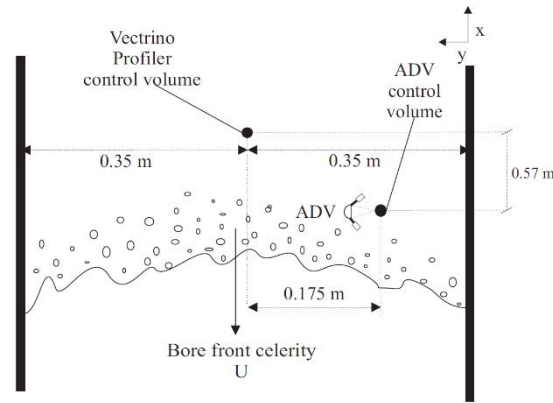
| Q (m ³ /s) | d_1 (m) | x (m) | Fr_o | Fr_l | Radial gate opening (m) | h (m) | z/d_1 | Instrumentation | Remark |
|----------------------------|--------------|--------------|--------|--------|-------------------------------|------------|-----------|-----------------|--|
| 0.100 | 0.177 | 2, 7.87, 8.5 | 0.60 | 1.58 | N/A | 0 | 0.00-0.73 | ADV & Profiler | Steady flow & ensemble-averaged unsteady velocity measurements |
| 0.085 | 0.161 | 7.87 | 0.60 | -- | N/A | N/A | 0.00-0.60 | ADV & Profiler | Steady flow |
| 0.071 | 0.144 | 7.87 | 0.59 | -- | N/A | N/A | 0.00-0.63 | ADV & Profiler | Steady flow. |
| 0.100 | 0.215 | 7.87 | 0.45 | -- | 0.112 | N/A | 0.00-0.70 | ADV & Profiler | Steady flow. |
| 0.086 | 0.211 | 7.87 | 0.40 | -- | 0.090 | N/A | 0.00-0.71 | ADV & Profiler | Steady flow. |
| 0.071 | 0.21 | 7.87 | 0.33 | -- | 0.670 | N/A | 0.00-0.71 | ADV & Profiler | Steady flow. |
| 0.055 | 0.201 | 2 | 0.27 | -- | 0.05 | N/A | 0.00-0.75 | ADV & Profiler | Steady flow. |

Table 2. Descriptions of instrumental setups

| Setup | Instrumentation | Profiler location | ADV location | Remarks |
|-------|------------------|---------------------------|-----------------------------|-----------------------------------|
| 1 | Profiler only | $x = 8.5$ m, $y = 0.35$ m | N/A | |
| 2 | Profiler and ADV | $x = 8.5$ m, $y = 0.35$ m | $x = 7.93$ m, $y = 0.225$ m | ADV emitter facing right sidewall |
| 3 | Profiler and ADV | $x = 8.5$ m, $y = 0.35$ m | $x = 8.5$ m, $y = 0.215$ m | ADV emitter facing right sidewall |
| 4 | Profiler and ADV | $x = 8.5$ m, $y = 0.35$ m | $x = 7.93$ m, $y = 0.225$ m | ADV emitter facing Profiler |
| 5 | ADV only | N/A | $x = 8.5$ m, $y = 0.35$ m | |



(A) Setup 1 (Profiler only, marked by solid outline) and 2 (with ADV, marked by dashed outline) side view



(B) Setup 2 (Profiler working with ADV) elevation view

Figure 3. Experimental channel and instrument setup of the ensemble-averaged measurements.

4. STEADY FLOW MEASUREMENTS USING VECTRINO II PROFILER

4.1. Steady Flow Velocity Measurements

For all flow conditions (Table 1), steady flow velocity measurements showed a close agreement between Profiler and ADV data in terms of time-averaged velocity components. This was consistent with the findings of Craig et al. (2011), Zedel and Hay (2011), and Macvicar et al. (2014). However, some outlying points occurred slightly above the outer edge of the boundary layer. This is illustrated in Figure 4, showing typical vertical profiles of time-averaged longitudinal velocity V_x and velocity fluctuations at two longitudinal locations. The occurrence of such suspicious points was consistent with all velocity components: i.e. if the longitudinal velocity showed outlying data at particular vertical elevations, similar outliers would be observed at the same vertical elevations for the other velocity components. The velocity fluctuations were characterized by the standard deviation of velocity data v' . Figure 4 highlights some inconsistent vertical pattern in terms of velocity fluctuation data throughout the water column, especially in a thin boundary layer (Figure 4, right). Zedel and Hay (2011) and Macvicar et al. (2014) also showed errors in velocity variance using a Profiler. Larger differences were observed in terms of vertical velocity fluctuations, compared to other velocity components. This could be some effect of the bed proximity on the receiver for the vertical velocity component, as previously observed with ADVs (Martin et al. 2002, Chanson et al. 2007). The experiments were conducted at two longitudinal locations $x = 7.87$ m (Figure 4-left) and $x = 2$ m (Figure 4-right) to examine the occurrence of error points in relation to the boundary layer thickness. The results suggested no obvious difference in terms of both locations and quantity. However, the number of error points was significantly larger with measurements conducted with the smaller discharge ($Q = 0.055$ m³/s) at both locations.

Overall, the steady flow velocity measurements highlighted a number of advantages and issues with the Profiler. The Profiler was reliable for the measurements of mean velocity profile in the longitudinal, transverse, and vertical directions in a turbulent flow with high temporal resolution (100 Hz), together with the ability to simultaneously sample velocity characteristics at up to 35 closely-spaced locations. Some error points existed in the sampling profile for which the recorded velocity values were not meaningful. The error points were typically located outside the outer edge of the boundary layer. Although their occurrences seemed to be random and discontinuous, their locations in a single profile at fixed vertical elevation were consistent and can be reproduced by repetition; therefore, such locations are relatively easy to avoid. The presence of error points in the Profiler measurements was related to flow discharge and vertical elevation rather than turbulent flow properties.

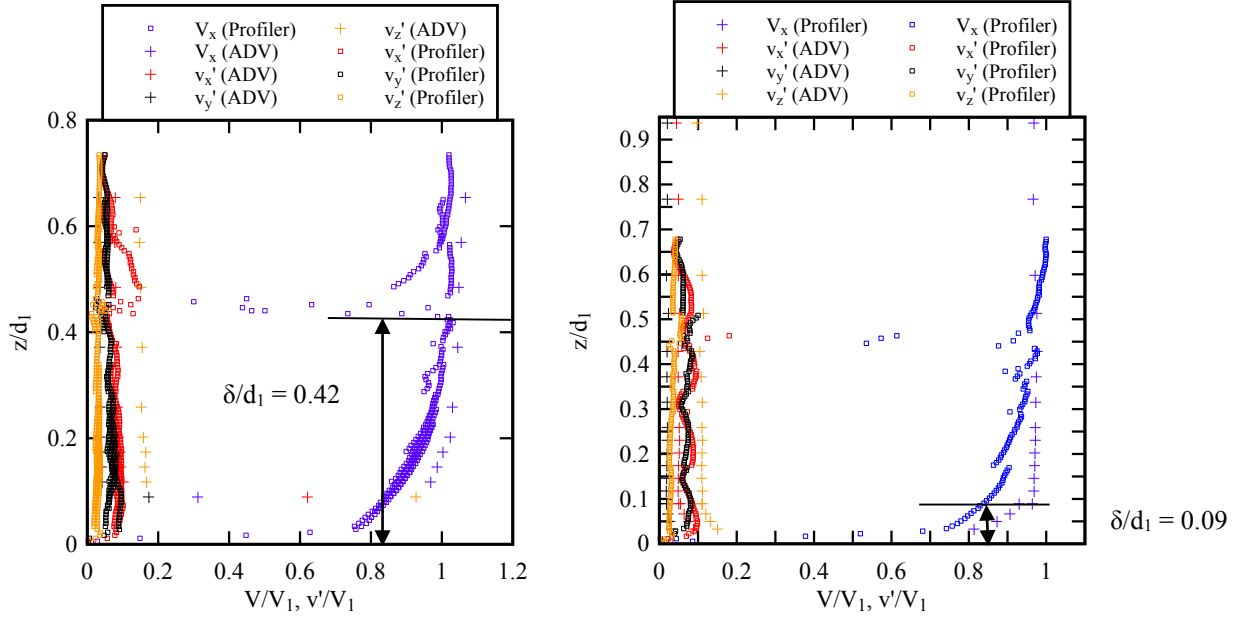


Figure 4. Vertical profile of the time-averaged longitudinal velocity and velocity fluctuations in steady flow: comparison between ADV and Profiler data - $Q = 0.100 \text{ m}^3/\text{s}$, $d_1 = 0.177 \text{ m}$, $x = 7.87 \text{ m}$ (left) and 2 m (right).

4.2. Discussion: Interactions Between ADV and Profiler

During the steady flow measurements, interactions between ADV and Profiler units were observed and their effects in terms of data magnitude and quality were investigated. Five instrumental setups were experimented under the same flow condition ($Q = 0.100 \text{ m}^3/\text{s}$, $d_1 = 0.177 \text{ m}$) for the same vertical range ($z/d_1 = 0.09$ to 0.28). This vertical range was selected based on preliminary measurements, during which a zero error point was found within the range. Table 2 describes the five setups, where y is the transverse distance positive towards the left sidewall. Figure 5 presents typical velocity statistics with different setups. The results clearly showed some interactions between ADV and Profiler units when both instruments were sampled simultaneously. While they did not affect the values of the mean velocity for the majority of the profile, the interactions had more impacts on the velocity fluctuations. The velocity fluctuations at the upper and lower portions of the profiler were most adversely affected. The interactions between the instruments and impacts on the data quality were reduced by simply rotating the ADV emitter by 180° to face the side wall instead of facing the Profiler control volume, as in Setups 2 and 3. Further improvements were achieved by moving the ADV longitudinally and transversely away from the Profiler, as in Setup 2. In summary, Setups 1 and 2 provided data that were best compared to the ADV data (Setup 5) among all setups.

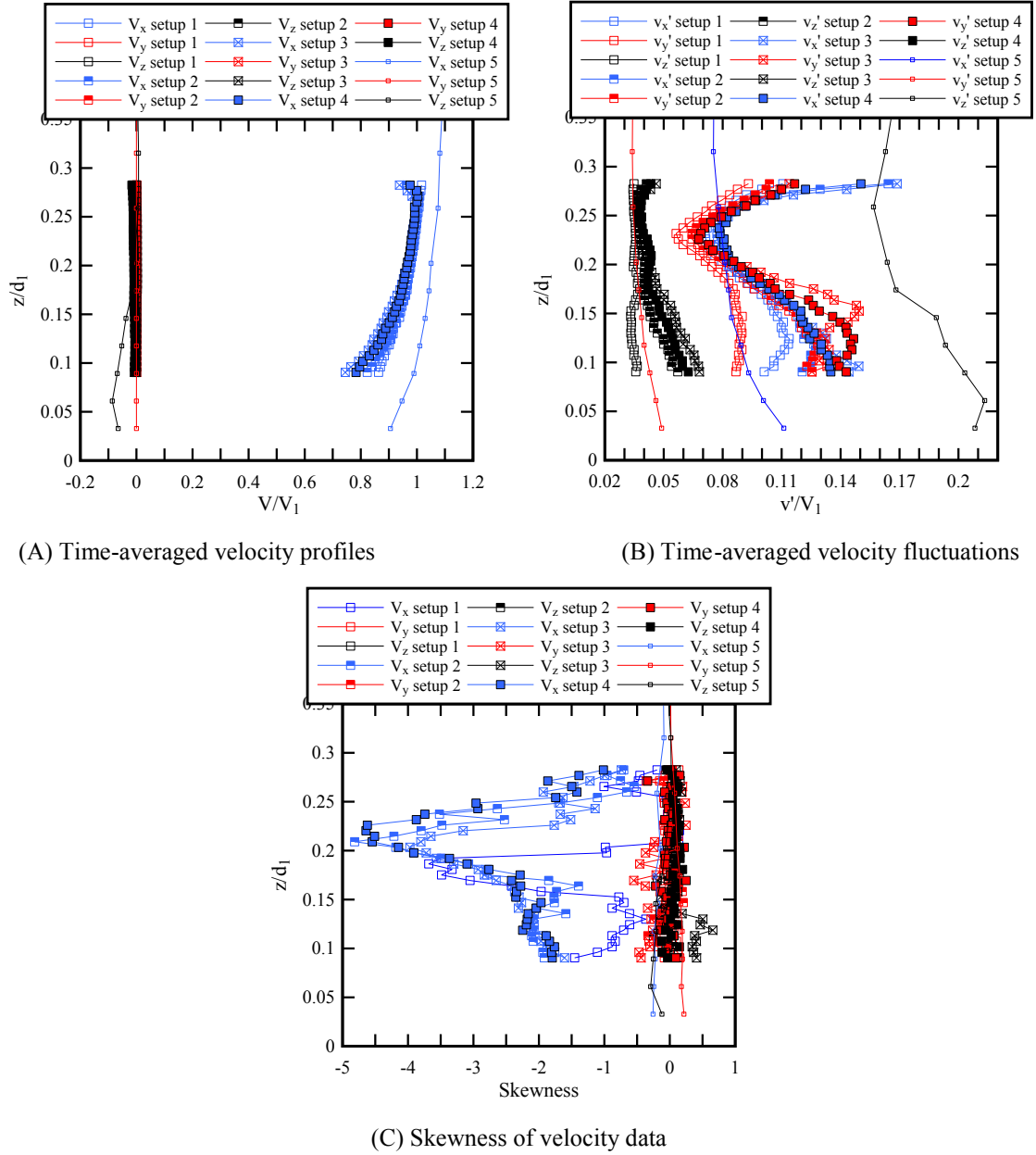


Figure 5. Velocity statistics measured by Profiler sampling alone (setup 1), sampling with ADV using Setups 2, 3 and 4 (denoted "setup 2/3/4") compared to ADV measurements sampling alone (setup 5).

5. ENSEMBLE-AVERAGED MEASUREMENTS AND SENSITIVITY ANALYSIS

5.1. Presentation

The positive surge propagation was highly repeatable and reproducible in the current experimental setup. The free-surface and velocity characteristics were analyzed by repeating the experiment for a number of times and obtaining the median of the instantaneous data (i.e. the ensemble-average) at a point at an instant, which can be used to represent the mean property of the relevant parameters (Docherty and Chanson 2012). The synchronization between different runs for a single flow condition was critical. This was done by taking the ADM located downstream of the gate as a reference. When the gate was closed, it generated a negative surge propagating downstream, which was characterized as a sudden drop of water elevations at the same time as the generation of the bore. All 50 runs were synchronized according to the time at which the leading edge of the negative surge reached the ADM sensor located downstream of the gate. Mathematically, this time is equal to

the instance at which the first derivative of the free-surface elevation with respect to time becomes non-zero. The ensemble-averaged velocity measurements were performed using Setups 1 and 2 (Fig. 3, Table 2) because they produced the least instrumental interference. The results were ensemble-averaged over the total 50 runs, as well as over 35 runs with some data overlapping, 25 runs, 15 runs, 10 runs, and 5 runs with no data overlapping.

A number of characteristic unsteady turbulent fluctuating properties were examined. Previous experimental analysis suggested that these properties were characteristics associated with the turbulent flow nature (Leng and Chanson 2016b). Thus, the sensitivity analysis focused on the following properties: the maximum longitudinal velocity fluctuations occurring shortly after the passage of the bore, the time lag for the maximum longitudinal velocity fluctuation to occur after the bore passage, and the longitudinal recirculation velocity (Figure 6). In Figure 6, t_{bore} denotes the time at which the free-surface elevation started to rise. Mathematically, this time is equal to the instance at which the first derivative of the free-surface elevation with respect to time becomes non-zero. The longitudinal velocity fluctuations were quantified by the difference between the third and first quartile of the total ensemble ($V_{75}-V_{25}$). The maximum velocity fluctuations $(V_{75}-V_{25})_{max}$ were found to occur shortly after the passage of the bore, and the associated time lag Δt_V was quantified as the delay relative to the time when the free-surface elevation started to rise up. The longitudinal recirculation velocity V_{recirc} marked the minimum velocity reached at the end of the longitudinal deceleration, typically a negative value for the experimental flow conditions. Such a negative velocity indicated a transient flow reversal and recirculation beneath the surge front. A definition sketch of the above fluctuating properties is illustrated in Figure 6.

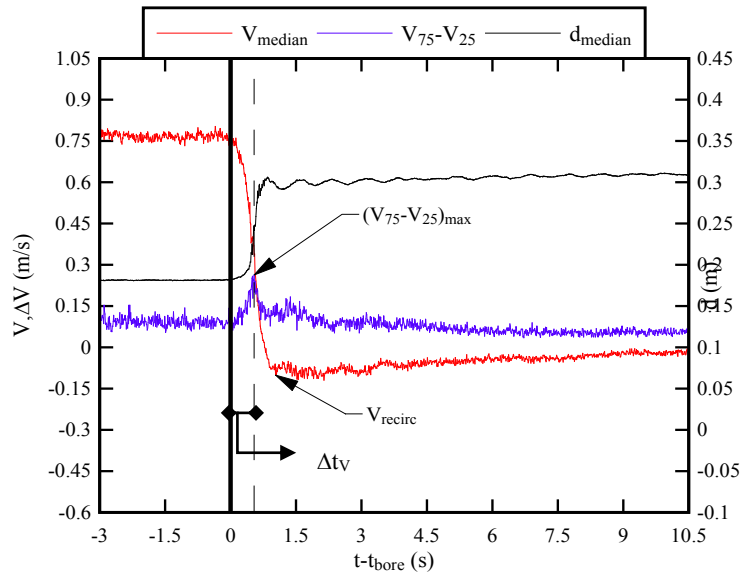


Figure 6. Definition sketch of characteristic unsteady turbulent fluctuating properties during a positive surge propagation.

5.2. Ensemble-Averaged Unsteady Velocity Measurements

Overall, the ensemble-averaged unsteady velocity measurements showed a close agreement between Profiler and ADV velocity data for the same flow and vertical elevation. Figure 7 presents the time-variations of ensemble-averaged longitudinal velocity measured by the ADV (left) and Profiler (right) at a similar vertical elevation, both calculated based on 50 runs. The results showed close agreement in terms of shape and magnitude of the ensemble-median velocity measured by the two instruments. The velocity fluctuations in terms of $(V_{75}-V_{25})$ produced by both instruments showed marked peaks shortly after the passage of the surge front ($t-t_{bore} > 0$). The Profiler data seemed to show a more pronounced recirculation zone in comparison to the ADV data, as highlighted by negative velocity of larger magnitudes reached at the end of the longitudinal deceleration, indicating a stronger flow reversal. Altogether, the time-variations of the unsteady velocity measured by the Profiler, instantaneous or ensemble-average, were very similar to those measured by the ADV for all three components. Table 3 compares the turbulent fluctuating characteristics measured by Profiler and ADV at similar vertical elevations. The Profiler measurements are presented for two setups, ensemble-averaged over 50 runs. The ADV measurements included present data (Setup 2) ensemble-averaged over 50 runs, and data by Leng and Chanson (2016b) ensemble-averaged over 25 runs. The results showed a close agreement between the Profiler data, working alone or with the ADV, and ADV data, working alone or with the Profiler, at a given elevation. Clearly, the Profiler was suitable to conduct

high-frequency measurements in highly unsteady turbulent flows and captured rapidly fluctuating characteristics with good accuracy, provided that the measurements were taken at vertical elevations where no spurious points existed.

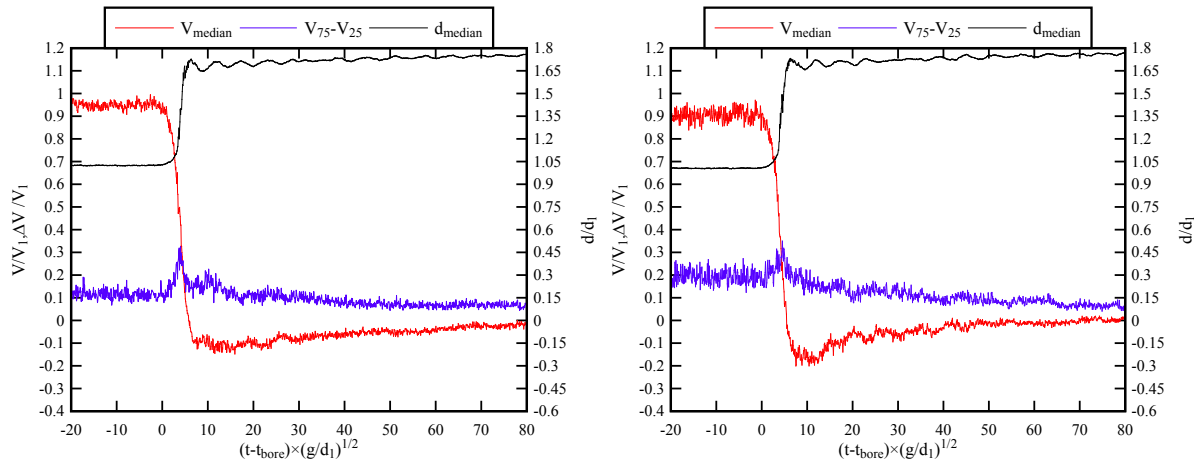


Figure 7. Ensemble-averaged time-variations of the longitudinal velocity and free-surface elevation at the velocity sampling point during a positive surge: comparison between ADV data (left, Setup 2) and Profiler data (right, Setup 1), both calculated from 50 runs - Flow conditions: $Q = 0.100 \text{ m}^3/\text{s}$, no radial gate, $h = 0 \text{ m}$, $z/d_1 = 0.12$ for ADV and Profiler.

Table 3. Comparison of turbulent fluctuating characteristics in a positive surge between instruments and setups

| Instrument and setup | z/d_1 (m) | $(V_{75}-V_{25})_{\max}$ (m/s) Ensemble-averaged | Δt_V (s) Ensemble-averaged | V_{recirc} (m/s) Ensemble-averaged |
|---------------------------|----------------|---|---------------------------------------|--|
| Profiler with ADV Setup 2 | 0.13 | 0.305 | 0.52 | -0.146 |
| ADV Setup 2 | 0.12 | 0.263 | 0.54 | -0.119 |
| Profiler alone (Setup 1) | 0.13 | 0.282 | 0.61 | -0.162 |
| ADV 2016 ^[1] | 0.10 | 0.215 | 0.61 | -0.239 |

Remarks: [1] ADV measurements collected by Leng and Chanson (2016b) at $x = 8.5 \text{ m}$ on channel centreline for the same flow condition. Results were ensemble-averaged over 25 runs.

5.3. Sensitivity Analysis

The longitudinal velocity data at 7 vertical elevations, that is 1 in 5 measuring points out of 35 points in a profile, were analyzed to examine the effect of number of runs on the fluctuating characteristics $(V_{75}-V_{25})_{\max}$, Δt_V , and V_{recirc} . Figure 8 presents typical results for Setup 1 (Profiler only), each for two vertical elevations ($z/d_1 = 0.27$ and 0.10). For all flow conditions, the turbulent characteristics showed asymmetrical envelopes of data distribution when the number of runs varied from 50 down to 5. The maximum fluctuations calculated based upon 50 runs tended to be smaller than the average of the results calculated from 35 or 25 runs. The time delay Δt_V obtained from a total ensemble of 50 runs was very close to the average of the time delay obtained from 35 and 25 runs, with 25 runs producing results that were closer to that of the 50 runs at some elevations. The magnitude of the recirculation velocity tended to decrease on average as the number of runs increased. The longitudinal deceleration took place in typically less than 0.8 s, a period within which the flow was highly unsteady and intensive turbulent mixing occurred, and the turbulence was likely anisotropic. The time of occurrence of the peak velocity fluctuation was different, although only by a few milliseconds, in every single run, and the recirculation velocity, defined as the minimum velocity reached at the end of the deceleration phase, occurred at slightly different time as well. Hence, the ensemble-averaging over a large number of runs tended to 'smooth' the maximum velocity fluctuation and recirculation velocity. In practice, the number of runs must be large enough to accurately represent the turbulent fluctuating quantities in the rapidly varied flow but not too large so that the attenuation is minimized. Herein, 25 and 35 runs were considered most suitable for ensemble-average velocity measurements using the Profiler, with 25 runs being selected because of time limitations.

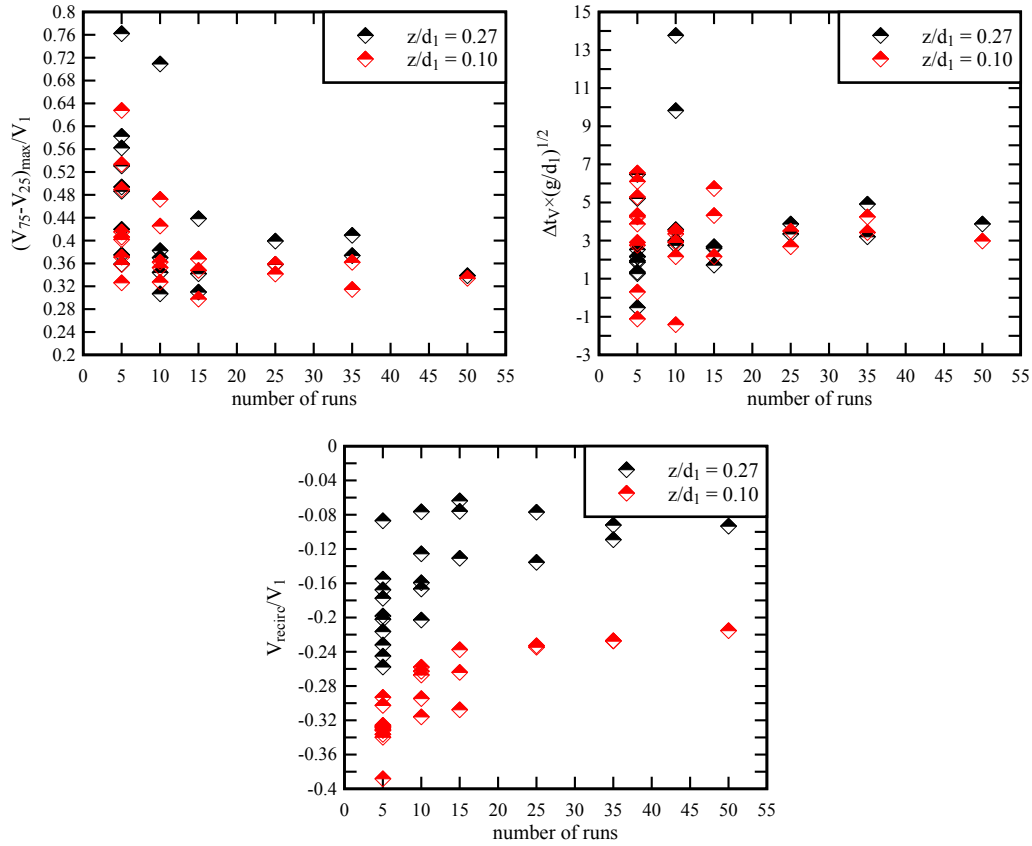


Figure 8. Sensitivity analysis of the characteristic turbulent fluctuating properties in a positive surge at two vertical elevations: ensemble-averaged results over different number of runs; Profiler sampling alone (Setup 1).

6. CONCLUSION

New steady and unsteady velocity measurements were conducted in open channel flows using a NortekTM ADV Vectrino II Profiler equipped with a fixed stem and down-looking head. Steady and unsteady velocity measurements using the Profiler showed a close agreement with experimental results obtained using a NortekTM ADV Vectrino+ for the same flow conditions, in terms of the instantaneous median velocity and velocity fluctuations, longitudinal velocity recirculation, longitudinal velocity deceleration, etc. The instantaneous velocity fluctuations were of the same order of magnitude between the Profiler and ADV results. A careful sensitivity analysis was conducted to test the number of runs appropriate for ensemble-averaging. The results indicated that the selection of 25 runs was suitable. Some instrumental error was observed. Outside the boundary layer, the Profiler tended to produce errors in terms time-averaged velocity data and velocity fluctuations for a number of points in a profile. Even at vertical elevations where the time-averaged velocity was meaningful, the vertical distribution of the velocity fluctuations contained errors.

Overall, the study demonstrated that the propagation of positive surges is a highly unsteady turbulent process, and the performance of ADV Vectrino II Profiler in such an unsteady turbulent flow was satisfactory, provided that a careful validation was undertaken for all Profiler outputs.

7. ACKNOWLEDGMENTS

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