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# Turbulence and Turbulent Events in Tidal Bores: Field Observations

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## Abstract

A tidal bore is a compressive wave of tidal origin, propagating upstream as the tidal flow turns to rising when a macro-tidal flood flow enters a funnel shaped river mouth with shallow waters. New field measurements were conducted in the Garonne River tidal bore at Arcins in 2015. Instantaneous velocity measurements were performed continuously at high-frequency prior to, during and after each bore. The bore occurrence had a marked effect on the velocity and turbulent Reynolds stress field, with large and rapid fluctuations, during the bore passage and the early flood tide. A turbulent event analysis was conducted in the highly-unsteady rapidly-varied tidal bore flow. The method detects bursting events by comparing the absolute value of an instantaneous turbulent flux with its standard deviation. This analysis, based upon basic concepts, was extended to the rapidly-varied, highly-unsteady tidal bore flood flow motion. The turbulent event data analysis showed relatively close results for all studies and all fluxes. A very large majority of turbulent events had a duration less than 0.01 s, with on average 20 turbulent events per second. During all studies, the event duration showed some tidal trend, with longer turbulent events immediately after the tidal bore passage, occurring simultaneously with sediment erosion processes.

## Introduction

Turbulence is not a Gaussian process, in particular in Nature, and many turbulent flows are often dominated by coherent structure activities and turbulent events. A turbulent event corresponds to a series of turbulent fluctuations containing more energy than the average turbulent fluctuations [6]. Turbulent event analyses were successfully applied to steady laboratory flows [7], and quasi-steady field observations [8, 11]. They were however never applied to unsteady rapidly-varied open channel flows, like a tidal bore.

A tidal bore is a compressive wave of tidal origin, propagating upstream as the tidal flow turns to rising when a macro-tidal flood flow enters a funnel shaped estuary with shallow waters [1, 12]. Figure 1 shows the tidal bore of the Garonne River in 2015. The occurrence of tidal bores has a significant impact on the natural systems, the bore propagation being associated with sediment scouring and massive suspension of bed materials [3, 5].

The tidal bore of the Garonne River was extensively investigated in the Arcins channel in 2010, 2012 and 2013 with a focus on turbulent and suspended sedimentary processes [2, 5, 9]. Herein new field measurements were repeated systematically at the same site in the Garonne River (France) on 29 August, 30 August, 31 August and 1 September 2015 and on 27 October 2015. Instantaneous velocity measurements were performed continuously at high-frequency (200 Hz) prior to, during and after each afternoon tidal bore. A detection of turbulence bursting events was developed based upon the technique of [8]. While it differs from more traditional event detection techniques, this method was found to be well-suited to tidal bore flow.

Figure 1. Tidal bore of the Garonne River (France) on 28 October 2015. Top: Arcins at 16:24 - note the pontoon on right where velocimeter was installed; Middle: Cambes, 29 min later and 9.6 km upstream of Arcins; Bottom: Langoiran, 21 min later and 6.6 km upstream of Cambes.

## Field investigation and instrumentation

Field measurements were performed in the tidal bore of the Garonne River (France), close to Lastrene, at a site previously used [2, 5, 9]. The Arcins channel is 1.8 km long, 70 m wide and about 1.1 to 2.5 m deep at low tide, between the Arcins Island and the river right bank (Fig. 1, Top). The bathymetric data indicated a progressive siltation of the Arcins channel at the sampling site between 2012 and 2015. Although the tides are semi-diurnal, the tidal data indicated slightly different periods and amplitudes typical of diurnal inequality.

Detailed field measurements were conducted under spring tide conditions between 29 August and 1 September 2015, and on 27 October 2015, while additional observations were performed on 28 August 2015, 26 October and 28 October 2015, with a tidal range between 5.85 m to 6.32 m, and tidal bore Froude numbers between 1.18 and 1.7 [10]. All measurements were started prior to the passage of the tidal bore and ended at least one hour after the bore passage.

On each day, free surface elevations were recorded using a survey staff, while instantaneous velocity components were measured using a Nortek™ ADV Vectrino+ equipped with a down-looking head. The ADV unit was fixed beneath a heavy pontoon and its control volume was located 1.0 m below the free-surface. The ADV system was sampled continuously at 200 Hz, starting at least 1 h before and ending at least 1 h after the bore passage. The velocity signal post-processing included the removal of communication errors, the removal of average signal to noise ratio (SNR) data less than 5 dB, the removal of average correlation values less than 60% and despiking using the phase-space thresholding technique. The percentage of good samples ranged between 60 and 90% for the entire data sets.

### Turbulent event analysis

A turbulent event may be defined as a series of turbulent fluctuations that contain more energy than the average turbulent fluctuations within a studied data section [6]. While more traditional event detection techniques were developed for steady flows [4], the detection of turbulence bursting events was herein based upon the technique of [8], since it was found to be a more robust method applicable to tidal bore flow. The method detects bursting events by comparing the absolute value of an instantaneous turbulent flux q (e.g. $q = v_x \times v_z$) with the standard deviation q' of that flux over the data section. That is, a turbulent event occurs when:

$$|q| > k \times q' \qquad (1)$$

where $|q|$ is the absolute value of the instantaneous flux q, k is a positive constant setting the threshold and q' is the standard deviation of the flux. Herein k =1 was selected following [8] and [11].

In the present study, the turbulent Reynolds stress components $v_x \times v_y$ and $v_x \times v_z$ were analysed, where $v_i = V_i - \overline{V_i}$ (i = x, y, z), with $\overline{V_i}$ being the low-pass filtered velocity, x the longitudinal coordinate positive downstream, y the transverse coordinate positive towards Arcins Island and z the vertical coordinate positive upwards. (The low-pass filtering was based upon a cut-off frequency $F_{cutoff}$ = 2 Hz [10] and the fluctuations corresponded to the high-pass filtered signals.) The standard deviation of the flux q' was calculated as: $q' = \overline{(q-\bar{q})^2}^{1/2}$, where each overbar denotes a low-pass filtering process.

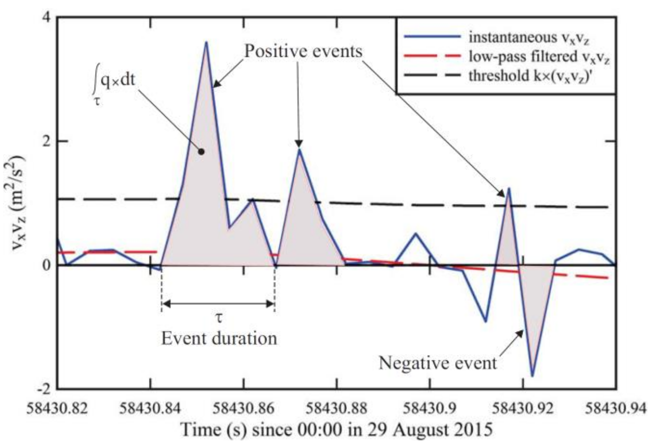



Figure 2. Momentum flux data collected on 29 August 2015 and turbulent flux event definitions

For each data set, the information of each detected event was summarised. Figure 2 shows four isolated events and introduces a number of basic definitions. The event duration τ is the time interval between the zeroes in momentum flux (e.g. $q = v_x \times v_z$= 0), nearest to the sequence of data points satisfying Equation (1). The dimensionless amplitude A of an event is the ratio of the averaged flux amplitude during the event to the long-term mean flux of the entire data section, and the relative contribution of an event to the total momentum flux of the data section is called the relative magnitude m.

### Basic observations

On 28 August 2015 afternoon, no tidal bore was observed at the sampling site. On 29, 30 and 31 August, 1 September and 27 October 2015, the tidal bore formed at the northern end of the Arcins channel. The bore extended rapidly across the entire channel width as a breaking bore in this very shallow region. The tidal bore was undular at the sampling location (Fig. 1 Top). While the bore was undular, the free-surface elevation rose very rapidly during the bore passage: i.e., by 0.3 m to 0.5 m in the first 10-15 s. More details on the water elevation data are presented in the next paragraphs. The tidal bore propagated up to the southern end of the channel for the entire channel length. At the sampling site and on each day, the bore passage was followed by a series of strong whelps lasting for several minutes, with a wave period about 1 s.

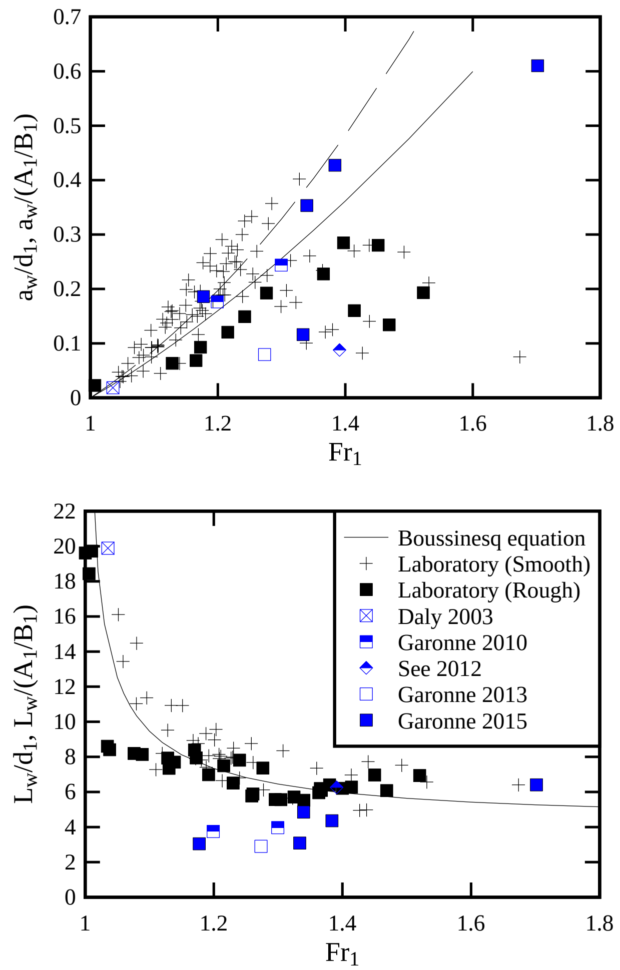



Figure 3. Free-surface characteristics of the undular tidal bore of the Garonne River (France). Top: secondary wave amplitude; Bottom: secondary wave length. Comparison between laboratory data on smooth and rough beds, and field observations. Same legend for both graphs

The tidal bore was characterised by a marked rise in free-surface elevation, as illustrated in Figure 1. The bore shape was characterised its Froude number $Fr_1 = (V_1+U)/(g \times A_1/B_1)^{0.5}$, where $V_1$ is the initial flow velocity positive downstream, U is the bore celerity positive upstream, g is the gravity acceleration, $A_1$ is the initial flow cross-section area and $B_1$ is the initial free-surface width (which were derived from bathymetric surveys conducted daily). Herein the Froude number ranged from 1.2 to 1.7, consistent with the undular nature of the bore except on 31 August 2015. On 31 August 2015, the bore front was undular on the channel centreline and towards to the right bank, but breaking close to the left bank.

The passage of the tidal bore was associated with a very rapid rise of the water elevation, followed by free-surface undulations or secondary waves. The dimensionless wave amplitude and wave length data are presented in Figure 3, in which the present data are compared to field and laboratory data as well as analytical solutions of the linear wave theory (dashed line) and of the Boussinesq equations (solid line). The results indicated an increase in wave amplitude $a_w/(A_1/B_1)$ with increasing Froude number up to $Fr_1$ = 1.3 to 1.4 (Fig. 3 Top). Such a maximum in wave amplitude was linked to the appearance of breaking at the first wave crest. For larger Froude numbers, the data tended to decrease with increasing Froude number. In Figure 3 (Top), the data for $Fr_1$ = 1.7 was an exception, possibly linked to the three-dimensional nature of the bore front on that day. The wave length data decreased with increasing Froude number (Fig. 3 Bottom). All data were close to a solution of the Boussinesq equation.

During the end of ebb tide, the current velocity decreased in the Arcins channel with time. Immediately prior to the bore, the surface velocity dropped down to +0.2-0.3 m/s at the channel centre. The tidal bore occurrence had a marked effect on the velocity field, as illustrated in Figure 4. This included a rapid flow deceleration and flow reversal during the bore passage, followed by large and rapid fluctuations of all velocity fluctuations during the early flood tide. The maximum flow deceleration ranged from -0.65 m/s$^2$ to less than -1.4 m/s$^2$.

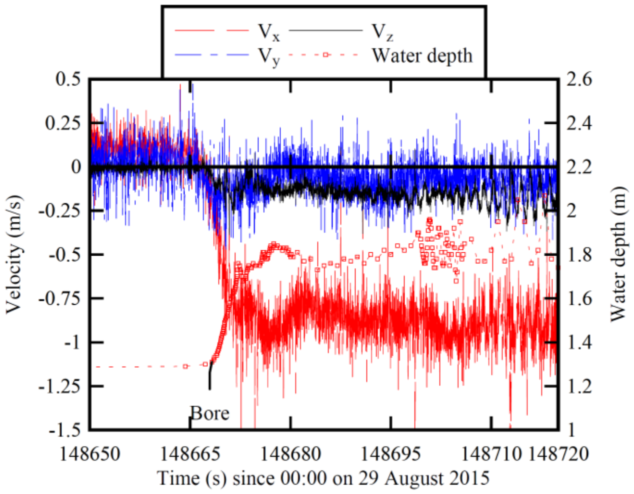



Figure 4. Time-variation of free-surface elevation and instantaneous velocity components during the tidal bore of the Garonne River (France) on 30 August 2015.

The bore passage was associated with large fluctuations of all velocity components, lasting throughout the flood tide. The flood flow was very energetic. The turbulent Reynolds stress tensor was calculated as the product of velocity fluctuations times the water density, the instantaneous turbulent velocity fluctuation v being calculated from the deviation to the low-pass filtered velocity. For all field data sets, the results indicated large turbulent shear stresses, together with large and rapid fluctuations, during the passage of and the early flood tidal flow after the tidal bore, for all Reynolds stress tensor components. Maximum instantaneous normal shear stress amplitudes in excess of 150 Pa were recorded, as well as maximum instantaneous tangential stress magnitude up to more than 100 Pa.

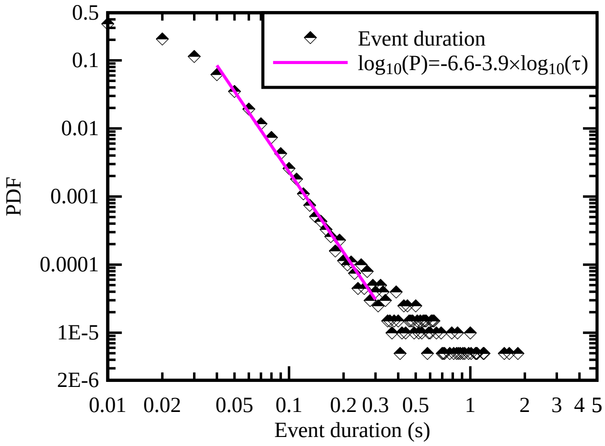
## Unsteady turbulent event results

The event amplitude and event duration for momentum fluxes $v_x \times v_y$ and $v_x \times v_z$ were calculated for the velocity data sets collected on 29, 31 August and 27 October 2015. Typical data are presented in Figure 5. The results highlighted a skewed distribution of event duration with a well-defined mode, consistent for all turbulent fluxes. Typically the event durations ranged from 0.002 to 2 s, with some extreme events longer than 2 s (less than $3 \times 10^{-4}$ %), although it is acknowledged that the low-pass filtering cutoff frequency (2Hz) might influence the upper range of data. When successive Reynolds stress data gave large values of opposite sign, events of very short duration could occur, sometimes for less than 0.002 s. Herein a majority of the events (~60%) lasted less than 0.02 s, and only 0.2% of events had a duration longer than 0.1 s. In Figure 5a, the normalised probability density function showed a linear decrease with increasing event duration between 0.04 s to 0.3 s.

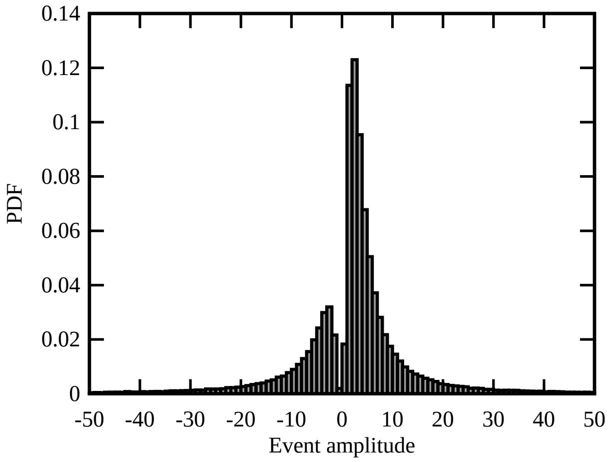
The event amplitude data showed a bi-modal distribution for all fluxes, with a mean value close to 0 (Fig. 5b). The higher mode with probability of 6% to 10% was associated with positive event amplitudes ranging from 2 to 3. The lower mode was associated with negative event amplitudes between -2 to -3, and a probability about 3-4%. The event amplitude data showed that the majority of the events were associated with positive amplitudes for all fluxes. However, negative events and positive events had amplitude magnitude of the same order of magnitude.

The relationship between event amplitude and duration was investigated for all data sets. Figure 5c shows a typical result for all events detected throughout the sampling duration on 31 August 2015. For all flux data, the event duration ranged from 0.002 s to 2.5 s, and the event amplitude ranged from $-1 \times 10^7$ to $1 \times 10^7$. The relationship between event amplitude and duration showed a diamond-like shape, symmetrical about the horizontal axis (event duration) for over 99.8% of the data. The event amplitude magnitude increased with event duration, for event duration $\tau$ of less than 0.01 s. For $\tau > 0.01$ s, the event amplitude magnitude decreased with increasing event duration. The results implied maximum event amplitudes associated with event durations of approximately 0.01 s. Extremely long events, with over 2 s duration, were associated with small amplitude magnitude between 0 and 10. The symmetrical shape of the data sets indicated an equal percentage of positive and negative events. The tangential momentum flux $v_x \times v_y$ data showed a large scatter towards higher values of amplitude and duration, while the momentum flux $v_x \times v_z$ data presented a more concentrated data distribution towards the line of symmetry.

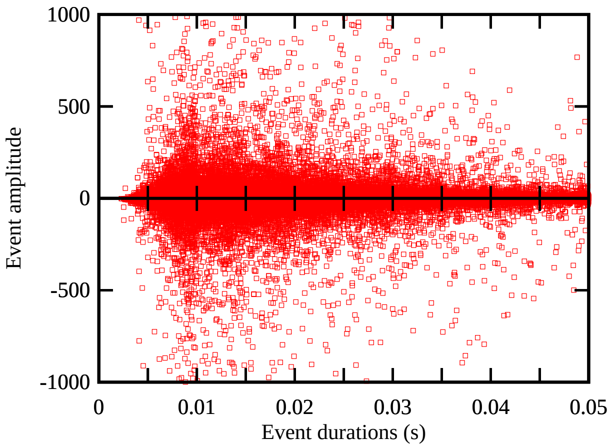
Since the propagation of tidal bore in a natural river is a highly unsteady and turbulent process, the time-variations of turbulent event duration and amplitude were analysed with respect to the time-variations of the free-surface elevation and bore passage. For all momentum fluxes, large fluctuations in event amplitude and durations were observed throughout the entire sampling duration. For the data collected on 29 and 31 August 2015, the event duration for all fluxes showed an abrupt peak with values in excess of 2 s shortly after the bore passage. Such extremely long events were associated with comparatively small magnitude of amplitude: i.e., less than 1. Such a peak in event duration was likely associated with the rapid increase of suspended sediment concentration and rapid increase in the suspended sediment flux magnitude, shortly after the bore passage (~ 100 to 400 s) It would correspond to a two-stage erosion process during the tidal bore propagation: an initial surface erosion and some delayed bulk mass erosion [5].




(a) Normalised probability density functions of event duration




(b) Normalised probability density functions of event amplitude




(c) Relationship between event amplitude and event duration

Figure 5. Event amplitudes and event durations for the momentum flux $v_x \times v_z$, on 31 August 2015

## Conclusion

The tidal bore of the Garonne River was extensively investigated in the Arcins channel in 2015. Instantaneous velocity measurements were performed continuously at high-frequency (200 Hz) prior to, during and after several afternoon tidal bores. The tidal bore occurrence had a marked effect on the velocity and turbulent stress field, including a rapid flow deceleration and flow reversal during bore passage.

A turbulent event analysis was conducted in the highly-unsteady rapidly-varied tidal bore flow, based upon basic concepts, in which turbulent bursting events were defined in terms of the instantaneous turbulent flux. Close results for all studies and all fluxes were observed. Namely (a) a very large majority of turbulent events had a duration less than 0.01 s; (b) there were on average 20 turbulent events per second; (c) for all studies, the event duration showed some tidal trend, with longer turbulent events immediately after the tidal bore passage, occurring simultaneously with sediment erosion processes; and (d) a comparison between present data and a field study in a micro-tidal estuary [11] showed shorter dimensionless event durations, larger event amplitudes and magnitudes. Altogether the present analysis suggested that the turbulent event analysis may provide quantitative details into the turbulent bursts that are responsible for major mixing and sedimentary processes.

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