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On turbulence and turbulent events in a breaking bore

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ABSTRACT

A breaking bore is a highly unsteady turbulent motion that may affect both riverine and estuarine systems. Like many steady turbulent flows, the turbulent motion is dominated by intense coherent structure and turbulent event activities. A novel analysis of unsteady turbulent events is developed for transient breaking bores in which turbulent bursting events are defined in terms of the instantaneous relative turbulent flux. Using new physical data collected in a large facility under controlled flow conditions, the data analysis is applied to a breaking bore. The unsteady event data show some intense bursting during the flow deceleration associated with the bore passage. The results indicate that a turbulent event analysis may deliver valuable quantitative details into the turbulent bursts beneath bores, with applications relevant to turbulent mixing and sedimentary processes.

1. Introduction

In an estuary, a bore may propagate upstream in response to macrotidal conditions (tidal bores) and offshore tsunami generation [2,18]. In a river, the sudden failure of a dam wall can cause a dam break wave led by a bore front propagating downstream [10,13]. The shape of the bore is linked to its Froude number defined as: $(V_1 + U)/(g.d_1)^{1/2}$, with V_1 the initial velocity, U the bore celerity, g the gravity constant, and d_1 the initial depth of the flow [3]. When the Froude number is larger than 1.4 to 1.6, the bore is characterised by a well-defined breaking roller [6,12] (Fig. 1). Fig. 1 illustrates two breaking bores. Key features of the roller include a discontinuity of the free-surface and pressure and velocity fields, while its toe acts as a line source of vorticity and entrapped air [11,20].

Turbulence is not a truly random process [1]. Many geophysical flows are subjected to intense eddy activities and events. A turbulent event is a series of turbulence fluctuations carrying more energy than the average turbulence fluctuations within the investigated data set [14]. Turbulent events are linked to bursting, and associated with major sediment processes and contaminant transport [5,16,17]. Turbulent events were successfully investigated in a number of large-scale applications assuming quasi-steady flows [15,19]. The application to transient flow situations is very recent [9].

In the current note, a turbulent event analysis is developed for a breaking bore, extending the work of Leng et al. [9] and applied to some new physical data set. The method is based upon a definition of turbulent bursting in terms of the instantaneous relative turbulent flux. The outcomes give an insight into the complicated transient turbulence beneath a breaking bore.

2. Physical modeling and signal analysis

The physical study was performed in a 19 m long 0.7 m wide tilting flume, with glass sidewalls and smooth PVC bed. The water discharge was supplied by two pumps, delivering a constant flow rate $Q = 0.099$ m^3/s. The initial flow conditions corresponded to a water depth $d_1 = 0.09$ m for a bed slope $S_o = 0.0077$. A breaking bore was generated by closing rapidly and fully a downstream Tainter gate, located at $x = 18$ m, where x is measured from the upstream of the channel. The duration of the gate closure was less than 0.3 s to minimize any impact of the gate on the bore characteristics. The bore propagated upstream with a celerity $U = 0.6$ m/s, corresponding to a Froude number Fr = 2.1. The water surface levels were recorded using a number of Acoustic Displacement Meters (ADMs) Microsonic^{TM} Mic + 25/IU/T. An Acoustic Doppler Velocimetry (ADV) Nortek^{TM} Vectrino+ (Serial No. VNO 0436) was utilised to measure the instantaneous velocity. The ADV was installed at $x = 8.5$ m and sampled synchronously with the ADMs at 200 Hz. Fig. 1B shows a photograph of the breaking bore.

A turbulent event is a series of turbulence fluctuations containing more energy than the 'average' turbulence fluctuation. Herein, the detection of a bursting event was based upon an extension of the approach of Narasimha et al. [15]. In steady and quasi-flows,

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(A) Tidal bore of Qiantang River at Jiuxi (China) on 20 September 2016 - Bore propagation from left to right (shutter speed: 1/320 s)

(B) Laboratory experiment - Flow conditions: Q = 0.099 m³/s, Fr = 2.1, S_o = 0.0077, bore propagation from left to right (shutter speed: 1/1,000 s)

Fig. 1. Breaking bores.

a turbulent event is detected when the magnitude of an instantaneous turbulent flux, e.g. $q = v_x v_y$, is greater than the standard deviation q' of the flux times a constant [15,19]. In a highly-transient flow like a bore, the standard deviation is meaningless. In the current study, a turbulent event is defined by comparing the deviation of an instantaneous flux from its ensemble-median to the difference between the third and first quartiles times a threshold constant:

$$|q - \bar{q}| > k(q_{75} - q_{25}) \quad (1)$$

where k is the constant, $\bar{q}$ is the instantaneous ensemble-median flux, q_{25} and q_{75} are respectively the first and third quartiles of the instantaneous flux ensemble. For a Gaussian distribution of the flux data about its mean, q_{75}-q_{25} would equal 1.3 times the standard deviation. The event duration τ is defined between the zero crossings of the flux fluctuation, e.g. as in Fig. 2. Fig. 2 shows a typical time variation of instantaneous flux fluctuations. The dimensionless amplitude A of a turbulent event is the ratio of the averaged flux of an event to the mean flux over the whole data set, while the relative contribution of an event to the total momentum flux, for a data section, is called the relative magnitude m. A and m are defined respectively as:

$$A = \frac{1}{\tau} \int_{\tau} \left(\frac{q}{\bar{q}} - 1 \right) dt \quad (2)$$

$$m = \frac{A\,\tau}{T} \quad (3)$$

Earlier field studies applied a threshold constant $k = 0.77$, i.e. $k = 1/1.3$ [9,15,19]. In the steady flow prior to the bore arrival, a sensitivity analysis was undertaken in terms of the tangential stresses $v_x v_z$ and $v_x v_y$ for $0 < k < 1.54$ and at the vertical elevation $z/d_1 = 0.13$. The data analysis indicated a decreasing number of turbulent events with increasing threshold constant, with a large negative gradient for $k < 0.77$, possibly related to some electronic noise in the ADV. The median event duration τ, event amplitude A and magnitude m increased with increasing threshold k, regardless of the turbulent flux. All data presented larger gradients for

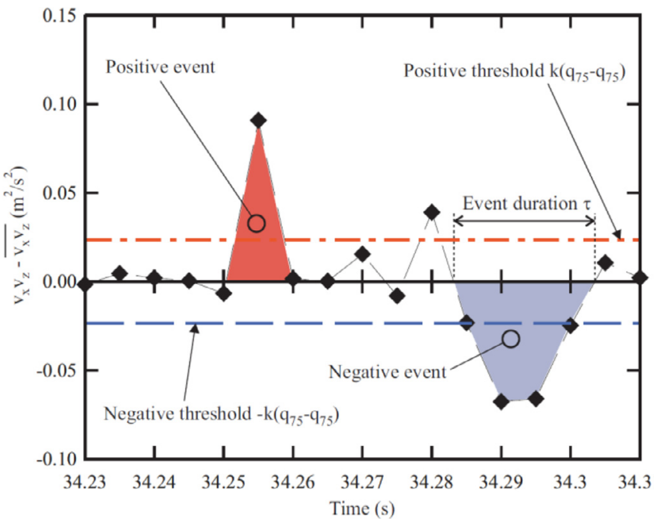

Fig. 2. Definition of turbulent flux event in terms of instantaneous tangential stress $v_x v_z$, showing both positive and negative flux events - Flow conditions: $Q = 0.099$ m³/s, $x = 8.5$ m, $z/d_1 = 0.13$.

$k < 0.77$, than for k 0.77, hinting that a large value of k would filter out a sizeable amount of small-duration turbulent events. The impact of threshold constant was also tested in terms of the first four statistic moments of turbulent event duration, amplitude and magnitude. Although fluctuating data were recorded for k 0.15, a monotonic data trends was observed for k 0.15. Altogether, the results of this sensitivity analysis suggested that a threshold constant within $0.77 < k < 1.54$ would be suitable in steady flows.

In a breaking bore, the unsteady flow motion consists of a rapid deceleration followed an early flood flow immediately after the bore passage [8]. A further sensitivity analysis was similarly performed in terms the threshold constant k for both deceleration and early flood flow sequences, using $0 < k < 1.92$. Typical results are presented in Appendix A (supplementary material). With increasing threshold k, the number of unsteady turbulent events per second decreased dramatically for $k < 1$, tending to some asymptotic value for $k > 1$. A marked increase in unsteady turbulent event duration was seen with increasing k for $k < 1$, with a more moderate trend for k 1. The unsteady turbulent event amplitude and magnitude data showed symmetrical distributions for positive and negative events about the horizontal x-axis, with increasing absolute values with increasing k. Herein, the value $k = 1$ was adopted for the unsteady bore motion analysis.

3. Basic flow patterns

The propagation of a breaking bore is a highly turbulent, three-dimensional process (Fig. 1). The rapid Tainter gate closure induced a violent bore generation, with water piling up against the closed gate. After formation, the bore roller initially accelerated, before decelerating until reaching a quasi-constant celerity U. At the sampling location ($x = 8.5$ m), the bore was fully-breaking (Fig. 1B). The leading edge of the bore was characterised by a sudden increase in flow depth, intensive air entrainment and strong turbulence mixing. The water surface ahead of the roller was flat and the passage of the roller induced a marked discontinuity in the water elevation (Fig. 3).

The ensemble-median longitudinal velocity data showed a marked deceleration for all elevations. Both the transverse and vertical velocity data fluctuated about zero value in the steady flow, and they presented large fluctuations during and after the passage of the breaking roller. The finding hinted the occurrence of large

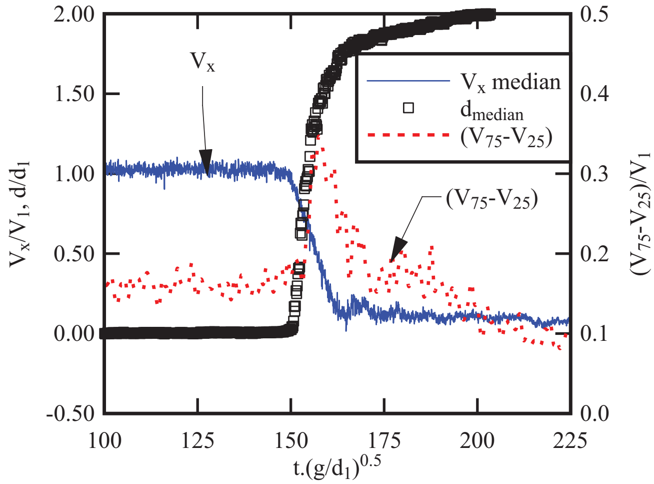

Fig. 3. Dimensionless time variations of ensemble median water depth and ensemble median longitudinal velocity V_x and velocity fluctuation (V_{75}-V_{25}) during a breaking bore passage - Velocity sampling location $x = 8.5$ m, $z/d_1 = 0.13$, Fr = 2.1.

vortical structure in the longitudinal or vertical directions. The instantaneous velocity fluctuations V_{75}-V_{25}, defined as the difference between the third and first quartiles, highlighted a sharp increase in velocity fluctuations during the bore passage for all three velocity components, at all elevations. Fig. 3 presents typical experimental data.

4. Transient turbulent event properties

During the passage of the bore, the rapid increase in water level induced a major modification in velocity fields. Vertical distributions of unsteady turbulent event data are reported in Appendix B (supplementary data). The results showed consistent numbers of events per second between the two different flow sequences. For a given turbulent flux, the event duration in the deceleration phase was slightly larger than the event duration during the early flood flow, and the large number of events corresponded to small event durations. The data in terms of the unsteady event amplitude and relative magnitude for the positive event and negative events showed a quasi-symmetrical distribution about zero amplitude, suggesting similar patterns between positive and negative events. For a given turbulent flux, the event amplitude during the deceleration process was significantly larger than the amplitude of the early flood flow phase. Further, the amplitude of $v_x v_y$ were relatively higher than $v_x v_z$, implying a more intense turbulent process in the x-y horizontal plane. The relative magnitude data showed higher values during the deceleration phase than during the early flood flow motion, hinting that the unsteady turbulent events had a major contribution to the total turbulent flux.

A comparison study of the unsteady turbulent event analysis at the vertical location $y/d_1 = 0.13$ was conducted for different transverse locations (data not shown). The results showed transverse variations in turbulent event characteristics, without definite trend. The transverse fluctuations might reflect the three-dimensional nature of the bore roller, with the existence of transverse vortical structures discussed by Leng and Chanson [7] and Chanson [4]. Probability distribution functions (PDFs) of instantaneous transient event duration and amplitude are presented in Fig. 4 for three sequences: steady flow, deceleration phase and early flood flow. The data showed a right skewed distribution of transient event duration, with most data ranging from 0.005 s to 0.06 s. The event amplitude PDFs presented quasi-symmetrical distributions about the zero value (Fig. 4B).

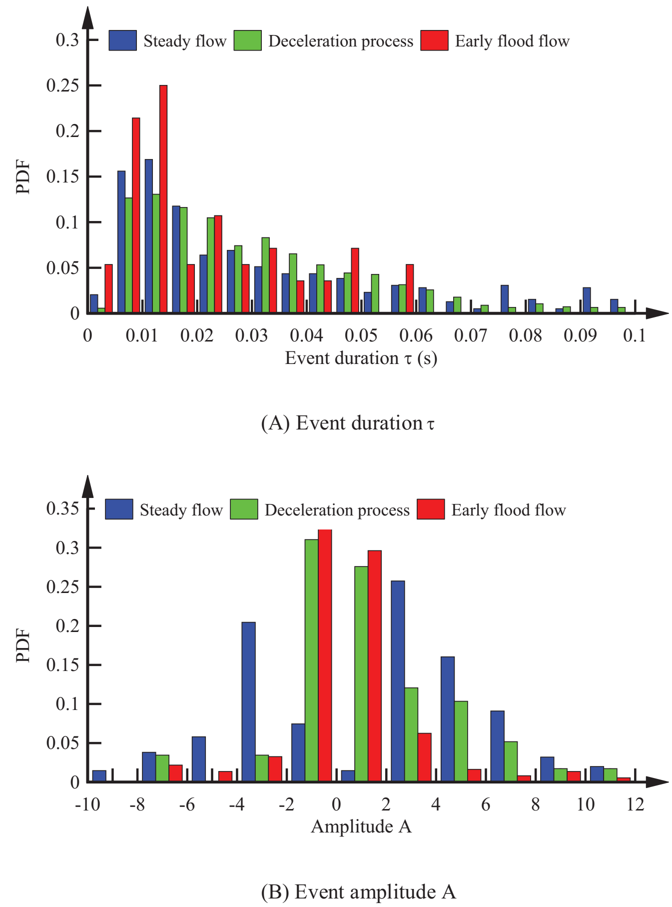

Fig. 4. PDF of turbulent event duration and amplitude for turbulent flux $v_x v_y$ in a breaking bore - Flow conditions: $Q = 0.099$ m^3/s, $x = 8.5$ m, $z/d_1 = 0.59$, Fr = 2.1.

It is worth noting that any event duration less than 0.01 s is possibly not meaningful and the peak in event duration about 0.01 s could be a typical period of the instrument Doppler noise from ADV. Indeed, Leng et al. [9] reported that velocity data might be biased by the Doppler noise from frequency above 30–40 Hz.

5. Conclusion and future work

The current study indicates that a turbulent event analysis may be conducted in a transient turbulent flow like a breaking bore. The approach requires an ensemble data set, by repeating systematically under carefully-controlled conditions the experiments, yielding the instantaneous ensemble statistics of the bore properties. A novel turbulent event analysis was developed for the transient flow. The sensitivity analysis of the threshold constant k suggested a value $k = 1$ in the transient bore motion.

The ensemble-median results showed an increase in the water depth and rapid decay in streamwise velocity during the breaking bore passage. The unsteady turbulent event results highlighted that, for a given turbulent flux, the deceleration phase presented larger event duration, amplitude and relative magnitude than the early flood flow phase, indicating intense bursting process during the flow deceleration. Overall, the results indicated that the turbulent event analysis may provide valuable quantitative details into the turbulent bursts that are responsible for major mixing and sedimentary processes.

Decleration of Competing interest

The authors have no conflict of interest or competing interest

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mechrescom.2020.103478.

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On Turbulence and Turbulent Events in a Breaking Bore. Appendix I - Effect of the event threshold constant k on the ensemble-median turbulent event characteristics

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In the current study, a turbulent event is defined by comparing the deviation of an instantaneous flux from its ensemble-median to the difference between the third and first quartiles times a threshold constant, because the mean and standard deviation are meaningless parameters in a highly-transient turbulent bore. A turbulent event was herein defined as:

$$\left|q-\overline{q}\right| > k(q_{75}-q_{25}) \qquad (I.1)$$

where q is an instantaneous turbulent flux, e.g. $q = v_x v_y$, $\overline{q}$ is the instantaneous ensemble-median flux, k is the constant, q_{25} and q_{75} are respectively the first and third quartiles of the instantaneous flux data set.
The event duration τ is defined between the zero crossings of the flux fluctuation. The dimensionless amplitude A of a turbulent event is the ratio of the averaged flux of an event to the mean flux over the whole data set, while the relative contribution of an event to the total momentum flux, for a data section, is called the relative magnitude m, both parameters being defined as:

$$A = \frac{1}{\tau}\int_{\tau}\left(\frac{q}{\overline{q}}-1\right)dt \qquad (2)$$

$$m = \frac{A\,\tau}{T} \qquad (3)$$

In a breaking bore, the unsteady flow motion consists of a rapid deceleration followed an early flood flow immediately after the bore passage (Leng and Chanson 2016). A sensitivity analysis was similarly performed in terms the threshold constant k for both deceleration and early flood flow sequences, using 0 < k < 1.92. Typical results are presented in Figure I-1. With increasing threshold k, the number of unsteady turbulent events per second decreased dramatically for k < 1, tending to some asymptotic value for k >1. A marked increase in unsteady turbulent event duration was seen with increasing k for k < 1, with a more moderate trend for k > 1. The unsteady turbulent event amplitude and magnitude data showed symmetrical distributions for positive and negative events about the horizontal x-axis, with increasing absolute values with increasing k. Herein, the value k = 1 was adopted for the unsteady bore motion analysis.

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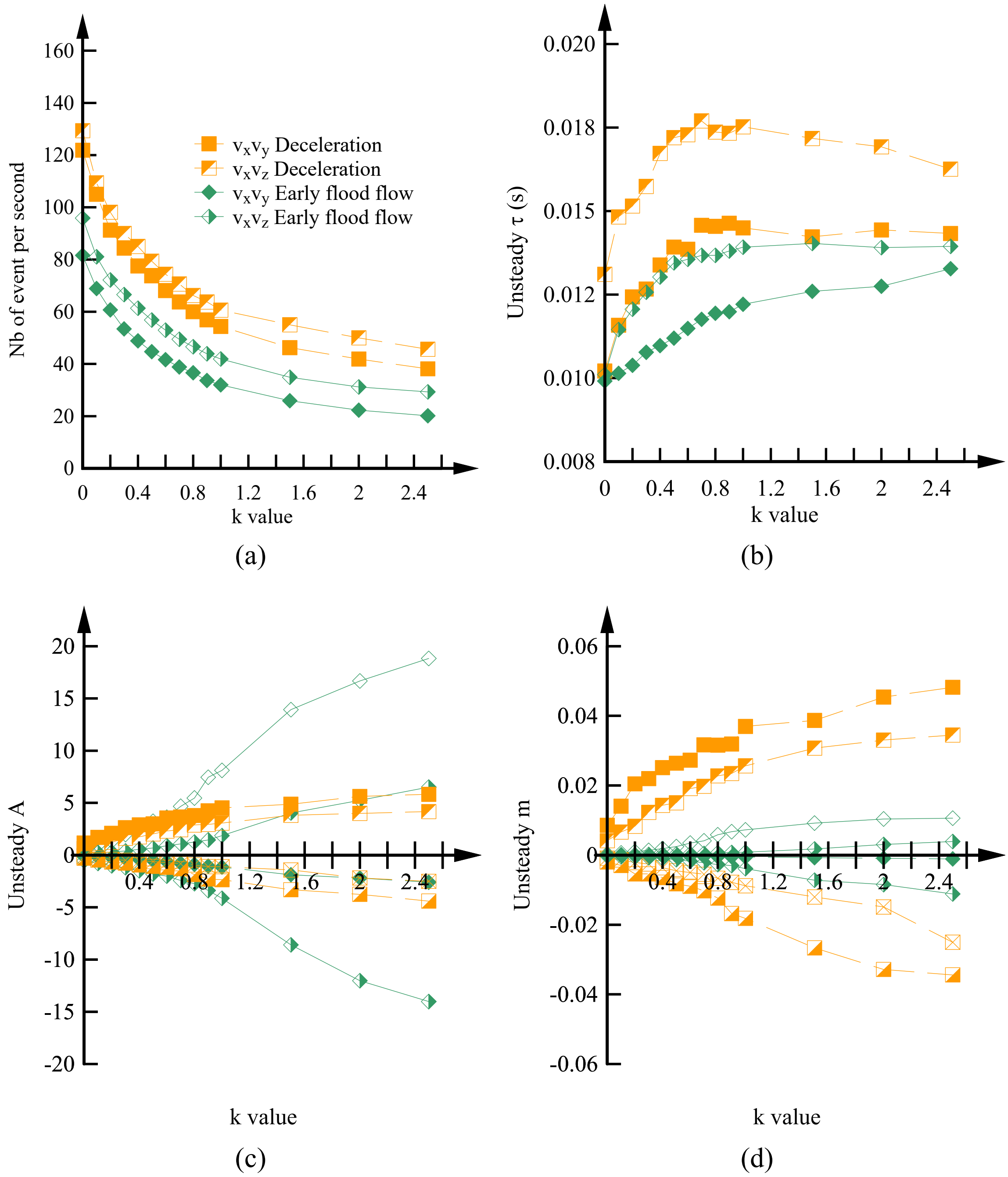

Fig. I-1 - Effect of turbulent event threshold constant k on ensemble-median turbulent event characteristics during the deceleration and early flood flow of a breaking bore - Flow conditions: Q = 0.099 m^3/s, x = 8.5 m, z/d_1 = 0.067, y/B = 0.5, Fr_1 = 2.1. (a) Number of Unsteady turbulent event per second; (b) Unsteady turbulent event duration; (c) Unsteady turbulent event amplitude; (d) Unsteady turbulent event magnitude

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On Turbulence and Turbulent Events in a Breaking Bore. Appendix II - Vertical distributions of ensemble-median transient turbulent event properties

by Rui Shi ([1]), Xinqian Leng ([1,2]) and Hubert Chanson ([1]) (*)
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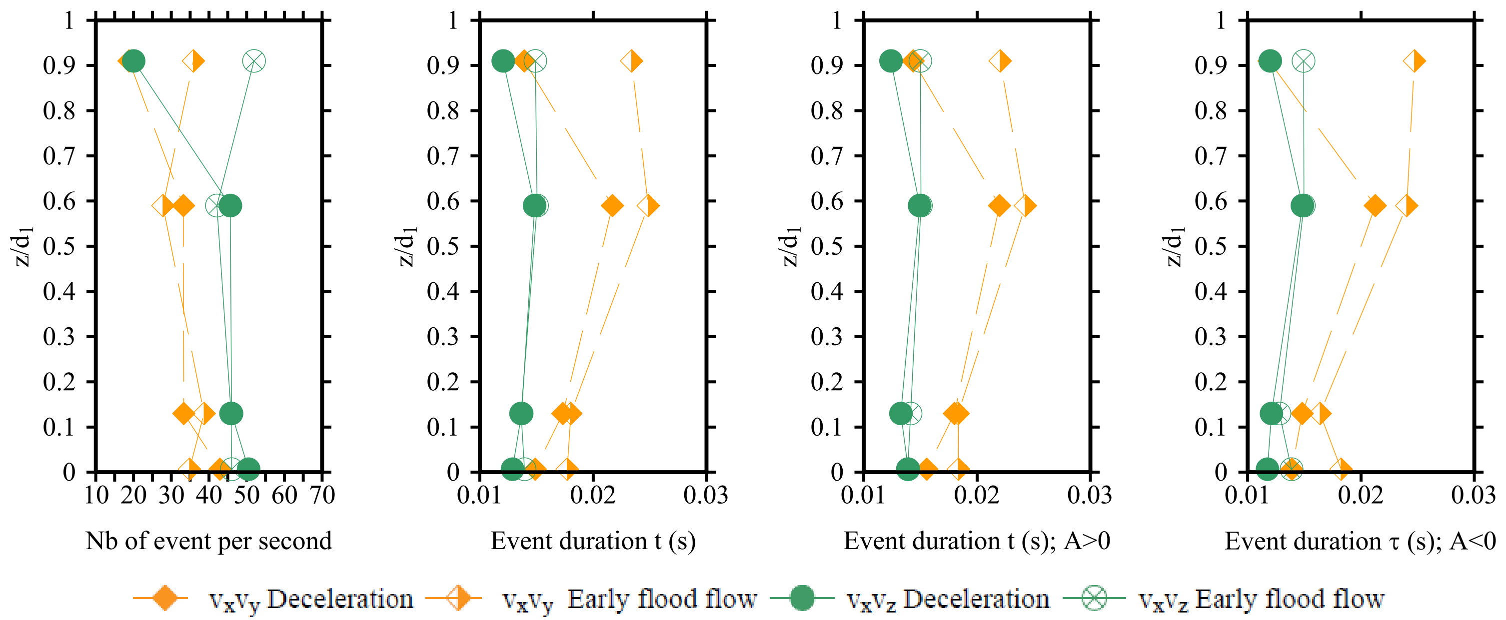

(a) Number of event (b) Event duration (c) Event duration A > 0 (d) Event duration A < 0

Fig. II-1 - Vertical distributions of ensemble-median values of unsteady turbulent event properties during deceleration and early flood flow phases - Flow conditions: Q = 0.099 m^3/s, x = 8.5 m, Fr = 2.1, y/B = 0.50 (channel centreline)

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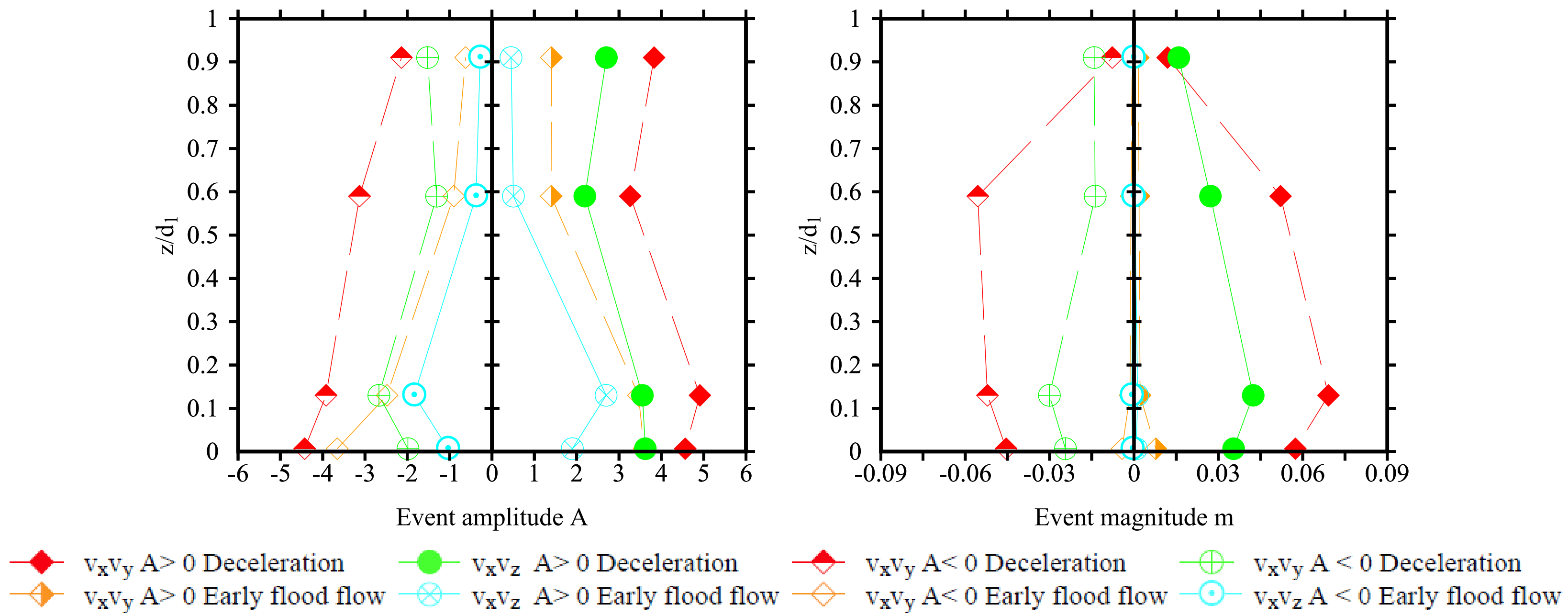

(e) Event amplitude (f) Event magnitude

Fig. II-1 - Vertical distributions of ensemble-median values of unsteady turbulent event properties during deceleration and early flood flow phases - Flow conditions: Q = 0.099 m^3/s, x = 8.5 m, Fr = 2.1, y/B = 0.50 (channel centreline)