17th Australasian Fluid Mechanics Conference
Auckland, New Zealand
5-9 December 2010

# Unsteady Turbulence in Tidal Bores: Ensemble-average or VITA?

**H. Chanson[1] and N.J. Docherty[1]**

[1]School of Civil Engineering
The University of Queensland, Brisbane 4072, Australia

## Abstract

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising in a macro-tidal estuary with a funnel shape. The tidal bore front is a hydrodynamic discontinuity. In this study, the characteristics of breaking tidal bores were investigated physically under controlled flow conditions. The highly unsteady turbulence properties were analysed using an ensemble-average (EA) technique and a variable interval time average (VITA) method. Both the EA and VITA methods showed some comparable long-term trends superposed to some rapid turbulent fluctuations, and close results in terms of the turbulent Reynolds stress components. But the variable interval time averaged (VITA) data based upon a single run presented some non-negligible differences compared to the ensemble-averaged (EA) median results in terms of all velocity components.

## Introduction

A tidal bore is a wall of water propagating upstream as the tidal flow turns to rising and the flood tide rushes into a funnel shaped river mouth with shallow waters (Figure 1). The bore forms during the spring tides when the tidal range exceeds 5–6 m and the estuary bathymetry amplifies the tidal range [2, 10]. The bore front is a discontinuity of the water depth and of the velocity and pressure fields: i.e., it is a hydrodynamic shock. Some unsteady velocity measurements were performed using PIV and ADV techniques by Hornung et al. [5] and Koch and Chanson [6]. The data highlighted the strong turbulence induced during the bore passage, but these studies presented some instantaneous velocity data only. The characterisation of the unsteady turbulence remained incomplete.

In this study, the turbulence properties of breaking bores were investigated in laboratory under controlled flow conditions. The free-surface fluctuations and turbulent velocity components were measured simultaneously at relatively high frequency. The unsteady turbulent properties were analysed using an ensemble-average (EA) technique and a variable interval time average (VITA) method. The techniques were compared and the results provided a new understanding of the unsteady turbulent field in tidal bores.

## Turbulence Characterisation in Steady and Unsteady Flows

In a steady turbulent flow, the instantaneous velocity is typically decomposed into a time-averaged component $\overline{V}$ and a turbulent fluctuation v, with the instantaneous velocity $V = \overline{V} + v$. $\overline{V}$ is the time-averaged velocity component is defined as:

$$\overline{V} = \frac{1}{T} \times \int_{t-T/2}^{t+T/2} V \times dt' \tag{1}$$

in which the integration period T must be large such that the time-average becomes independent of the limits and of the time t.

When the flow is unsteady, a time average is meaningless because the long-term trend and the short-term, turbulent fluctuations differ [1, 7]. The unsteady turbulence may be analysed using a number of different techniques including ensemble-averaging (EA), phase-averaging and variable interval time averaging (VITA). The first technique is applicable to all unsteady flow conditions. The same experiment is repeated N times and the ensemble average is defined as:

$$\overline{V}(x,y,z,t) = \frac{1}{N} \times \sum_{i=1}^{N} V_i(x,y,z,t) \tag{2}$$

Figure 1. Breaking tidal bore of the Garonne River (France) on 28 September 2008. Bore propagation from right to left.

The turbulent velocity fluctuation v becomes the deviation of the instantaneous velocity V from the ensemble average [1]. The phase averaging method may be used for simple periodic flows (e.g. regular wave motion). The technique is not relevant to a shock and will not be discussed thereafter. The VITA technique distinguishes between the long-term trend and short-term fluctuation frequencies [9]. $\overline{V}$ is the low-pass filtered component, or variable-interval time average. A cutoff frequency $F_{cutoff}$ must be selected such that the time scale $1/F_{cutoff}$ is greater than the turbulent fluctuation time scale, and small with respect to the period for the time-evolution of the mean properties [4, 6].

## Experimental Setup and Instrumentation

The experiments were performed in a 12 m long, 0.5 m wide tilting flume (Figure 2). The channel was made of smooth PVC bed and glass walls and the water was supplied by a constant head tank. A fast-closing gate was located next to the channel downstream end. Two experiments were conducted with similar tidal bore conditions but different bed roughness (Table 1). The experimental conditions are summarised in Table 1 where Q is the initially steady flow rate, $S_o$ is the bed slope, $d_o$ is the initial flow depth at the sampling location, Fr is the tidal bore Froude number and U is the bore celerity positive upstream. One experiment was conducted on the smooth PVC invert. For the other experiment, the bed was covered with plywood sheets covered by natural blue granite gravels which were sieved between 4.75 mm and 6.70 mm, glued in resin and covered by a spray gloss surface finish. The hydraulic roughness of the gravel bed was tested, and the equivalent Darcy friction factor was $f = 0.036$ on average, corresponding to an equivalent sand roughness height $k_s = 3.4$ mm.

The flow rate was measured with two orifice meters that were calibrated on site with a volume per time technique. The percentage of error was expected to be less than 2%. In steady flows, the water depths were measured using rail mounted pointer gauges. The unsteady water depths were recorded using several acoustic displacement meters Microsonic™ Mic+25/IU/TC, with a response time of less than 50 ms and an accuracy of 0.2 mm. The turbulent velocity measurements were performed with an acoustic Doppler velocimeter (ADV) Nortek™ Vectrino+ equipped with a side-looking head (Figure 2B). The velocity range was set to 1.0 m/s, and the data accuracy was 1% of the velocity range. The translation of the ADV probe in the vertical direction was controlled by a fine adjustment travelling mechanism connected to a Mitutoyo$^{TM}$ digimatic scale unit. The error on the vertical position of the probe was less than 0.025 mm. Herein all the measurements were taken on the channel centreline, and the ADV and displacement sensors were synchronised and sampled simultaneously at 200 Hz. Further information on the experimental apparatus was reported in [3].

### Inflow conditions and bore generation

For each experimental run, the steady gradually-varied flow conditions were established for 5 minutes prior to the measurement start. The tidal bore was generated by the rapid partial closure of the downstream gate. The gate closure time was less than 0.15 s. After closure, the bore propagated upstream (Figure 2) and each experiment was stopped before the bore front reached the channel upstream end to avoid any wave reflection. The ADV measurements were conducted at x = 5 m downstream of the channel upstream end. In steady flows, the detailed velocity measurements indicated that the flow was partially-developed: $\delta/d_o = 0.47$ and 0.64 for smooth bed and fixed gravel bed respectively, where $\delta$ is the boundary layer thickness.

At several vertical elevations, a series of twenty instantaneous velocity records were repeated. The same well-defined initially steady flow conditions were established for each run. An ensemble-median of each instantaneous velocity component was produced for each vertical elevation. Similarly a VITA method was applied to each run using a cut-off frequency $F_{cutoff} = 2$ Hz derived upon a sensitivity analysis [3].

| **Q**<br>m3/s | **$S_o$** | **$d_o$**<br>m | **Fr** | **U**<br>m/s | **Bed** |
|---|---|---|---|---|---|
| 0.050 | 0 | 0.117 | 1.6 | 0.87 | PVC |
| | 0.002 | 0.126 | 1.5 | 0.88 | Gravel |

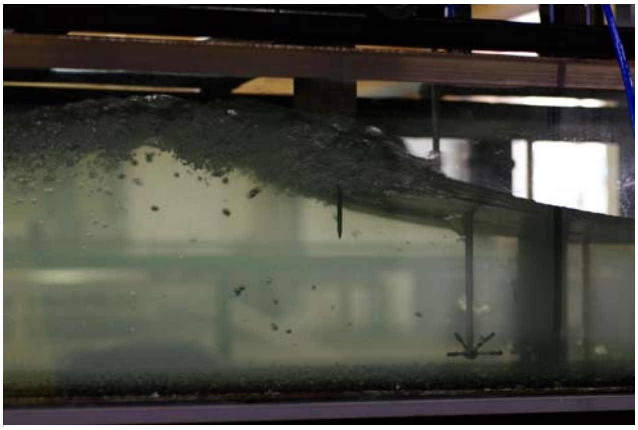
Table 1. Experimental flow conditions: turbulent velocity measurements.

## Basic Observations

Some visual observations were conducted for a range of flow conditions. Several patterns were observed to be functions of the tidal bore Froude number: $Fr=(V_o+U)/(g\times d_o)^{1/2}$ where $V_o$ is the initial flow velocity, and g is the gravity acceleration. For a Froude number between unity and 1.5 to 1.6, the tidal bore was undular: that is, the tidal bore front was followed by a train of secondary, quasi-periodic waves called undulations. For larger Froude numbers, a breaking bore with a marked roller was observed (Figure 2). The findings were identical for smooth and rough bed.

For the two experiments listed in Table 1, the free-surface and velocity components were sampled simultaneously on the channel centreline at x = 5 m for $0.0058 < z < 0.9$ m where z is the vertical elevation above the bed. On the fixed gravel bed, z was measured from the top of the gravel bed using a semi-circular footing with a 25.1 cm$^2$ area. On the smooth PVC bed, the tidal bore was a breaking surge, whereas, on the rough gravel bed, the bore had a marked roller followed by some residual undulations because of the slightly smaller Froude number (Figure 2).

(A) Looking downstream at the advancing breaking bore roller: Q = 0.050 m$^3$/s, $d_o$ = 0.120 m, Fr = 1.58, fixed gravel bed, shutter: 1/60 s.

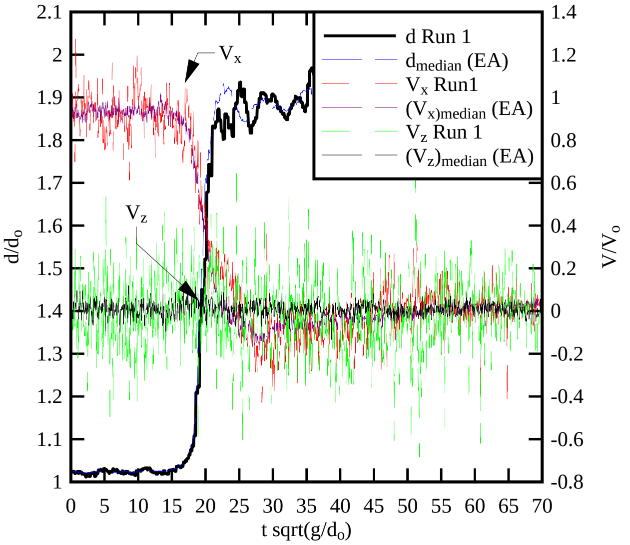


(B) Bore propagation from left to right: Q = 0.050 m$^3$/s, $d_o$ = 0.125 m, Fr = 1.5, fixed gravel bed, shutter: 1/100 s. Note the underwater bubble "trail" behind the bore roller (Left) and the ADV head on the right.

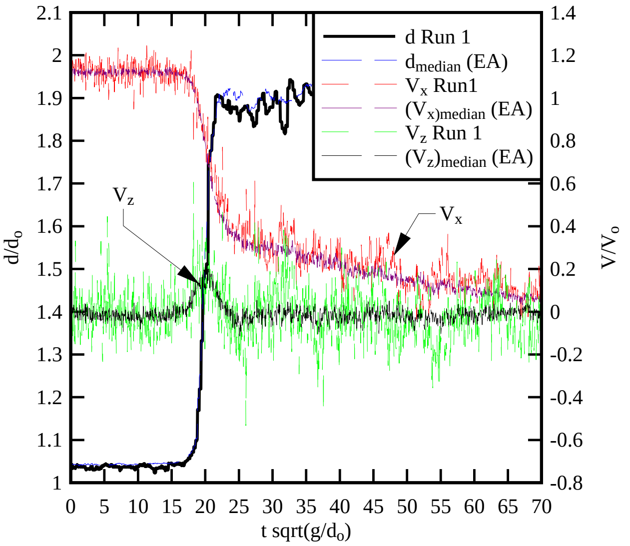
Figure 2. Breaking tidal bores in the laboratory channel.

### Turbulent velocity measurements

The turbulent velocity measurements showed that the arrival of the tidal bore and the sudden increase in water depth yielded a rapid change in longitudinal velocity to satisfy the conservation of mass. The longitudinal velocities were characterised by a rapid flow deceleration at all vertical elevations, while some large fluctuations of longitudinal, transverse and vertical velocity components were observed beneath the tidal bore. The tidal bore was basically a shock characterised by a sudden change in the velocity field [8]. The shock was followed by a highly turbulent flow motion with significant fluctuations of all velocity components. Typical Eulerian measurements are presented in Figure 3. Figure 3 shows the instantaneous free-surface elevation, longitudinal and vertical velocity components as function of time for one experiment.



(A) $z/d_o = 0.135$.



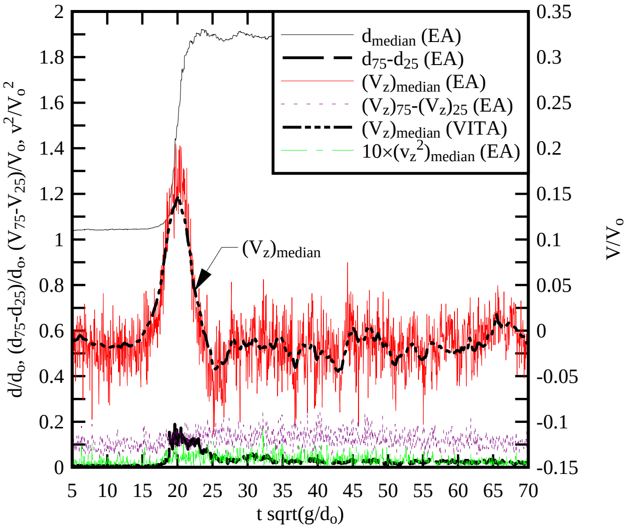
(B) $z/d_o = 0.733$.

Figure 3. Free-surface and turbulent velocity measurements under a breaking tidal bore. Smooth PVC bed configuration.

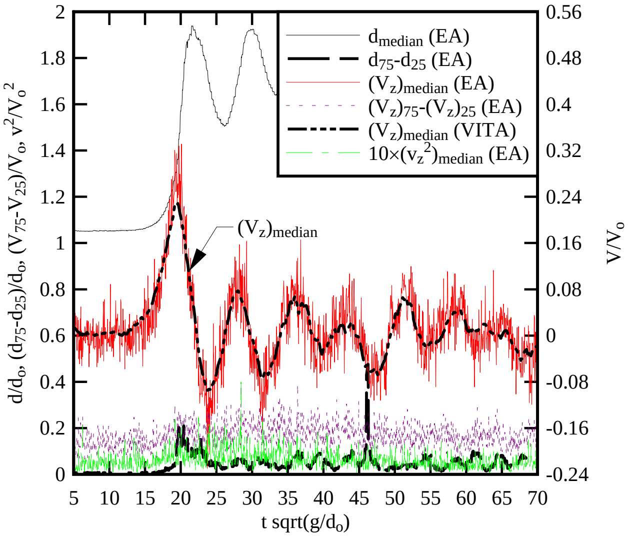
An ensemble-median of each instantaneous velocity component was produced at selected vertical elevations. Some results are presented also in Figure 3 and compared with the instantaneous data for one run. Both the instantaneous and ensemble-averaged (EA) data showed some key features of the unsteady turbulence in breaking tidal bores. These included a rapid flow deceleration during the passage of the tidal bore roller above the sampling volume, some negative longitudinal velocity component next to the bed (Figure 3A) highlighting some transient recirculation "bubble", and some positive vertical velocity component beneath the roller (Figure 3B). The latter was believed to be closely linked with the streamline curvature immediately prior to the bore roller. The experimental results showed further that the passage of the roller was associated in some large free-surface fluctuations, linked with some large longitudinal velocity fluctuations and some transient upwards flow motion ($V_z > 0$) (Figure 3).

## Unsteady Turbulence

The ensemble-averaged (EA) and variable-interval time averaged velocity data were compared at several elevations. An example is shown in Figure 4 for smooth and gravel bed at $z/d_o = 0.733$.. Figure 4 presents the ensemble-averaged median water depth $d_{median}$, the ensemble-averaged (EA) median velocity component $(V_z)_{median}$ (median of 20 runs, thick red dashed line), the median value of VITA velocities (median value of 20 runs, thick blue dashed line), as well the difference between 3rd and 4th quartiles for the water depth ($d_{75}$-$d_{25}$), the difference between 3rd and 4th quartiles of the velocity ($V_{75}$-$V_{25}$), and the variance of the velocity component $v_z^2$. Herein the median water depth and velocity components were ensemble-averaged over the 20 runs, while the variance was calculated for the 20 runs. The median VITA value was calculated as the median VITA for the 20 Runs.



(A) Smooth PVC bed configuration.



(B) Fixed gravel configuration.

Figure 4. Free-surface and vertical velocity measurements under a breaking tidal bore at $z/d_o = 0.733$. Comparison between EA and VITA techniques.

Both the ensemble-averaged (EA) and VITA data showed the same basic features. Simply the experimental results indicated that the ensemble-average (EA) median data were very close to the median VITA value for the 20 runs (Figure 4). The finding was interesting considering that the ensemble-averaging method required significantly less post-processing, and tended to support the sound selection of the threshold frequency $F_{cutoff}$ for the VITA technique. The results highlighted however some differences between the EA and VITA processing techniques. The time-variations of the VITA data for each individual run presented some significant scatter compared to the ensemble-averaged median value [3]. A single experiment could not provide a long-term trend comparable to the ensemble-averaged median value.

## Turbulent shear stresses

The instantaneous turbulent Reynolds stresses were calculated using the ensemble-averaging (EA) and variable interval time averaging (VITA) techniques for the experimental flow conditions summarised in Table 1. Some typical results are presented in Figure 5.

The turbulent stress results showed a number of seminal features. The Reynolds stress data suggested that the passage of breaking tidal bores was associated with large turbulent stresses at all vertical elevations. The magnitude of the Reynolds stress tensor components was significantly larger than prior to the bore passage. The finding was consistent with the observations of Koch and Chanson [6], who deduced the turbulent stresses from a VITA analysis performed on a single experiment.

## Conclusion

Herein the highly unsteady turbulence in breaking tidal bores was investigated experimentally under controlled conditions with two types of bed roughness: smooth PVC and gravel bed. Using an ensemble-averaging technique, the free-surface fluctuations of breaking bores were characterised. Immediately prior to the roller, the free-surface curved gradually upwards. The bore roller passage was associated with some large water depth fluctuations. Some detailed turbulent velocity measurements were performed at several vertical elevations during and shortly after the breaking bore passage. Both the instantaneous and ensemble-averaged velocity data highlighted some seminal features of breaking bores. A systematic comparison between ensemble-average (EA) and variable interval time average (VITA) velocity calculations was developed. The EA and VITA results showed some comparable velocity pattern with some relatively-long-term data trend superposed to some high-frequency turbulent fluctuations. The data showed however that the VITA calculations over a single experiment presented some non-negligible difference with the EA median value for all velocity components. Overall the study demonstrated the intensive turbulence and turbulent mixing under a breaking tidal bore.

## References

[1] Bradshaw, P. (1971). *An Introduction to Turbulence and its Measurement*. Pergamon Press, Oxford, UK, 218 pages.

[2] Chanson, H. (2010). Current Knowledge in Tidal bores and their Environmental, Ecological and Cultural Impacts. Environmental Fluid Mechanics, Vol. 10, No. 5 (DOI: 10.1007/s10652-009-9160-5). (In print)

[3] Docherty, N.J., and Chanson, H. (2010). Characterisation of Unsteady Turbulence in Breaking Tidal Bores including the Effects of Bed Roughness. *Hydraulic Model Report No. CH76/10*, School of Civil Eng., Univ. of Queensland, Brisbane, Australia, 112 pages.

[4] Garcia, C.M., and Garcia, M.H. (2006). Characterization of Flow Turbulence in Large-Scale Bubble-Plume Experiments. *Experim. in Fluids*, Vol. 41, No. 1, pp. 91-101.

[5] Hornung, H.G., Willert, C., and Turner, S. (1995). The Flow Field Downstream of a Hydraulic Jump. *Jl of Fluid Mech.*, Vol. 287, pp. 299-316.

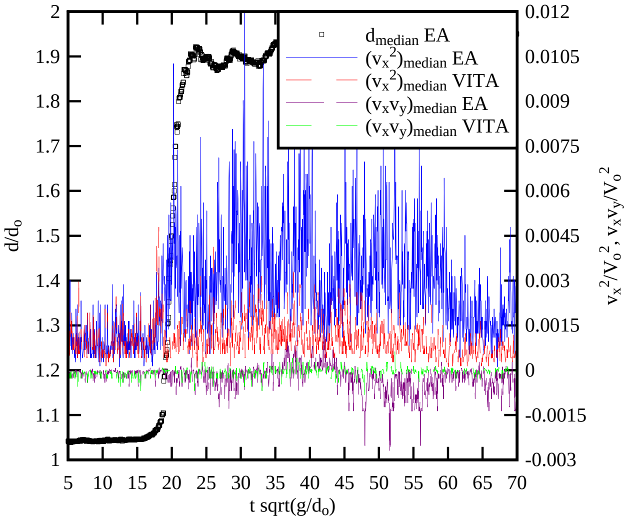
[6] Koch, C., and Chanson, H. (2009). Turbulence Measurements in Positive Surges and Bores. *Jl of Hydraulic Research*, IAHR, Vol. 47, No. 1, pp. 29-40.

[7] Liggett, J.A. (1994). *Fluid Mechanics*. McGraw-Hill, New York, USA.

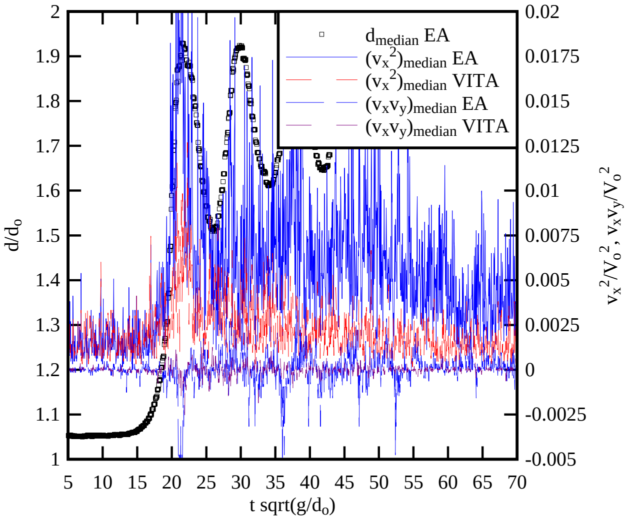
[8] Lighthill, J. (1978). *Waves in Fluids*. Cambridge University Press, Cambridge, UK, 504 pages.

[9] Piquet, J. (1999). *Turbulent Flows. Models and Physics*. Springer, Berlin, Germany, 761 pages.

[10] Tricker, R.A.R. (1965). *Bores, Breakers, Waves and Wakes*. American Elsevier Publ. Co., New York, USA.



(A) Smooth PVC bed configuration.



(B) Fixed gravel configuration.

Figure 5. Dimensionless ensemble-averaged median water depth $d_{median}/d_o$ and median Reynolds stresses $v_x^2/V_o^2$ and $v_x \times v_y/V_o^2$ on smooth PVC and fixed gravel beds at $z/d_o$ = 0.733. Comparison between ensemble-averaged and VITA calculations.