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# TIDAL BORES, AEGIR AND POROROCA: THE GEOPHYSICAL WONDERS

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## Abstract

Tidal Bores, aegir and pororoca are a surge of waters propagating upstream as the tidal flow turns to rising and the flood tide rushes into a funnel shaped river mouth. The bore forms during the spring tides when the tidal range exceeds 4 to 6 m and the rising tide waters are confined to the narrow funnelled estuary during the dry season. Herein the author aims to share his enthusiasm and passion for these geophysical wonders by explaining the basic theory, supported by field and laboratory observations. Behind the bore, some strong turbulent kinetic energy is produced next to the boundaries and some macro-turbulence is advected behind the tidal bore front. Transient fronts may also develop behind a bore inducing further secondary circulation. The paper intends to bridge the gap between the general knowledge, engineering practice and scientific expertise on the tidal bores.

**Key Words :** Tidal bores, Aegir, Pororoca, Hydrodynamics, Geophysical flows, Turbulent mixing, Secondary currents, Transient front, Mascaret, Benak, Bono, Burro.

## 1. INTRODUCTION

A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during the spring tide conditions when the tidal range exceeds 4 to 6 m and the flood tide is confined to a narrow funnelled estuary (Fig. 1). The origin of the word 'bore' is believed to derive from the Icelandic 'bara' ('billow', 'wave') indicating a potentially dangerous phenomenon: i.e., a breaking tidal bore (Coates 2007). An older name was 'eagre', used today for the tidal bore of the Trent River (UK). It derives from the Latin word 'augurium' or 'augurum' for 'fruit of the act of divination; omen, prophecy' meaning flood. The French name is 'mascaret' that is said to derive from the Gascony word 'masquaret' meaning a 'galloping ox' (Petit Robert 1996). In Japan, a tidal bore is called 'shio-tsunami' but a tsunami-induced bore is called 'kaisho'. In China, the "Silver Dragon" is the name of the Qiantang River tidal bore. Other local names of tidal bores include the 'benak' (Batang Lupar River, Malaysia), the 'bono' (Rokan River, Indonesia), 'le montant' (Garonne River, France), 'la barre' (Seine River, France), 'le mascarin' (Vilaine, France), the 'pororoca' (Amazon River, Brazil), the 'burro' (Colorado River, Mexico).

The tidal bore is a positive surge associated with a discontinuity in water depth and velocity, and the bore front is a flow singularity. In Nature, however, a tidal bore may have a variety of different shapes, and the photographs illustrate in particular that the bore front is not a sharp, vertical discontinuity of the water surface because of the necessary curvature of the streamline and the associated pressure and velocity redistributions (Fig. 1).

In this work, the author aims to share his enthusiasm and passion for tidal bores. A tidal bore is an integral part of our environment and cultural heritage, but it is an endangered phenomenon that can be too easily affected adversely by human interventions. The unique features of tidal bores are presented, discussed and explained. It is shown that they are geophysical wonders and yet very fragile.

(A) Pororoca in the Araguari River (Brazil) in 2007 (Courtesy of Jean-Michel Cousteau Ocean Adventures & Carrie Vonderhaar)

(B) Qiantang River tidal bore (China) on 11 Nov. 2003 (Courtesy of Dr Cheng Liu)

(C) Tidal bore of the Sée River in the Baie du Mont Saint Michel (France) on 19 October 2008 - Note the Mont Saint Michel in the background

(D) Tidal bore in Turnagain Arm, Cook Inlet (Alaska) (Courtesy of Ken Wilkinson)

(E) Tidal bore of the Batang Lupar River (Malaysia) (Courtesy of Mr Lim Hiok Hwa, Department of Irrigation & Drainage, Sarawak)

**Fig. 1 -** Photographs of tidal bores

## 2. BASIC THEORY

### 2.1 Presentation

A bore is an unsteady flow motion generated by the rapid water level rise at the river mouth during the early flood tide. When the ocean level rises with time during the early flood tide, the leading edge of the flood tide, called the tidal wave, becomes steeper and steeper, until it forms an abrupt front that is the tidal bore (Fig. 1). The flow properties immediately upstream and downstream of the bore front must satisfy the continuity and momentum principles: i.e., the Bélanger principle (Rayleigh 1908, Henderson 1966, Liggett 1994, Chanson 2004). Considering a tidal bore travelling upstream with a celerity U, the integral equations of conservation of mass and momentum give a series of relationships between the flow properties in front of and behind the bore front:

(1) $$\frac{d_2}{d_1} = \frac{1}{2}\left(\sqrt{1+8\times Fr_1^{\,2}} - 1\right)$$

(2) $$\frac{Fr_2}{Fr_1} = \frac{2^{3/2}}{\left(\sqrt{1+8\times Fr_1^{\,2}} - 1\right)^{3/2}}$$

where $Fr_1$ is the tidal bore Froude number defined as

(3) $$Fr_1 = \frac{V_1 + U}{\sqrt{g\times d_1}}$$

and the Froude number $Fr_2$ is defined as

(4) $$Fr_2 = \frac{V_2 + U}{\sqrt{g\times d_2}}$$

with g the gravity acceleration, V the flow velocity positive downstream towards the river mouth, d the water depth, and the subscript 1 refers to the initial flow conditions while the subscript 2 refers to the new flow conditions. Simply $d_1$ and $d_2$ are respectively the flow depths immediately before and after the tidal bore passage (Fig. 2).

The Froude number of the tidal bore $Fr_1$ is always greater than unity and ($Fr_1$-1) is a measure of the strength of the bore. If the Froude number $Fr_1$ is less than unity, the tidal wave cannot become a tidal bore. For a tidal bore Froude number between unity and 1.5 to 1.8, the bore front is followed by a train of well-formed, quasi-periodic waves called undulations, secondary waves or whelps (Fig. 2 & 3). This is the undular (non-breaking) bore. For larger Froude numbers $Fr_1$, the bore is characterised by a breaking front. Both types of tidal bores are illustrated in Figure 1. Energy considerations show that a tidal bore can occur only with a net flux of mass from downstream to upstream (Liggett 1994). This characteristic sets apart the tidal bore from a wave or soliton.

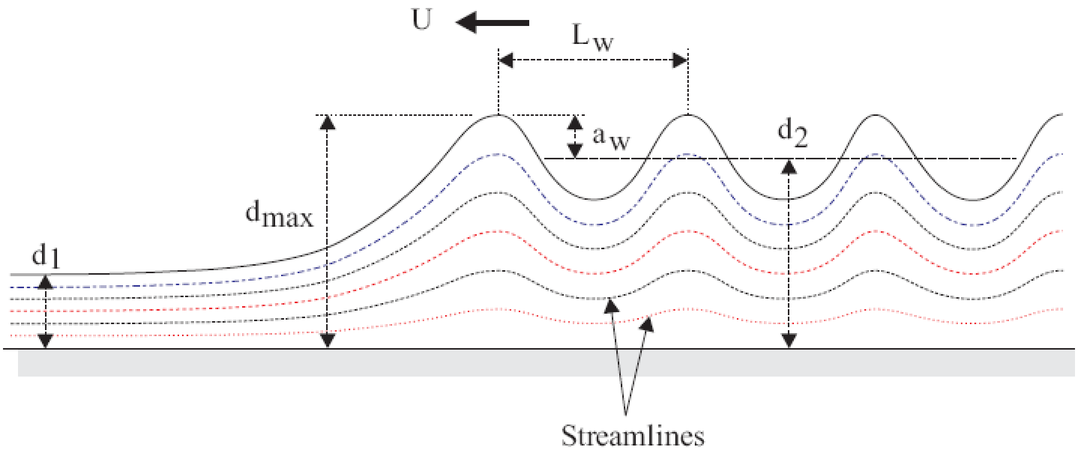


**Fig. 2 -** Definition sketch of an undular tidal bore

(A) Mascaret (Courtesy of Francis Fruchart)

(B) In front of Port de Saint Pardon on 27 September 2008 at 15:50 - The two kayakers were riding the second wave and the surfer was surfing on the third wave

**Fig. 3 -** Photographs of the undular tidal bore of the Dordogne River (France)

## 2.2 Undular bore properties

The very large majority of tidal bores have an undular shape, with the leading wave followed by a train of well-developed undulations (Fig. 3). The shape of the undular tidal bore is directly linked with its Froude number $Fr_1$. In tidal bores and hydraulic jumps, the equations of conservation of mass and of momentum are applied across the jump front (Eqs. (1) & (2)). When the rate of energy dissipation is negligible as in an undular tidal bore, there is a quasi-conservation of energy. Let us follow the tidal bore in the system of coordinates in translation with the undular bore front. The equations of conservation of momentum and energy may be rewritten as:

(5) $$\frac{M}{d_c^2} = \frac{d_c}{d} + \frac{1}{2} \times \left(\frac{d}{d_c}\right)^2 = \text{constant}$$

(6) $$\frac{E}{d_c} = \frac{d}{d_c} + \frac{1}{2} \times \left(\frac{d_c}{d}\right)^2 = \text{constant}$$

where M is the momentum function, E is similar to the energy per unit mass, also called the specific energy, and $d_c$ is the critical flow depth. For a tidal bore, $d_c$ equals:

(7) $$d_c = \sqrt[3]{\frac{((V_1 + U) \times d_1)^2}{g}}$$

In tidal bores and hydraulic jumps, Equation (5) is always valid but Equation (6) is an approximation only applicable to small Froude numbers close to unity as in an undular tidal bore. For an undular bore, Equations (5) and (6) give a parametric representation of the relationship between the dimensionless momentum $M/d_c^2$ and energy $E/d_c$ (Benjamin and Lighthill 1954, Montes 1986) (Fig. 4). The function M-E has two branches intersecting at $M/d_c^2 = 1.5$ and $E/d_c = 1.5$ which correspond to the minimum values that both functions could have in a fully-developed tidal bore with hydrostatic pressure distributions. The intersecting point relates to the critical flow conditions ($d = d_c$). The right branch of the curve M-E corresponds to the supercritical flow while the upper branch (or left branch) corresponds to a subcritical flow. The domain of variation of the dimensionless momentum and energy is bounded by the two branches. The two lines represent the only possible relationship between $M/d_c^2$ and $E/d_c$ in an undular tidal bore with "horizontal" streamlines. The regions outside of the branches are not physically possible.

Figure 4 shows a comparison between Equations (5) and (6) and experimental data. The data include the initial flow conditions (symbol *) and the undular flow properties between the first and fourth wave crests. First the results justify the approximation of negligible energy losses: all data samples are located on the parameteric curve M-E. The finding shows that Equations (6) and (6) are satisfied. Second the quasi-totality of the undular flow data are on the subcritical flow branch of the M-E curve. Third note a seemingly greater momentum function and specific energy at the first wave crest than in the initial flow. This is incorrect but reflects that, in an undular bore, the pressure field is not hydrostatic while Equations (5) and (6) are based upon the assumption of hydrostatic pressure distributions. In an undular bore, the free-surface curvature implies some non hydrostatic pressure distributions. At the wave crest, the pressure gradient is less than hydrostatic, hence associated to a smaller momentum function and specific energy than predicted by Equations (5) and (6).

In an undular tidal bore, the dissipation mechanisms are complicated with contributions by (a) some energy radiated into a train of quasi-periodic waves behind the bore front, (b) boundary friction at the bed and sides of the channel, (c) flow recirculation and separation regions, and (d) turbulent dissipation at the surface with some breaking at the first wave crest.

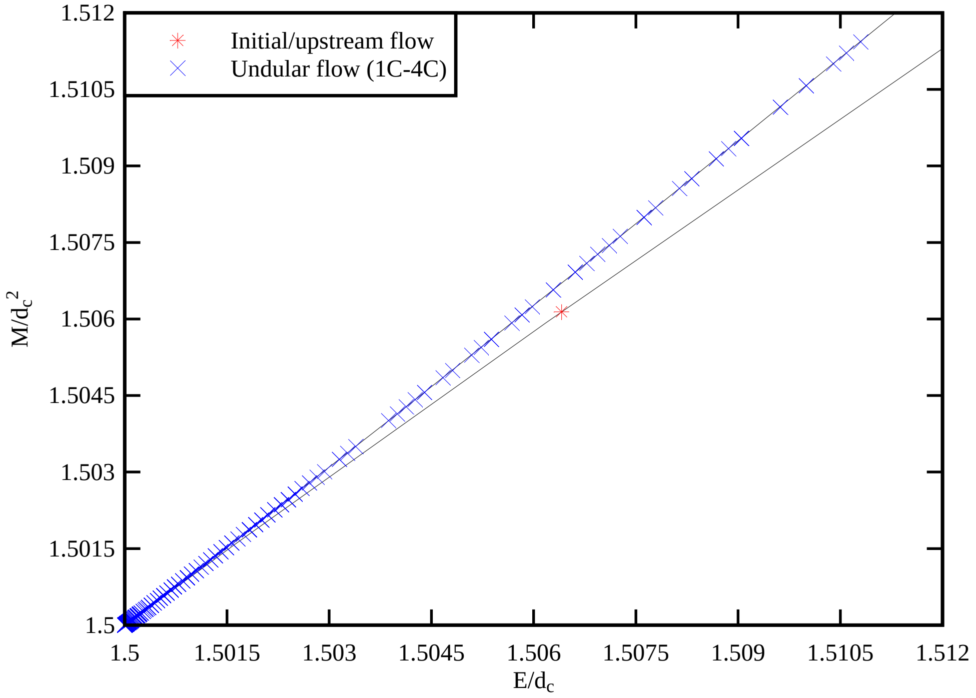


**Fig. 4** - Dimensionless relationship between the momentum and energy fluxes in undular tidal bores: comparison between Equations (5) and (6) and experimental data (Q = 0.0299 $m^3/s$, $d_1$ = 0.2055 m, Fr = 1.10, U = 1.316 m/s (Chanson 2009)) - Upstream flow conditions (symbol *) and undular flow data between the first and 4th wave crests

Some typical free-surface profiles of undular tidal bores are presented in Figures 5 and 6. Figure 5 shows the water depth as a function of the time for two field studies, while Figure 6 presents some laboratory data. The measurements highlight the pseudo-periodic shape of the free-surface undulations. In Figures 5 and 6, the data are compared with a sinusoidal curve and cnoidal wave function. Herein, each function was fitted for each half-wave length between a crest/trough and the adjacent trough/crest. Altogether there was a reasonable agreement between the data and mathematical functions, although neither the linear wave theory nor the Boussinesq equations captured the asymmetrical wave shape nor the fine details of the free-surface profile shape. The findings were consistent with an earlier study of relatively large amplitude shallow water waves concluding that "*none of the commonly used wave theories are in exceptional agreement with data*" (Le Méhauté et al. 1968).

Noteworthy, the agreement between the free-surface data and cnoidal function was best achieved only using the parameter of the elliptic function m > 0.5 between a wave crest and trough, while m < 0.5 between a wave trough and crest. For m = 0, the cnoidal wave function equals the sinusoidal profile and more generally the nonlinearity causes little departure from the linear wave theory for small values of m. As m increases, the crest becomes more peaky and the trough shallower. The experimental observations highlight the asymmetry of the free-surface undulations, with some differences in wave shape between a crest and trough, and between a trough and the next wave crest (Fig. 5 & 6). The undulation asymmetry was already noted in the stationary undular hydraulic jumps in terms of both the free-surface profile and the vertical distributions of pressure and velocity (Donnelly and Chanson 2005).

Note that it is important to distinguish with regards to the boundary conditions between some experiments in which the bore propagated into a channel with water initially at rest ($V_1$ = 0) (Hornung et al. 1995), and measurements in a bore advancing against a current as in Figures 5 and 6. In the former case, the initial flow can be made arbitrary uniform. In the latter case, the upstream flow was non-uniform and was often a fully-developed boundary layer flow in which the boundary friction effects may be significant.

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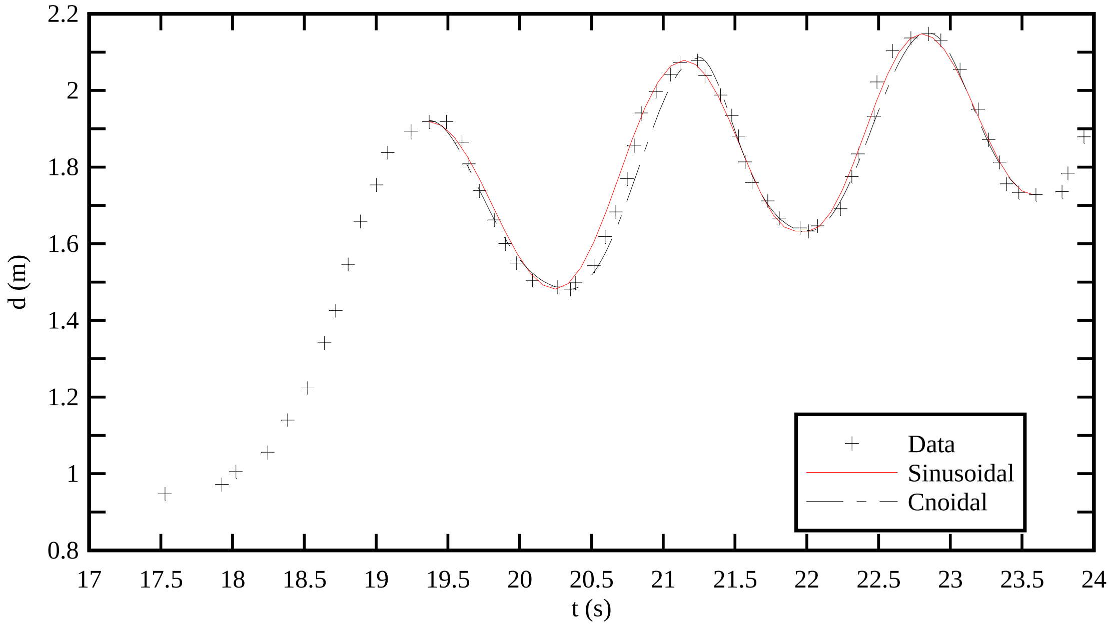
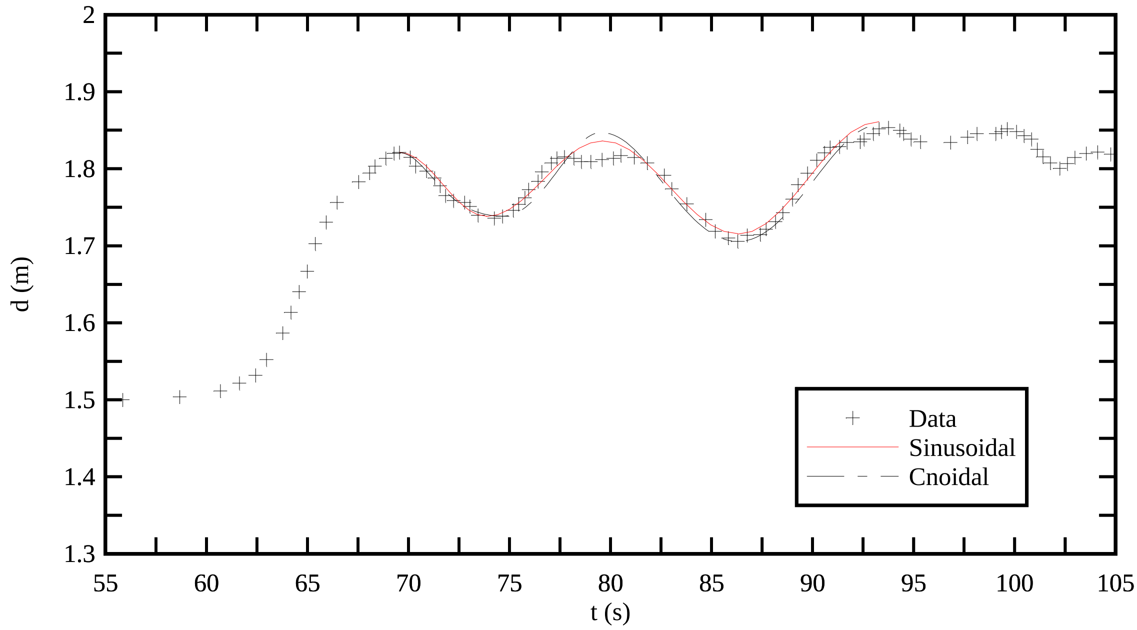



(A) Dee River tidal bore on 22 September 1972 at 10:34 - Data: $d_1$ = 0.941 m, $Fr_1$ = 1.5, U = 3.44 m/s, Run 12 (Lewis 1972)




(B) Daly River tidal bore on 2 July 2003 at 07:30 - Data: $d_1$ = 1.5 to 4 m, U = 4.7 m/s, Site C (Data: Wolanski et al. 2004)

**Fig. 5** - Free-surface profiles of undular tidal bores: field data - Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal)

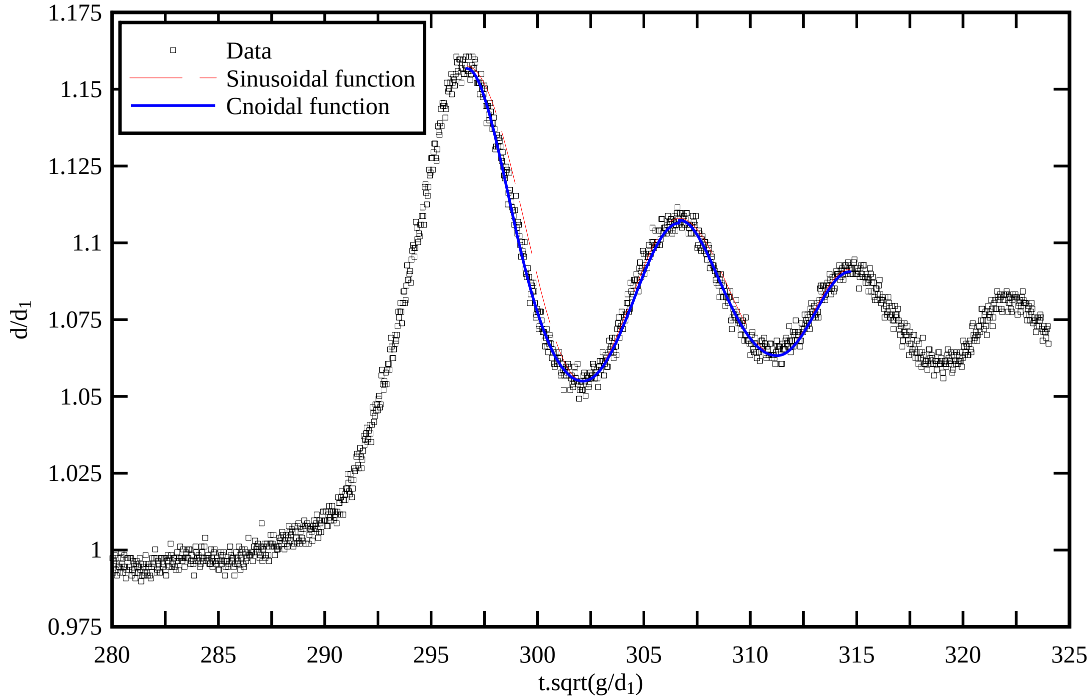



**Fig. 6** - Dimensionless free-surface profile of a laboratory undular tidal bore - Data: $d_1$ = 0.206 m, $Fr_1$ = 1.10, U = 1.27 m/s (Chanson 2009) - Comparison with the linear wave theory (sinusoidal) and Boussinesq equation solution (cnoidal)

The flow properties immediately upstream and downstream of the tidal bore front must satisfy the continuity and momentum principles (Eq. (1) & (2)). A comparison between Equation (1) and a number of field and laboratory data show in average a slightly lower experimental sequent depth ratio $d_2/d_1$ for $1.05 < Fr_1$ (Chanson 2009c) Some factors may affect the results. For example, in an undular tidal bore, the estimate of the new flow depth is somewhat arbitrary: the conjugate depth is usually averaged between wave crest and trough assuming a symmetrical wave pattern.

For the undular, non-breaking bores, some field and laboratory data in terms of the maximum wave heights attained by the undulations are presented in Figure 7. The maximum wave height $d_{max}$ is that of the first wave crest (Fig. 2) and it is limited by breaking. The experimental data are compared with the calculations of Peregrine (1966), with the onset of wave breaking in tidal bores ($d_2/d_1$-1 > 0.4, or $Fr_1$ > 1.3 to 1.4), and with the maximum height of a solitary wave.

Further properties of the free-surface undulations are presented in Figure 8, regrouping both field and laboratory observations. Figure 8A shows the wave amplitude data while Figure 8B illustrates the wave steepness data. The experimental observations are compared with the analytical solutions of Lemoine (1948) and Andersen (1979) respectively based upon the linear wave theory and the Boussinesq equations. For a bore Froude number slightly larger than unity, the wave amplitude $a_w/d_1$ and wave steepness $a_w/L_w$ increase with an increasing bore Froude number $Fr_1$. However, both the wave amplitude and steepness show a maximum followed by a sharp decrease immediately before the disappearance of free-surface undulations. It is believed that the flow conditions associated with the maximum wave amplitude and steepness take place shortly before the appearance of some small wave breaking at the first wave crest for $Fr_1$ > 1.3 to 1.4. Note that, in Figure 8B, the undular bore data are compared with some stationary hydraulic jump data.

The pressure and velocity fields are affected by the free-surface curvature in an undular tidal bore. The free-surface is a streamline (Fig. 2) and a simple flow net analysis shows that the pressure gradient must be greater than hydrostatic beneath wave trough and less than hydrostatic beneath wave crest (e.g. Rouse 1938,1959, Peregrine 1966). This was also observed in stationary undular hydraulic jumps (Chanson and Montes 1995, Montes and Chanson 1998). The pressure redistributions between wave crests and troughs, and troughs and crests, are associated with a significant velocity redistribution between the upstream/initial flow cross section and the first wave crest, and between subsequent crests

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and troughs (see next section).

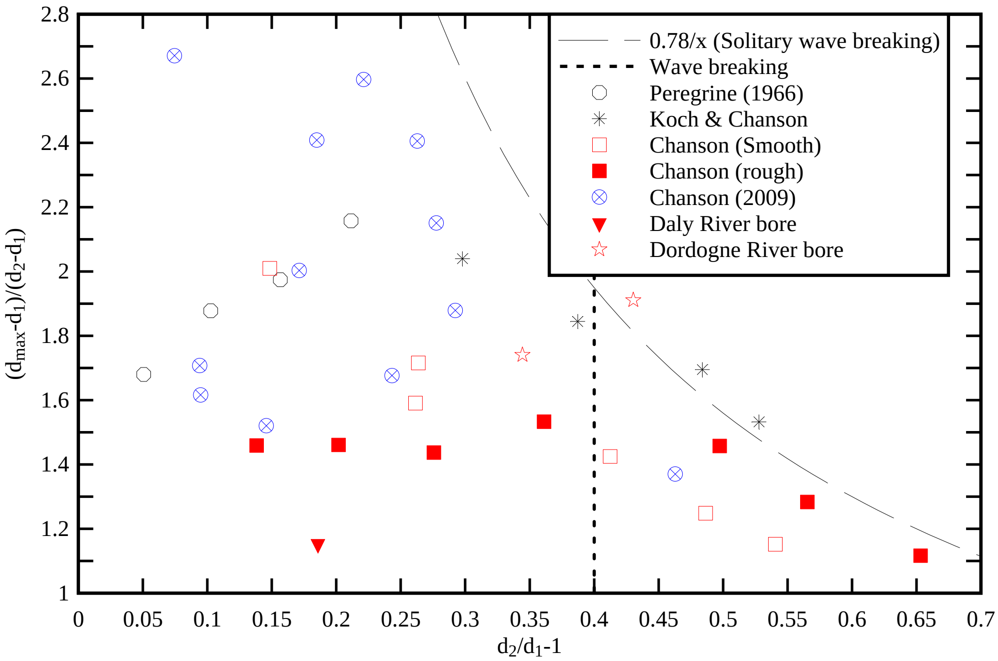
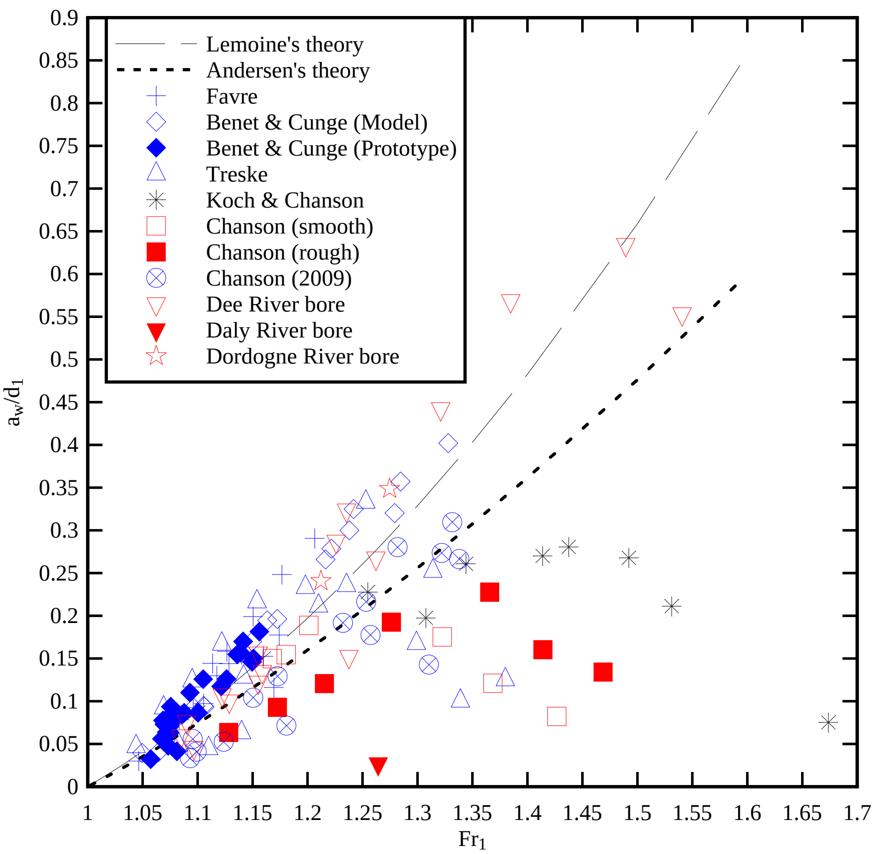
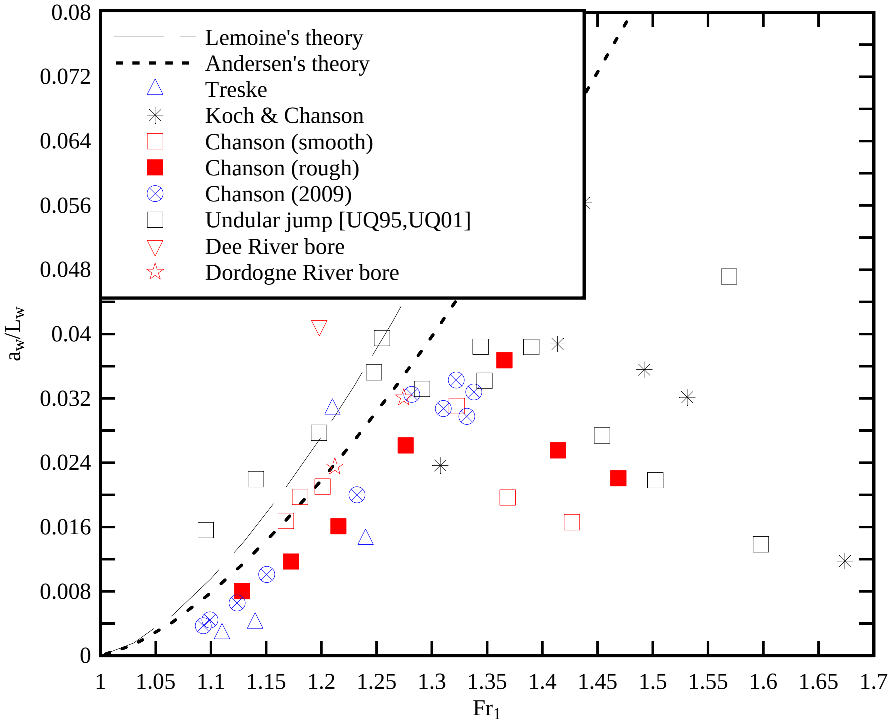



**Fig. 7** - Maximum wave height of undular tidal bores - Comparison between experimental data (Navarre 1995, Wolanski et al. 2004, Koch and Chanson 2008, Chanson 2008,2009), calculations (Peregrine 1966) and maximum solitary wave height




(A) Dimensionless wave amplitude $a_w/d_1$




(B) Wave steepness $a_w/L_w$ - Comparison with stationary undular hydraulic jump data: Chanson (1995,2005) [UQ95,UQ01]

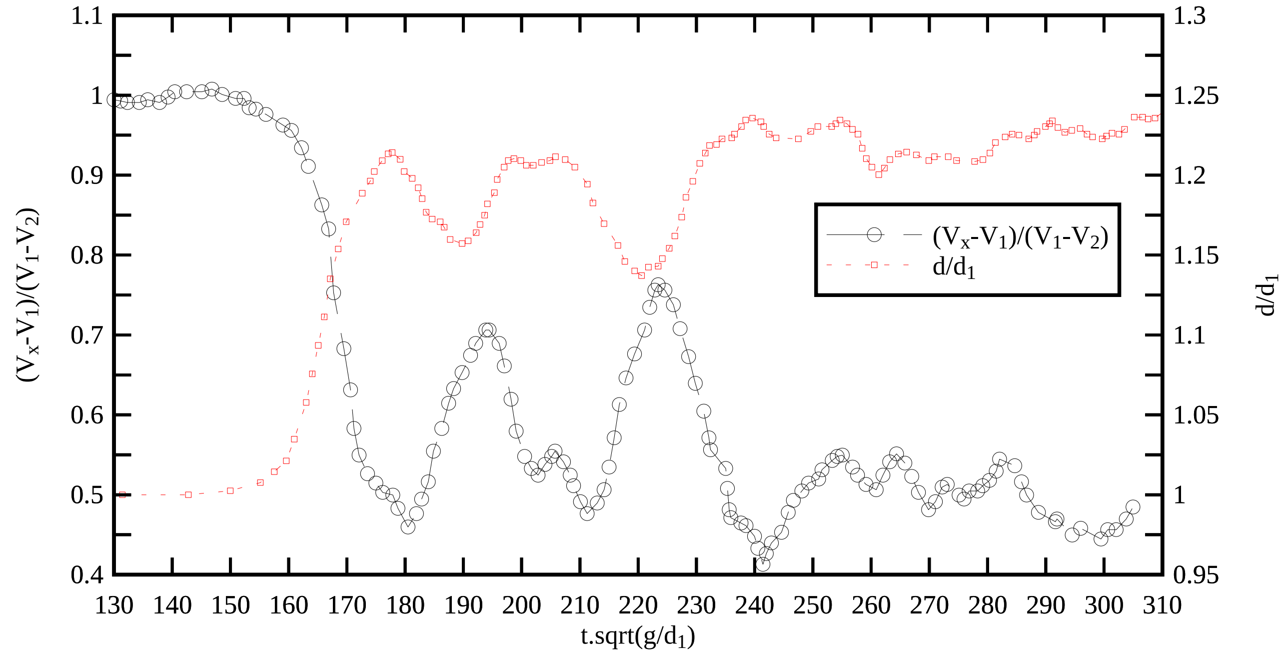
**Fig. 8** - Free-surface undulation characteristics in tidal bores - Data: Favre (1935), Benet and Cunge (1971), Treske (1994), Koch and Chanson (2008), Chanson (2009), Lewis (1972) [Dee River tidal bore], Navarre (1995) [Dordogne River], Wolanski et al. (2004) [Daly River tidal bore]

## 3. TURBULENT MIXING

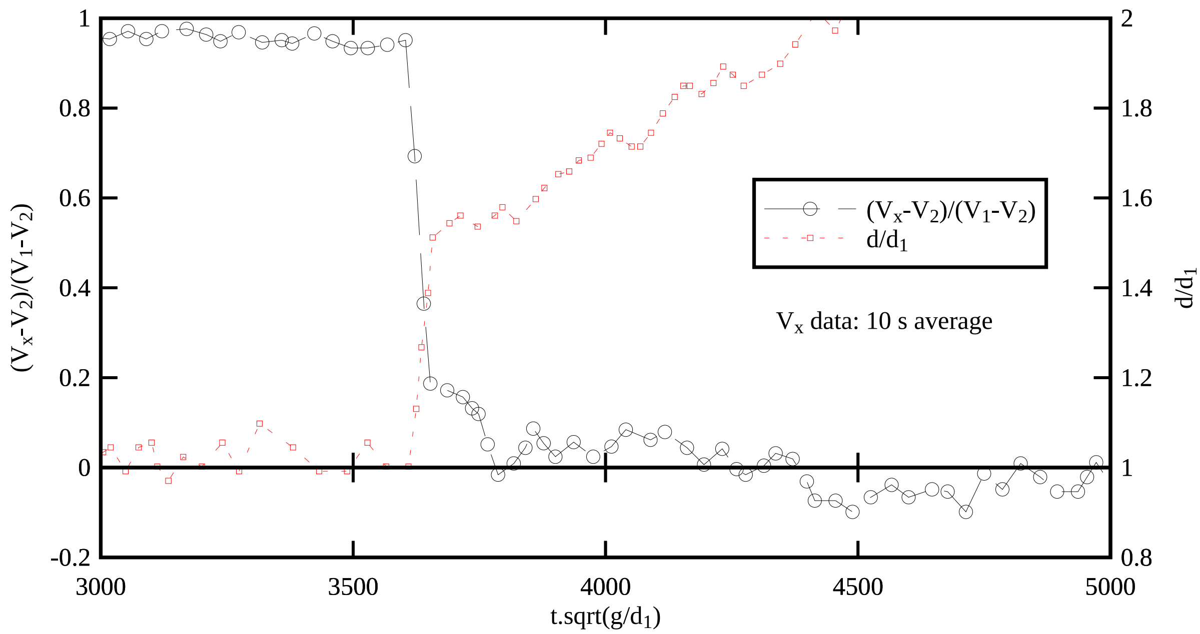
### 3.1 Presentation

The tidal bore induces a strong turbulent mixing in the estuarine zone, and the effects may be felt along considerable distances. In a natural river, the field measurements of turbulent velocities are extremely difficult and most studies recorded a limited number of parameters. Figure 9 presents some longitudinal velocity measurements in an undular tidal bore and breaking bore. Both graphs are field measurements. The velocity data are presented in dimensionless form where $V_x$ is the longitudinal velocity positive downstream, $d_1$ is the initial water depth, $V_1$ is the initial flow velocity, $V_2$ is the flow velocity immediately behind the tidal bore, and g is the gravity acceleration. Note the different vertical and horizontal scales between Figures 9A and 9B. All the data show a rapid deceleration of the flow associated with the passage of the bore. In the Daly River, the velocity measurements were conducted in an undular bore. After the first vave crest, the velocity record showed several undulations and the velocity oscillation pattern is consistent with the free-surface observations, but out of phase, although the irregular channel cross-section was responsible for some complicated whelp motion (Fig. 9A). In a breaking tidal bore, a brutal flow deceleration is observed at the passage of the bore roller (Fig. 9B).

To date, most field data were conducted with a very-coarse resolution in terms of time scales, vertical resolution and velocity magnitudes, and it is challenging to analyse conclusively the data. For example, Figure 9A presents some data recorded just below the free-surface but the data set lacks the information on the flow field next to the river bed; Figure 9B shows similarly some data next to the surface with the longitudinal velocity measurements averaged over 10 s. These incomplete data sets cannot give a complete description of the whole flow field, and more detailed informations are needed.




(A) Undular bore of the Daly River (Australia) on 2 July 2003 (Data: Wolanski et al. 2004) - $d_1 \sim 1.5$ m, $y/d_1 \sim 0.75$



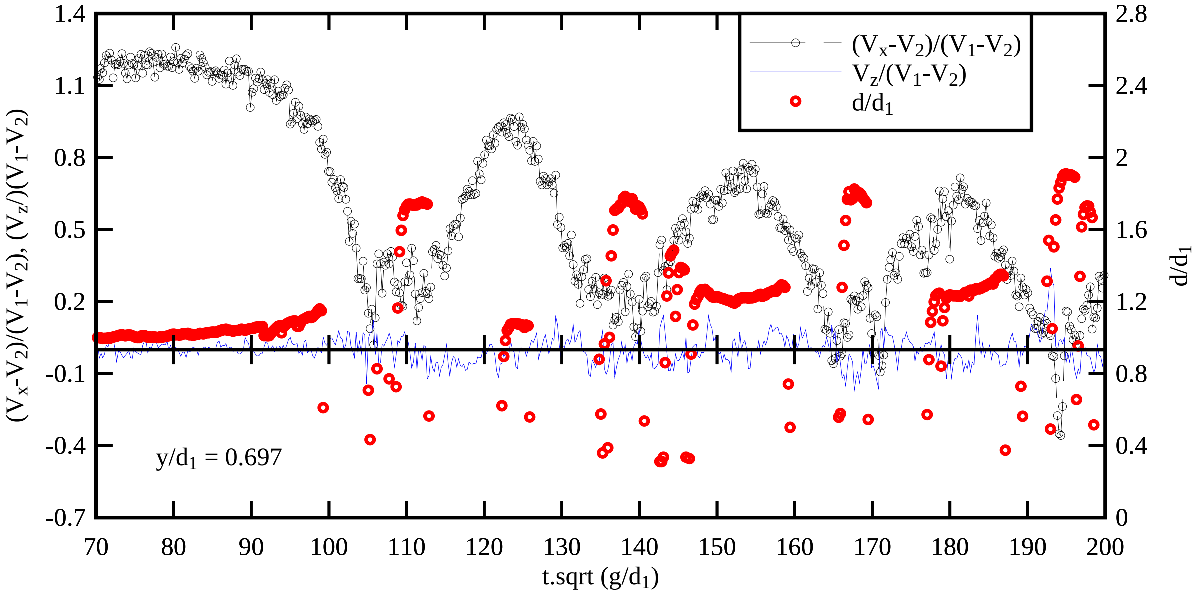

(B) Breaking bore of the Dee River (UK) on 6 September 2002 (Data: Simpson et al. 2004) - Note the longitudinal velocity data are 10 s averaged - $d_1 = 0.72$ m, $y/d_1 \sim 1$

**Fig. 9** - Dimensionless longitudinal velocity measurements $(V_x-V_2)/(V_1-V_2)$ in river tidal bores

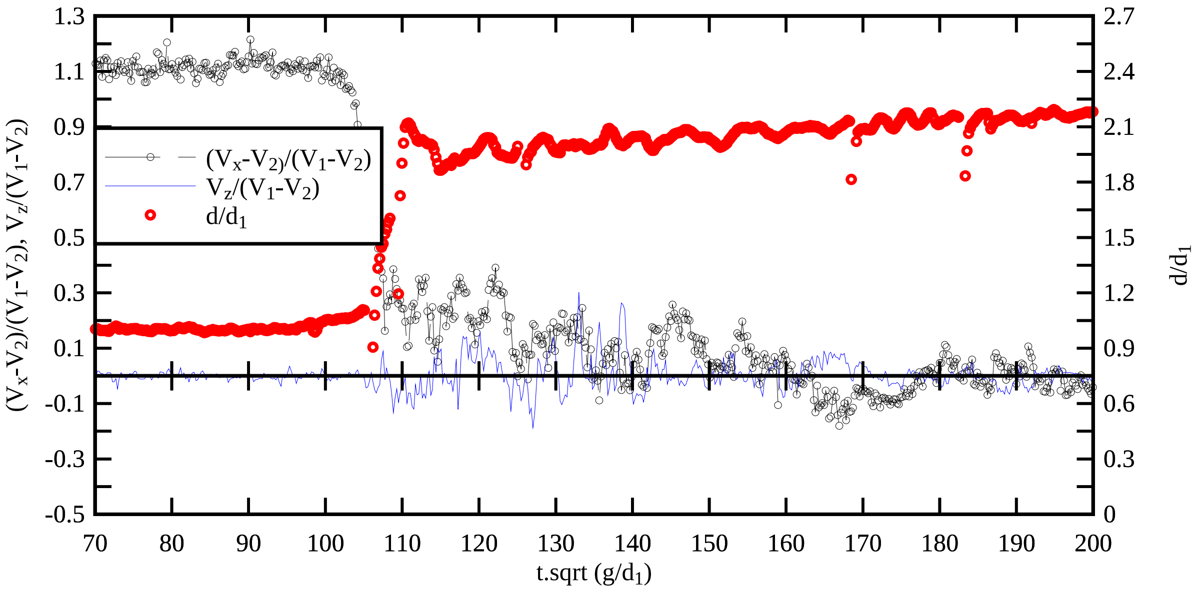
### 3.2 Velocity measurements

Recently, some simultaneous free-surface and turbulent velocity measurements were conducted in a large-size laboratory facility with detailed temporal and spatial resolutions (Koch and Chanson 2008,2009, Chanson 2008,2009). The unsteady flow results provide a solid characterisation of the tidal bore, its unsteady turbulent velocity field and the associated turbulent mixing. Figure 10 illustrates some examples for different flow conditions, vertical elevations y where $V_y$ is the vertical velocity positive upwards and $V_z$ is the horizontal transverse velocity. All the experimental data indicate systematically the same basic flow features. The arrival of the tidal bore and the sudden increase in water elevation are associated with a rapid deceleration to satisfy the conservation of mass. In a natural river, a flow reversal ($V_x < 0$) is often observed. The longitudinal velocities are characterised by a rapid flow deceleration at all vertical elevations, while large fluctuations of longitudinal, transverse and vertical velocity components are observed beneath the tidal bore. The tidal bore is basically a shock characterised by a sudden change in the velocity field (Lighthill 1978).

In an undular tidal bore, the longitudinal velocity $V_x$ oscillates with time with the same period as, but out of phase with, the free-surface undulations (Fig. 10A). When the undular bore front passes the sampling point, a relatively gentle longitudinal flow deceleration is observed at all vertical elevations. The longitudinal velocity component is minimum beneath the first wave crest and it oscillates afterwards with the same period as the surface undulations and out of phase. The vertical velocity data present a similar oscillating pattern beneath the free-surface undulations with the same periodicity, and out of phase. The data trends are consistent with the irrotational flow theory (Liggett 1994, Chanson 2009b).




(A) Undular tidal bore - Data: Koch and Chanson (2009), $d_1$ = 0.080 m, $Fr_1$ = 1.4, $y/d_1$ = 0.697




(B) Bore with a breaking roller - Data: Koch and Chanson (2009), $d_1$ = 0.080 m, $Fr_1$ = 1.8, $y/d_1$ = 0.728

**Fig. 10** - Instantaneous longitudinal and transverse velocity measurements beneath a tidal bore - Data: Koch and Chanson (2009), $d_1$ = 0.080 m, $Fr_1$ = 1.4, $y/d_1$ = 0.076 & 0.697

In contrast, a breaking bore presents a sharp front with a marked roller and some bubble entrainment as illustrated in Figure 1B. The free-surface is sometimes curved upwards immediately prior to the roller toe. The gentle rise of the free-surface may be linked with a gradual decrease of the longitudinal velocity component at all vertical elevations as shown by Hornung et al. (1995) and Koch and Chanson (2009). The roller passage corresponds to a sudden decrease of the longitudinal velocity component. The flow deceleration is notably sharper than that for an undular bore at all vertical elevations. In the breaking tidal bore, the velocity data show a further distinctive feature (Fig. 10B). Close to the bed ($y/d_1 < 0.2$), the dimensionless longitudinal velocity $(V_x-V_2)/(V_1-V_2)$ may become negative highlighting a relatively rapid transient associated with some unsteady flow separation (Fig. 10B). This flow feature was first reported by Koch and Chanson (2009) and investigated numerically by Furuyama and Chanson (2008).

### 3.3 Discussion

The velocity measurements indicate the existence of energetic turbulent events beneath and after the tidal bore front (Fig. 10). These are best seen by some sudden and rapid fluctuations of the transverse and vertical velocity data, while some recent numerical modelling highlights the production of large turbulent eddies beneath the bore front and their upstream advection behind the tidal bore (Furuyama and Chanson 2008). These vortices remain coherent structures as the bore propagates upstream while their persistent presence contribute to a large amount of sediment matters being placed in suspension and advected upstream. In the Daly River (Australia), a period of very strong turbulence was observed about twenty minutes after the bore passage that lasted for about three minutes: "*about 20 min after the passage of the undular bore, a 3-min-duration patch of macro-turbulence was observed. Horizontal eddies with peak velocity V of about 0.5 m/s were imbedded within a prevailing tidal current of about 0.7 m/s. This unsteady motion was sufficiently energetic to topple moorings that had survived much higher, quasi-steady currents of 1.8 m/s (Wolanski et al., 2001). Both clockwise and counterclockwise rotating eddies were observed.*" (Wolanski et al. 2004) (Fig. 11). The sampling location was located about 50 km upstream of the river mouth. The anecdote suggested the upstream advection of a "cloud" of turbulence and vorticity behind the tidal bore for possibly a considerable distance. The advection speed of the turbulence boils was slower than the tidal bore celerity, explaining the 20 minutes delay.

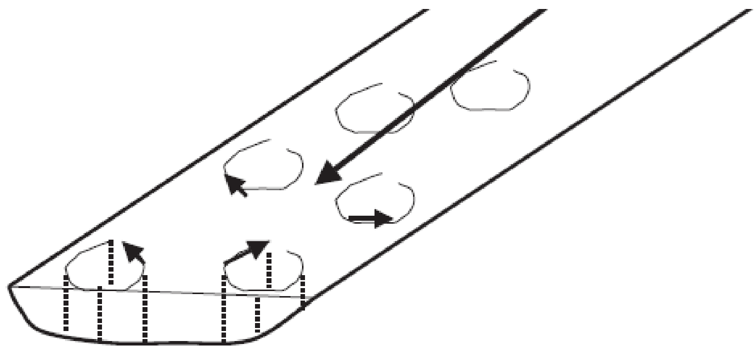


**Fig. 11 -** Surface macro-scale turbulence advected upstream behind the tidal bore of the Daly River and observed 20 minutes after the bore passage (after Wolanski et al. 2004)

Such vigorous and energetic turbulent events are some form of macro-turbulence that is likely induced by secondary motion. The experimental observations of large transverse and vertical velocity fluctuations showed the existence of transient secondary currents behind the bore front that are associated with some unsteady transverse shear pattern. The evidences of vorticity clouds encompass both undular and breaking bores (Koch and Chanson 2009). They are a feature of tidal bores that are linked with the secondary current motion. The secondary currents are currents that develop in the plane normal to the local axis of the main flow. In a prismatic channel, the vorticity profiles at the sidewall and on the invert interact next to the corner (Fig. 12, Inset). In the regions of high wall shear stress effects as in the channel corner, the local production of turbulent kinetic energy is greater than the local dissipation. Conversely the local production is lesser than the dissipation in regions of low wall shear stresses. As a result, there exists a mean flow in the y-z-plane that corresponds to the secondary current sketched in Figure 12. This secondary motion is driven by the Reynolds stress gradients (Hinze 1967, Bradshaw 1971). Secondary currents may also occur in the regions of transition from smooth to rough boundaries when the boundary roughness is not uniform (Hinze 1973). Considering a tidal bore propagating upstream in a rectangular channel, it induces some intense turbulent mixing and some strong turbulent kinetic energy production next to the step corners as sketched in Figure 12. The turbulent events interact with the mean flow and some energetic "clouds" of turbulence are advected within the main flow behind the bore. When the channel is not prismatic, there is a change in mean flow direction and the streamline curvature induces some longitudinal component of mean vorticity. Some vorticity may be generated additionally by the invisicid flow motion and complicated secondary currents may develop (Thorne and Hey 1979, Xie 1998, Trevethan et al. 2008). In some geometries, the effects of secondary currents are so strong that the main flow is forced to follow some change (Xie 1998).

During the field study of the Daly River bore, it is believed that the free-surface boil structures highlighted the intense production of turbulent kinetic energy and vorticity next to the boundaries when the bore front propagated upstream in the natural channel with river bends, shoals and bars. The macro-scale turbulence was advected behind the bore front, contributing to the energetic turbulent velocity fluctuation periods observed in the Daly River with the surface "*clockwise and counterclockwise rotating eddies* [...] *quasi two dimensional, rotating around a vertical axis*" about 20 minutes after the tidal bore passage (Wolanski et al. 2004) (Fig. 11).

Some transient fronts are also observed behind the tidal bore and induce further secondary currents and vertical circulation. Figure 13 illustrates an example in the Baie du Mont Saint Michel; the transient front arrived a couple of minutes after the bore front and lasted several minutes. The transient front is basically a zone of marked local gradients that indicates some form of singularity in terms of one or more parameters (Officer 1976, Dyer 1997). Secondary flows associated with such fronts can lead to enhanced surface concentrations of larvae and pollutants, and enhanced sediment transport motion. Their presence influences the horizontal dispersion and residual circulation, and has significant impacts on the local chemical and biological processes.

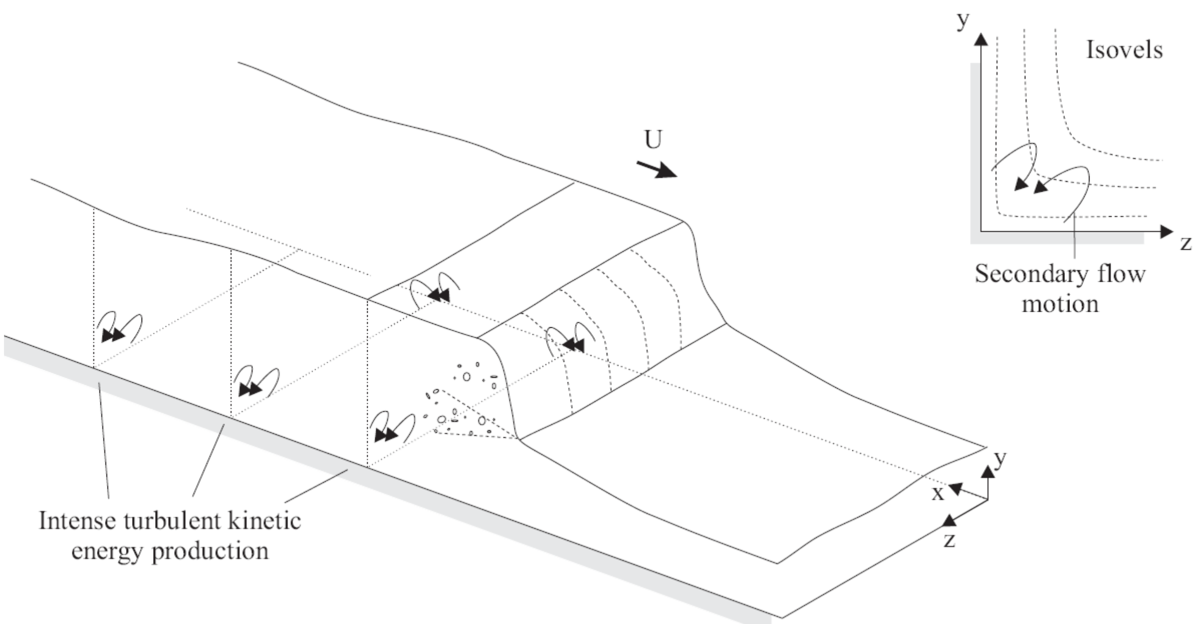



**Fig. 12 -** Secondary currents in a tidal bore propagating in a rectangular channel **-** Inset: secondary flow motion in the corner

**Fig. 13 -** Transient front in the Sélune River (France) on 3 August 2008 about 3 minutes after the tidal bore - View from the left bank with the flood flow propagation from left to right

## 4. CONCLUSION

A tidal bore is a sudden increase in flow depth that may take place during the flood tide in a funnel shaped estuary with spring tidal conditions and low freshwater level (Fig. 1 & 3). It is a sharp front followed by some waves ('whelps') that propagates upstream into the river mouth. The bore is a hydrodynamic shock with a sudden rise in water elevation; the flow singularity progresses upstream and may travel dozens of kilometres inland before vanishing. The presence of a tidal bore indicates some macro-tidal conditions (tidal range > 4 to 6 m) associated with an asymmetrical tide. The flood tide is usually shorter than the ebb tide period and the flood flow is much faster. Worldwide, it is believed that over 400 estuaries are affected by a tidal bore on all continents but Antarctica, and that number is likely an underestimate because it does not include the numerous tidal bores in small inlets, creeks and drainage canals in shallow-water bays (e.g. Baie du Mont Saint Michel, Bristol Channel) nor the small tributaries of large rivers (e.g., Seine, Hooghly, Garonne).

To date, limited quantitative information is available on the turbulence and mixing induced by the tidal bore because the field observations are difficult and most studies did not use a fine instrumentation under well-defined flow conditions. Some recent laboratory investigations provide some much needed details. The results demonstrate unequivocally that a tidal bore acts like a mixer that stirs the matters and sediments, and advects upstream the suspended materials into the upper estuarine regions. The velocity data sets suggest the upstream advection of vorticity behind the bore front. In a prismatic channel, some strong turbulent kinetic energy is produced next to the step corners behind the bore front. In a natural channel, some intense macro-scale turbulence is produced additionally by the river bends, shoals and bars where some intense vorticity is produced and advected behind the tidal bore front. Transient fronts may also develop behind a tidal bore inducing further secondary circulation.

A tidal bore is the result of delicate balance between the tidal conditions, the freshwater conditions and the estuarine bathymetry. It is observed typically during the spring tides, with low freshwater levels, in a converging shallow-water bay and river mouth that tends to amplify the tidal waves. This fragile balance can be easily disturbed: e.g., by a change in freshwater discharge or some variation in bathymetry (dredging, river training). Man-made interventions led to the disappearance of several tidal bores with often adverse impacts onto the eco-system. Natural events may also induce some tidal bore processes, including the storm surges in the Bay of Bengal and a tsunami propagation in a river mouth, while an earthquake or a flood may modify the inlet topography leading to an appearance or disappearance of a bore.

A tidal bore is an integral part of our environment and cultural heritage. But it is an endangered phenomenon that can be too easily affected adversely by human interventions. The present contribution aims to foster the research and engineering progresses that are required to preserve this beautiful natural wonder and cultural legacy. This work demonstrates that a tidal bore is a fascinating geophysical phenomenon for the surfers and kayakers as well as for the riverine populations and tourists. It remains a challenging research topic to the theoreticians, scientists and engineers. The shape of the undular tidal bore exhibits a pseudo-periodic profile that does not follow a simple mathematical theory. In a breaking tidal bore, the transient recirculation observed next to the bed remained unexplained despite its physical significance. No model can yet predict in advance where the best surf will be!

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