CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

Mixing and Sediment Processes induced by Tsunamis propagating Upriver

Hubert CHANSON [1,2], and Pierre LUBIN [1]

[1] Université de Bordeaux, I2M, Laboratoire TREFLE, 16 avenue Pey-Berland, Pessac, France, CNRS UMR 5295, Pessac, France
E-mail: p.lubin@i2m.u-bordeaux1.fr
[2] The University of Queensland, School of Civil Engineering, Brisbane QLD 4072, Australia
Email: h.chanson@uq.edu.au - Url: http://www.uq.edu.au/~e2hchans/

Abstract

The 26 December 2004 and 10 March 2011 tsunami disasters highlighted the rapid advance of the tsunami waters following rivers and canals causing massive damage deep inland. The leading edge of the tsunami formed a series of waves propagating upriver. This phenomenon is called 'shio-tsunami' (bore), 'kaisho' (tsunami-induced bore) or simply 'tsunami' (tidal wave) in Japan. After breaking, a tsunami wave propagating in shallow-waters is led by a bore. In these rivers and shallow-water bays, the propagation of the bores is associated with strong mixing and massive sedimentary processes upriver. This contribution reviews a number of tsunami-induced bore disasters, before studying the tsunami propagation upriver. The aim of the contribution is to provide compelling evidences on the turbulent mixing and sediment processes induced by tsunami bores based upon some recent field observations as well as physical and numerical studies of tidal bores. It is shown that the propagation of the bore front modifies drastically the water column properties and the tsunami waters behind the front may carry a large amount of sediments, explaining some of the sedimentological and morphological changes observed after some recent disasters.

Keywords

Tsunami, River bores, Mixing, Sediment processes, Physical modelling, Numerical modelling.

Introduction

Coastlines and rivers are places where large population densities with concentrated economical activities are found. It is critical to defend these regions against natural disasters including tsunami, one of the deadliest and most destructive natural hazards (Table 1). Rivers are natural breaches in coastlines, giving a natural path for the tsunami waters to flood inland areas. River mouths are often more vulnerable to tsunamis than other coastal areas protected by natural dunes, rock promontories and coastal structures. They are difficult to protect, but their critical funneling role is acknowledged in the extension of the inundations, sometimes further aided by the river discharge. This issue gained attention in the recent years, as tsunami waves shoaling into coastal regions are responsible for many phenomena such as inundations, wave propagation into rivers, erosion and overwash in sand spits (SHUTO 1985, TANAKA et al. 2012a,b, TINH et al. 2012).

A tsunami is a disturbance of the ocean surface usually caused by an earthquake triggering a displacement of the sea-bed, an underwater volcanic eruption or a landslide, either initiated underwater or sub-aerial (ABADIE et al. 2012). A tsunami is a long-period wave with a wave length as large as 200 to 350 km. As the tsunami approaches a shoreline, its wave slows down and the wave height increases until it breaks. Major tsunami disasters were associated with well in excess of 430,000 losses of life (Table 1). Recent media documentaries showed the explosive impact of tsunami waves during the 2004 Indian Ocean tsunami and 2011 Tohoku tsunami, in a manner somehow similar to HOKUSAI's Great wave off Kanagawa (HOKUSAI 1826-1833) (Fig. 1). Figure 1 shows a comparison between HOKUSAI's print and a typical tsunami warning sign post along a road to the Enshu coastline, Japan (CHANSON 2010a). (The Enshu shoreline was historically affected by several tsunamis.) It must be acknowledged that HOKUSAI's Great wave off Kanagawa was likely a freak wave rather than a tsunami wave (CARTWRIGHT and NAKAMURA 2009).

The 26 December 2004 and 10 March 2011 tsunami disasters highlighted the rapid advances of the tsunami waters following rivers and canals causing massive inland damage. Figures 2 and 3 illustrate a few examples. The leading edge of the tsunami formed a series of waves propagating upriver. This phenomenon is called 'shio-tsunami' (bore), 'kaisho' (tsunami-induced bore) or simply 'tsunami' (tidal wave) in Japan. After breaking, a tsunami wave propagating in shallow-waters is led by a bore. In shallow bay systems, the process is somehow similar to a storm surge induced bore like in the Bay of Bengal (SOMMER and MOSLEY 1972, DELWAR 2001) or a tidal bore in some rivers (CHANSON 2011a). The tsunami-induced bore may propagate far upstream. Some tsunami-induced river bores were observed in Hawaii in 1946 and in Japan in 1983, 2001 and 2003 (SHUTO 1985, OSHIKI et al. 2008). During the 26 December 2004 tsunami catastrophe, tsunami-induced bores were observed in shallow-water bays and river mouths in Malaysia, Thailand and Sri Lanka (Fig. 2). Numerous evidences were documented during the 10 March 2011 tsunami in Japan as well as in the west coast of North America (Fig. 2). In these rivers and shallow-water bays, the propagation of the bores is associated with strong mixing and massive sedimentary processes upriver (Fig. 3).

When a tsunami wave propagates in a river, the wave characteristics are substantially modified. A surge is formed, a sudden water level increase is observed and some dispersive wave train occurs at the wave front (TSUJI et al. 1991, YASUDA et al. 2004, TANAKA et al. 2008). Bottom friction, river bed slope, width, water depth, upstream river discharge can affect the tsunami surge propagation. To date the physics of tsunami waves in rivers is poorly known. YASUDA (2010) conducted a numerical analysis of various wave models about tsunami ascending into rivers. The results suggested that, after careful calibration, computed and measured values agreed relatively well in terms of arrival time and maximum water level, but more complex phenomena such as breaking criterion of undular bore travelling against non-uniform flow have yet to be taken into account. There is a critical need for comprehensive studies of bore propagation in rivers to gain in forecasting capacity. Some recent works aimed at studying possible scenarios of tsunami propagation in the Columbia River (YEH et al. 2012), the Targus River (BAPTISTA et al. 2011) and the Suez Canal (FINKL et al. 2012). Numerical

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

models were used to predict the inundation extents, but the limitations of the models were highlighted by the highly complex features of the flow: e.g., breaking of the bores, diffraction and wave dispersion, interactions with the river banks, energy dissipation due to friction or interaction with vegetation, soliton fission. Clearly it is critical to identify key physical factors that are important to tsunami hydrodynamics penetrating in rivers.

This contribution reviews a number of tsunami-induced bore disasters before studying the tsunami propagation upriver. The aim of the manuscript is to provide compelling evidences on the turbulent mixing and sediment processes induced by tsunami bores based upon some recent field observations as well as physical and numerical studies of tidal bores. It is shown that the propagation of the bore front modifies drastically the water column properties and the tsunami waters behind the front may carry a large amount of sediments, explaining some of the sedimentological morphological changes observed after some recent disasters.

Fig. 1 - Tsunami warning sign off the Enshu coast (Japan) and HOKUSAI's Great wave of Kanagawa

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

(A) Tsunami-induced bore on 26 December 2004 at Penang (Malaysia) during the second series of tsunami waves (Courtesy of Angela EGOLD & Sonja PREIN) - Note the breaking bore in the foreground while the bore was undular in deeper waters (background)
Fig. 2 - Photographs of tsunami-induced bores

(B) Aerial shot of the tsunami-induced bore propagating upriver in the Naka River at Hitachinaka City, Ibaraki Prefecture (Japan) on 11 March 2011 - Bore propagation from right to left - The bridge is the Mito by-pass bridge (Road [6]) located about 11 km upstream of the river mouth

(C) Tsunami-induced bore propagating upriver in Emeryville, California (USA), on 11 March 2011 - The bore was induced by the Tohoku earthquake and tsunami in Japan

Fig. 2 - Photographs of tsunami-induced bores

(A) Aerial view the central part of the town of Minamisanriku along the Hachiman River, Miyagi Prefecture on 12 March 2011 - Inland damage were observed more than 3,000 m from the shoreline along the river path - In that river, the gate at the Hachiman River mouth (bottom right) was effective for mitigating tsunami penetration into the river; on the contrary, the gate was a

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

flow obstacle during the period of return flow, causing severe erosion around the gate as seen in the figure (H. TANAKA, *Pers. Comm.*, 2013)

(B) Bore flow on the Hei River overtopping the left banks at Miyako, Iwate Prefecture, Japan on 11 March 2011 (Left) and 17 February 2012 (Right) - Close to the river mouth, looking downstream towards the river mouth (Courtesy of The Boston Globe, 7 March 2012)
Fig. 3 - Damage caused by tsunami-induced bore propagating upriver during the 10 March 2011 Tohoku earthquake and tsunami (Japan)

(C) Flooding induced by the bore in Miyako, Iwate Prefecture, Japan on 11 March 2011 (Left) and 17 February 2012 (Right) - Further upstream along the Hei River, looking downstream (Courtesy of The Boston Globe, 7 March 2012)
Fig. 3 - Damage caused by tsunami-induced bore propagating upriver during the 10 March 2011 Tohoku earthquake and tsunami (Japan)

Table 1 - List of some major tsunami disasters and associated losses of life

Date	Name	Losses of life
BC 1,500	Santorini island, Greece	--
30 July 1637	Gargano, Italy	5,000
1703	Shizoku Island, Japan	100,000
1 November 1755	Lisbon, Portugal	60,000
27 August 1883	Krakatoa, Indonesia	36,000
15 June 1896	Sanriku coast, Honshu, Japan	26,000
9 March 1957	Aleutian Tsunami	--
23 May 1960	Chile Earthquake & Tsunami	1,750
12 July 1993	Okushiri island, Japan	198
17 July 1998	Papua New Guinea	3,000
26 December 2004	Aceh, Indonesia	280,000
11 March 2011	Tohoku Earthquake & Tsunami	19,000

Note: (--): data not available.

Field observations

The upstream propagation of tsunami-induced bores was documented in several scientific studies. Historical documents reported some flooding of the downtown of Lisbon (Portugal) by the rising of the waters of the Targus River during the 1755 tsunami (BAPTISTA et al. 1998, 2011).
During the 26 May 1983 tsunami in the Sea of Japan, "*bores were observed in the Yoneshiro and Omono Rivers*" and "*the tsunami can be traced for up to 6.6 km from the mouth*" in the Omono River (ABE 1986); along a large river the tsunami travelled inland for about 15 km (ABE 1986). During the 2003 Tokachi-oki Earthquake and Tsunami, a tsunami propagated up several rivers on the Pacific coast of Hokkaido: "*six tsunami waves with a period of 30–40 min arrived at the mouth of the Tokachi River*"; "*these waves propagated up about 7 km from Ohtsu to Tabikorai in about 20 min*" (YASUDA 2010). Following the 27 February 2010 Chilean earthquake, tsunami-induced bores were observed in several Japanese rivers, and "*the tsunami wave can be affected up to about 33 km upstream*" (TANAKA et al. 2011). A recent data analysis suggested that the inland propagation distance (from the river mouth) is inversely proportional to the river bed slope S_o (KAYANE et al. 2012). About 500 people died from the 2010 Chilean tsunami. Many evidences of upriver tsunami propagation in Chile were detailed: large fishing boats were transported more than 10 km up the Maule River; video movies documenting tsunami propagation at least 15 km from the river mouth. Inundation and damage occurred more than a kilometer inland along several other rivers including at Coliumo and Tubul (FRITZ et al. 2011, KOSHIMURA et al. 2011). In 2004, the Sri Lanka coastlines were hardly hit by the 2004 Indian Ocean tsunami and 35,000 people died during the event. The western coast of the island suffered substantial impacts. Thousands of plantations (rice, mango, banana, etc.) were almost entirely destroyed. Many boats vital to industrial and artisanal fisheries, a major economical activity, were washed away. Tsunami disasters in Sri Lanka were studied showing evidences of tsunami

surges entering the rivers and travelling inland (TANAKA et al. 2008, WIJETUNGE et al. 2008, WIJETUNGE 2009a,b). In the Kalu River, a big wave was immediately followed by some smaller waves travelling up the river, propagating up to 20 km from the river mouth. The river path and its branching streams have had a significant influence on the distribution of inundation in Matara, a main city in southern Sri Lanka. In situ observations reported: "*rivers and streams that are open to the sea carry tsunami flood flow up stream in the form of a bore whilst spilling and inundating the low elevation terrain on either side*"; "*the surging tsunami front had first travelled over land and then fallen into water bodies such as lagoons, which in some instances, unable to absorb all of the overland flow, had spilt over and flooded inland areas that would otherwise not have received direct inundation*" (WIJETUNGE 2009a). The extent of inland inundation was thus facilitated by the river courses, streams, canals, lagoons and lakes. In other locations, the surging tsunami front moved across barrier spits, low points of dunes as well as sandbar formations at lagoon openings leading to flooding of onshore areas: "*the tsunami had climbed up the river and generated localized floods in the low-lying areas in the inlands*" (TANAKA et al. 2008).

The experiences of the 10 March 2011 Tohoku tsunami disaster highlighted tragically the turbulent transport induced by bores, including the transport of sediments, particulates and scalars with adverse implications in terms water quality and sediment processes. A survey data study summarised: "*the deepening of river water depth at the entrance due to tsunami impacts can cause a lot of problems such as floodplain erosion or deposition in the river due to waves further penetrating inside of river mouth*" (TANAKA et al. 2012a); "*many breaching places occurred along the coast and river mouth*", photography showed "*a huge morphologically changes*" of the river mouth: "*the river water depth and width are also become deeper and wider*" (TINH et al. 2012). The Tohoku tsunami was observed to penetrate up to 50 km in the Kitakami River, resulting in widespread inundation along the river banks for about 15 km from the sea (RAO and LIN 2011). Observations indicated that on-land run-up decayed exponentially with increasing distance, up to 5 km, from the shoreline, but much longer tsunami run-ups were measured along rivers (MORI et al. 2011).

The environmental impacts of tsunami-induced bores encompass the destruction of farming communities, fishing industries, and touristic activities, as well as the destruction of crops, the seawater contamination of water supplies, surface waters and ground waters impacting on drinking water, irrigation and industrial water resources, but also the destruction of sewage lines and sewage treatment plants (CHANSON 2005). Tsunami intrusion behaves differently when penetrating water bodies, compared to overland propagation. The intrusion distance was shown to be related to the bed slope, the river mouth type and the wave height after entering the river, and the upriver tsunami celerity was consistently larger than on land (ADITYAWAN et al. 2012a,b). Tsunamis are able to destroy most obstacles and structures at the river mouth, including constricted structures and sand spits (TANAKA et al. 2011, 2012b).

Basic theory

Theoretical analysis of tsunami-induced bores is not straightforward because of the complexity of the processes involved when a tsunami wave penetrates a river channel (CAPUTO and STEPANYANTS 2003, BUKREEV 2004, PELINOVSKY and RODIN 2011). Tsunami wave shoaling and runup were shown to be facilitated and amplified in some bathymetric configurations (DIDENKULOVA and PELINOVSKY 2011). While the tsunami wave amplitude is moderate in deep waters, the tsunami slows down and the wave height increases near the shoreline. The wave height might reach several metres above the natural sea level. When a tsunami wave reaches a river mouth, its transformation into a bore and the upriver propagation of the bore may be predicted using the shallow water equations. For an one-dimensional unsteady flow, the equations of conservation of mass and conservation of momentum yield a series of two equations, called Saint-Venant equations:

$$\frac{\partial d}{\partial t} + \frac{A}{B} \times \frac{\partial V}{\partial x} + V \times \frac{\partial d}{\partial x} + \frac{V}{B} \times \left(\frac{\partial A}{\partial x}\right)_{d=\text{constant}} = 0 \qquad (1)$$

$$\frac{\partial V}{\partial t} + V \times \frac{\partial V}{\partial x} + g \times \frac{\partial d}{\partial x} + g \times (S_f - S_o) = 0 \qquad (2)$$

where d is the water depth, V the flow velocity, t the time, x the longitudinal co-ordinate, A the flow cross-section area, B the free-surface width, S_o the bed slope and S_f the friction slope (LIGGETT 1994, MONTES 1998). These equations cannot be solved analytically usually because of the non-linear terms that include the friction slope:

$$S_f = \frac{f}{2} \times \frac{V \times |V|}{g \times D_H} \qquad (3)$$

where D_H is the hydraulic diameter, |V| the magnitude of the flow velocity and f the Darcy-Weisbach friction factor that is a non linear function of Reynolds number and relative roughness height. The friction slope has the same sign as the velocity. Equations (1) and (2) may be rewritten as:

$$2 \times \frac{\partial C}{\partial t} + 2 \times V \times \frac{\partial C}{\partial x} + C \times \frac{\partial V}{\partial x} = 0 \qquad (4)$$

$$\frac{\partial V}{\partial t} + V \times \frac{\partial V}{\partial x} + 2 \times C \times \frac{\partial C}{\partial x} + g \times (S_f - S_o) = 0 \qquad (5)$$

where C is the celerity of a small disturbance equal to C = $\sqrt{g \times d}$ (HENDERSON 1966, LIGGET 1994). Combining Equations (4) and (5), the Saint-Venant equations may be transformed into a characteristic system of equations:

$$\frac{D}{Dt}(V + 2 \times C) = -g \times (S_f - S_o) \qquad \text{forward characteristic} \quad (6)$$

$$\frac{D}{Dt}(V - 2 \times C) = -g \times (S_f - S_o) \qquad \text{backward characteristic} \quad (7)$$

along the respective characteristic trajectories :

$$\frac{dx}{dt} = V + C \qquad \text{forward characteristic} \quad (8)$$

$$\frac{dx}{dt} = V - C \qquad \text{backward characteristic} \quad (9)$$

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

where D/Dt is the absolute differential. For an observer travelling along the forward characteristics (Eq. (8)), Equation (6) is valid at any point; for an observer travelling on the backward characteristics (Eq. (9)), Equation (7) is satisfied everywhere.
With this transformation, the shallow water equations may be solved graphically. In the (x, t) characteristic diagram, the horizontal axis is the longitudinal distance x and the vertical axis is the time t (Fig. 4). Once the flow properties at t = 0 are known everywhere and the time-variations of the water depth at the river mouth are known, the upriver propagation of the tsunami wave and bore may be predicted. With the arrival of the tsunami wave, the water level at the river mouth increases rapidly with time. The backward characteristics issuing from the river mouth form a network of converging lines (Fig. 4). When two backward characteristics intersect, the water depth has two values at the same time: that is, the bore front. The bore forms at the first intersecting point. Afterwards, there is a water depth discontinuity along the forward characteristics forming the envelope of the bore front. The flow conditions across the bore leading edge satisfy the continuity and momentum principles.

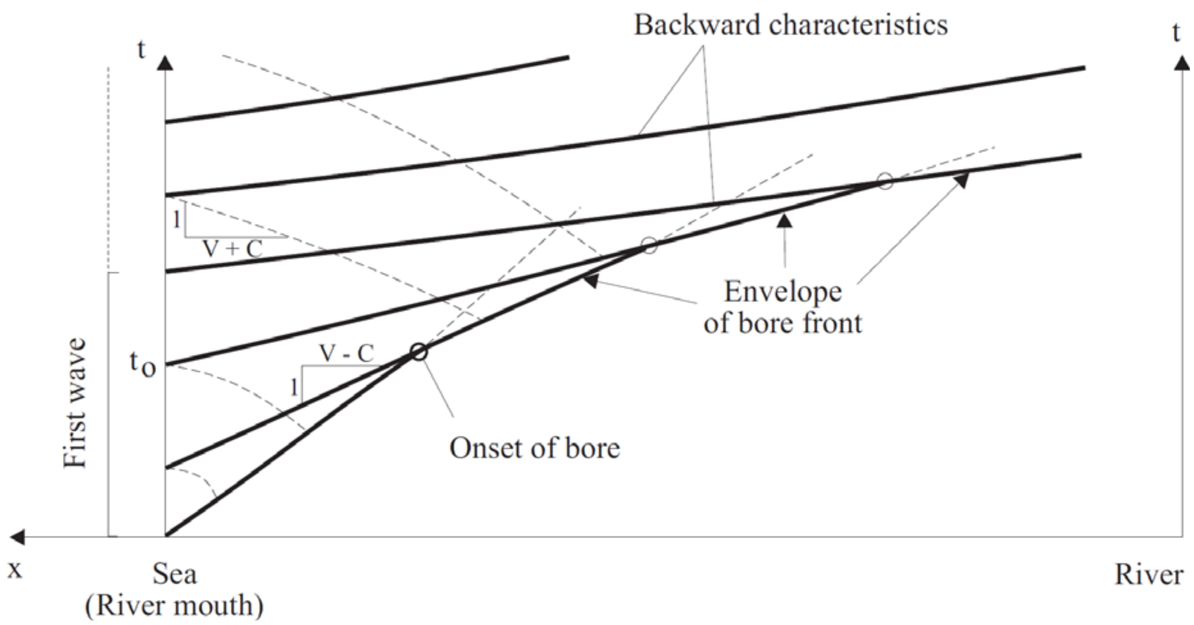


Fig. 4 - Characteristic diagram of a tsunami-induced bore propagating upriver

The bore is a hydrodynamic shock and flow discontinuity (LIGHTHILL 1978, LIGGETT 1994). In a system of reference following the bore front, the integral form of the continuity and momentum equations gives a series of relationships between the flow properties in front of and behind the bore (RAYLEIGH 1914, LIGHTHILL 1978):

$$(V_1 + U) \times A_1 = (V_2 + U) \times A_2 \qquad (10)$$

$$\rho \times (V_1 + U) \times A_1 \times (\beta_1 \times (V_1 + U) - \beta_2 \times (V_2 + U)) =$$

$$\iint_{A_2} P \times dA - \iint_{A_1} P \times dA + F_{fric} - W \times \sin\theta \quad (11)$$

where V is the flow velocity positive downstream towards the river mouth, U the bore celerity positive upriver (Fig. 5), ρ the water density, A the channel cross-sectional area measured perpendicular to the main flow direction, β a momentum correction coefficient, P the pressure, the subscript 1 refers to the initial flow conditions and the subscript 2 refers to the flow conditions immediately after the bore, F_{fric} is the flow resistance force, W the weight force and θ the angle between the bed slope and horizontal. Neglecting the flow resistance, the effect of the velocity distribution and for a flat channel (θ ≈ 0), Equations (10) and (11) give a relationship between the ratio of conjugate cross-section areas A_2/A_1 as a function of the Froude number Fr_1 (CHANSON 2012):

$$\frac{A_2}{A_1} = \frac{1}{2} \times \frac{\sqrt{\left(2 - \frac{B'}{B}\right)^2 + 8 \frac{B'/B}{B_1/B} \times Fr_1^2} - \left(2 - \frac{B'}{B}\right)}{\frac{B'}{B}} \quad (12)$$

where the Froude number is defined as:

$$Fr_1 = \frac{U + V_1}{\sqrt{g \times \frac{A_1}{B_1}}} \quad (13)$$

and B and B' are characteristic the free-surface widths defined as:

$$B = \frac{A_2 - A_1}{d_2 - d_1} \quad (14)$$

$$B' = \frac{\iint_{A_1}^{A_2} \rho \times g \times (d_2 - y) \times dA}{\frac{1}{2} \times \rho \times g \times (d_2 - d_1)^2} \quad (15)$$

Equation (12) is valid for any bore and hydraulic jump in an irregular channel (CHANSON 2012). Its application was tested against some field data in tidal river bores (Fig. 6). Figure 6 illustrates the good agreement between Equation (12) and the field data. The effects of the channel cross-section irregularity increase with increasing Froude number and bore height (d_2-d_1).

For completeness, the solution of the momentum equation for a smooth rectangular channel is shown in Figure 6:

$$\frac{A_2}{A_1} = \frac{1}{2} \times \left(\sqrt{1 + 8 \times Fr_1^2} - 1\right) \quad (16)$$

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

The results highlight the limitations of the simplistic Bélanger equation (Eq. (16)) in natural irregular channels for which the cross-sectional properties do have a significant impact on the definition of the bore Froude number (Fig. 6).

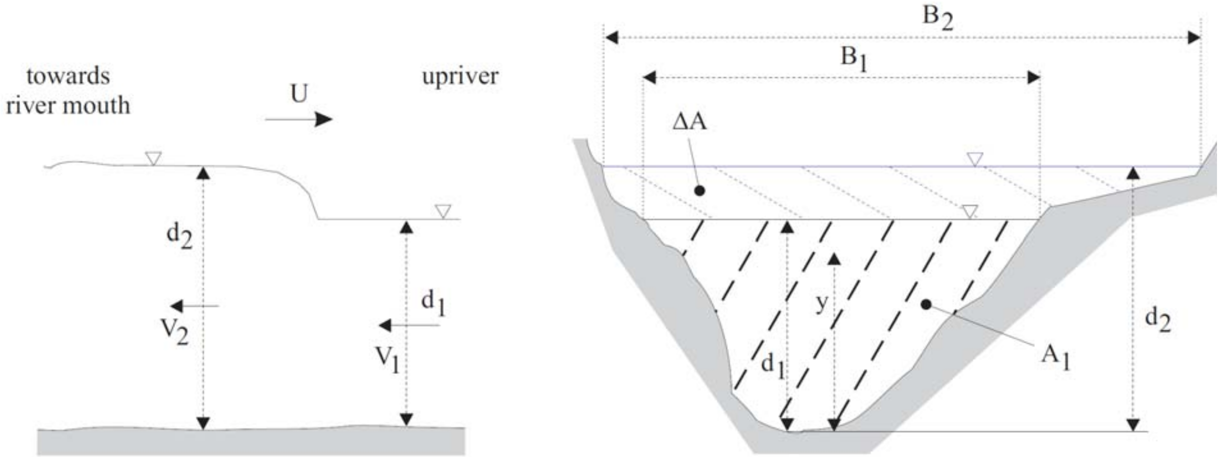


Fig. 5 - Definition sketch of a tsunami-induced bore propagating upriver

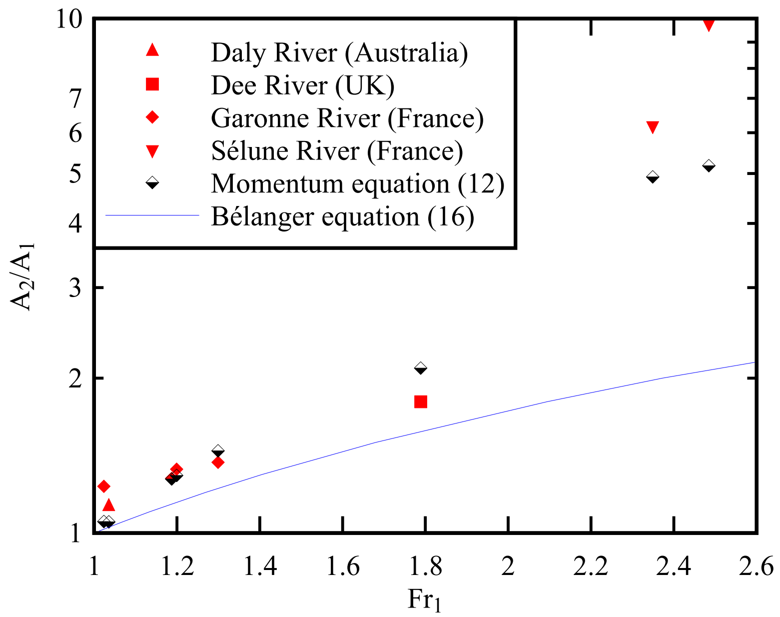


Fig. 6 - Semi-logarithmic relationship between the conjugate cross-sectional area ratio A_2/A_1 and Froude number Fr_1 - Comparison between the momentum equation (12), the Bélanger equation (Eq. (16)) for rectangular channels and tidal river bore data (SIMPSON et al. 2004, WOLANSKI et al. 2004, MOUAZE et al. 2010, CHANSON et al. 2011, REUNGOAT et al. 2012)

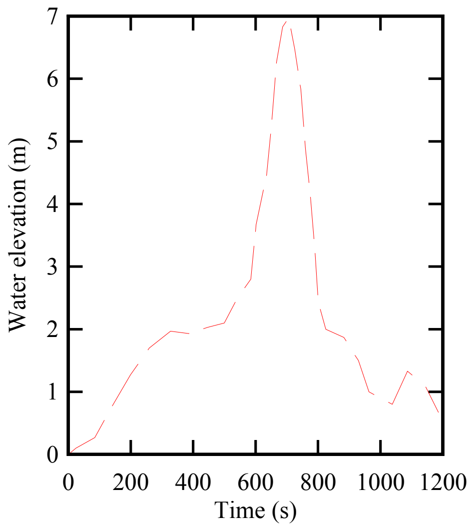
CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

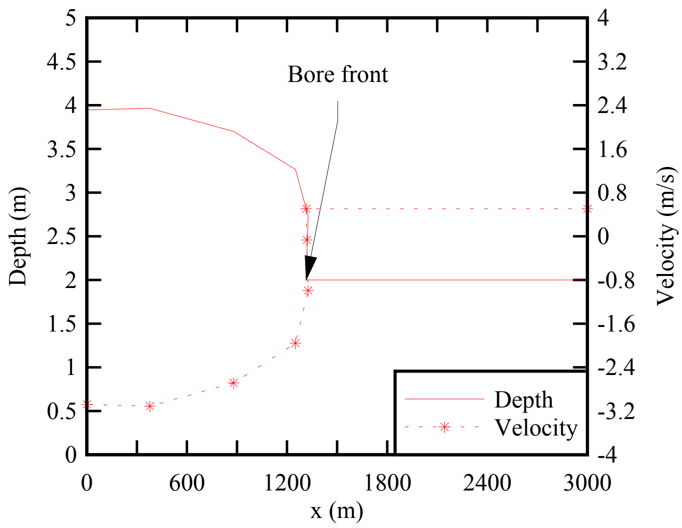
Application

The characteristic equations may be simplified when S_f - S_o = 0 anywhere anytime. A further simplification is the simple wave approximation defined as a wave for which S_f = S_o = 0 with initially constant water depth and flow velocity in the entire river section. Some detailed analytical solutions may be derived for the propagation of a shock in shallow waters (POINCARÉ 1910, LACOMBE 1952, CHANSON 2004).

Let us consider a river stretch, 3 km long and about 30 m wide, with a bed slope corresponding to a 1 m river bed drop over the reach. At the river mouth, an incoming tsunami wave imposes a time-variation of the water elevation as illustrated in Figure 7A. Initially the water depth was 2 m in the river and the mean velocity was 0.5 m/s.

Preliminary calculations are conducted assuming a simple wave solution for 0 < x < 3 km and neglecting reflection effects. The results show formation of a first bore about 500 m upstream of the river mouth at t = 130 s. The bore propagates upstream and reaches the channel upstream end at t = 9 min when the bore height (d_2-d_1) is about 1.3 m. A second bore, associated with the sharp peak of the tsunami wave, forms at t = 12 min. The calculations yield further the water elevation and cross-sectional averaged velocity in the river (Fig. 7B). Figure 7B illustrates the longitudinal free-surface profile at t = 5 min (300 s).





(A) Water elevation at the river mouth (B) Free-surface and velocity profiles at t = 5 min

Fig. 7 - Propagation of a tsunami wave into an idealised estuary

Turbulent mixing in bores propagating upriver: the experience with tidal bores

A tidal bore is an intense and powerful natural phenomenon observed in macro-tidal estuaries (CHANSON 2011a). It generally occurs during spring tide conditions when the flood tide is confined to river mouths exhibiting converging funneled channel forms. When the tidal flow turns to rising, a positive surge propagates upstream the river to form the tidal bore. The bore development is closely linked with the tidal range and the river mouth shape, and its existence is sensitive to any small change in boundary conditions. The flow of the river often flows upstream after its passage (CHANSON 2009, 2011c).

The existence of tidal bores is based upon an unstable hydrodynamic balance, which may be easily disturbed by changes in boundary conditions and freshwater inflow conditions. Despite numerous anecdotical evidences and archival documents, the tidal bore phenomenon remains poorly understood, rarely studied in details, due to its unsteady and turbulent nature. The number of field surveys and laboratory experiments of tidal bores has recently increased from the early historical descriptions (CHANSON 2011a). Few numerical studies were conducted, based on the shallow-water equations or the Navier-Stokes equations, compared to experimental results. Numerical studies are restricted because of the complexity of the unsteady turbulent multiphase flow (BOMBARDELLI and CHANSON 2009), and the limited field data sets available for validation. Tidal bores also imply free-surface deformations, a large variety of length scales and air entrainment, which cannot be taken into account by many numerical tools. MADSEN et al. (2005) developed numerical schemes dedicated to the nonlinear shallow water equations to allow for the treatment of tidal bores in the Qiantang River (China). Comparative results were shown, but an extensive calibration phase involving a sensitivity study of boundary conditions, bottom friction, and local bathymetric modifications was necessary. Unfortunately no velocity measurement was available and more information about the net currents in the Qiantang River estuarine zone is needed. A more recent attempt was based upon the Navier-Stokes equations, and the results were compared to laboratory experiments (FURUYAMA and CHANSON 2010). Some interesting flow features were observed, although the results could be improved with a finer mesh grid resolution and more accurate numerical schemes, as discussed by LUBIN et al. (2010a,b). The CFD modelling based upon the (full) Navier-Stokes equations give access to the most intricate flow features (aeration of the flow, unsteady turbulent flow motion, coherent structures), assuming that a sufficient number of grid points are used for discretisation.

The bore is a series of waves propagating upstream as the tidal flow turns to rising. Two different types of tidal bores are generally observed depending upon the Froude number Fr_1 (CHANSON 2009). For Fr_1 less than 1.4 to 1.6, tidal bores develop as undular bores characterised by a leading front followed by a train of advancing undulations, called whelps, and an absence of wave breaking, but close to the banks (Fig. 8A). Breaking bores are rarer ($Fr_1 > 1.6$), often restricted to high tide conditions and localised in some estuarine sections (Fig. 8B). About 95 % of the observed tidal bores are undular bores (CHANSON 2011a). Experimental results indicated systematically some basic flow features. The tidal bore is characterised by a sudden increase in water depth, yielding a rapid change in longitudinal velocity to satisfy the conservation of mass. In a natural river, a flow reversal is often observed. The longitudinal velocities highlight a rapid flow deceleration at all vertical elevations during the bore front passage, while some large fluctuations of longitudinal, transverse and vertical velocity components are observed beneath and behind the tidal bore. The tidal bore is basically a hydrodynamic shock followed by a highly turbulent flow motion with significant fluctuations of all velocity components.

In an undular tidal bore, the longitudinal velocity oscillates with time with the same period as, but out of phase with, the free-surface undulations immediately after the front (KOCH and CHANSON 2008, CHANSON 2010b, CHANSON and TAN 2010). The undular bore front passage is associated with a relatively gentle longitudinal flow deceleration observed at all vertical elevations. The longitudinal velocity component is found to be 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 presents a similar oscillating pattern beneath the free-surface undulations with the same periodicity, and out of phase. Maximum velocities are observed beneath the wave troughs and minimum velocities below the wave crests. This trend is seen at all vertical and transverse locations. The observations were reported in a number of physical observations.

The breaking tidal bore data show a sharp front with a marked roller and some air entrainment (Fig. 8B). 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 (HORNUNG et al. 1995, KOCH and CHANSON 2009, DOCHERTY and CHANSON 2012). The roller passage is associated with a sudden decrease of the longitudinal velocity component. The flow deceleration is notably sharper than that for an undular bore at all vertical elevations. Close to the bed, the instantaneous longitudinal velocity can become negative, highlighting a relatively rapid transient associated with some unsteady flow separation (KOCH and CHANSON 2009, CHANSON 2010b, MOUAZE et al. 2010, DOCHERTY and CHANSON 2012). The velocity measurements highlighted some energetic turbulent events beneath and behind the tidal bore front. Some sudden and rapid fluctuations of the transverse and vertical velocity components are experimentally observed (KOCH and CHANSON 2009, CHANSON 2010b), while some CFD modelling hinted the production of large turbulent eddies beneath the bore front and their upstream advection behind the bore (LUBIN et al. 2010a,b). These vortical structures remain next to the bed as the bore propagates upstream, while the presence of persisting coherent structures indicates that a great amount of sediment matters could be placed into suspension and advected upstream in a natural estuary.

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

(A) Undular tidal bore of the Colorado River (Mexico) on 13 October 1985 (Courtesy of Steve NELSON) - Bore propagation from right to left

(B) Breaking tidal bore of the Sélune River (France) on 24 September 2010 (Courtesy of Dominique MOUAZÉ) - Bore propagation from right to left

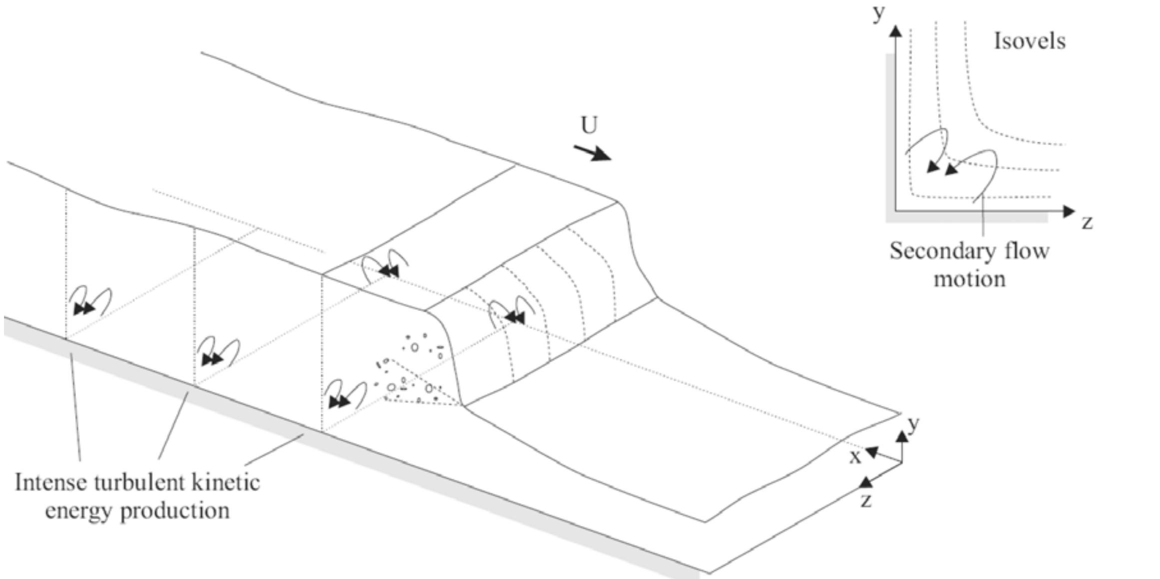
Fig. 8 - Photographs of undular and breaking bores

The visual observations of tidal bores highlight the turbulent nature of the propagating bores (Fig. 8) (CHANSON 2011a). Some energetic turbulent events are observed in natural rivers, probably due to some form of macro-turbulence likely induced by some secondary motion. KJERFVE and FERREIRA (1993) also account for the violence of the flows in the Rio Mearim (Brazil): "*Still, the field installations posed great difficulties. On 30 January 1991, one sawhorse and instrument tumbled along the bottom for 1.4 km with currents exceeding 3 m.s^{-1}, was buried in a sand bank, and had to be abandoned although the instrument was recovered*." In the River Dee (UK), SIMPSON et al. (2004) reported similar problems: "*During this second deployment, the instrument was repeatedly buried in sediment after the first tidal cycle and had to be dug out of the sediment, with considerable difficulty, at the time of recovery*." In the Daly River (Australia), WOLANSKI et al. (2004) described a period of very strong turbulence observed about twenty minutes after the bore passage, lasting for about three minutes: "*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)*" (Fig. 9B). In the Seine River (France), some field observations were undertaken in 1855 (BAZIN 1865): "*Floats were introduced at several heights prior to the arrival of the tidal bore. The float direction was observed after the bore passage. In one case, the surface float continued to float downstream for about 2 min after the bore, while the bottom float flowed downstream only for 1.5 min. Afterwards the floats flowed upstream.*" Repeated field work accidents were reported in the literature. CHANSON et al. (2011) performed a detailed study of turbulent and sedimentary processes in the tidal bore in the Garonne river (France) at the end of a dry summer, while REUNGOAT et al. (2012) surveyed the same site, but a few weeks after a major flood: "*During the field deployment, the authors experienced a major problem: the ADV stem was bent along the main upstream flow direction. The authors found the damaged unit when it was retrieved at the end of the study. […] Based upon the visual observations and ADV record, it is believed that the ADV unit stem was hit by submerged debris during the early flood tide…*" MOUAZE et al. (2010) conducted field measurements in the tidal bore of the Sélune River, in the Bay of Mont Saint Michel (France). They used an ADV system fixed to a tripod, consisting of three poles driven into the bed sediment materials and tightly fastened down together. "*About 40 s after the passage of the bore, the metallic frame started to move. Vibrations were followed by local liquefaction around each pile which then lost their friction stability inside the mobile bed. One pole was lost, and the ADV support failed completely 10 minutes after the tidal bore*." [The next morning] "*the remaining poles were dug out of the bed sediments to avoid any damage to the ADV unit during the tidal bore passage. It took three people nearly 25 minutes to remove the poles in the darkness of the early morning*." REUNGOAT et al. (2012) observed some unusual flow reversal delay between the bore front passage and longitudinal flow reversal. The recorded data showed the reversal in longitudinal flow direction about 50 s after the bore front, while the free-surface velocity next to the survey staff reversed direction about 6 s after the bore front. This unusual feature has been sometimes reported. In the Severn River (UK), some delayed flow reversal was seen depending upon the relative water elevation and bore strength: "*the water near the bed still flowing downwards for up to ten minutes after the surface has been suddenly reversed by the passage of a fairly large bore*", "*with small bores the normal downward flow comes gently to a standstill after the bore had gone by and it may be a minute before the upward stream gathers momentum*" (ROWBOTHAM 1983). KJERFVE and FERREIRA (1993) indicated some unusual flow reversal pattern in the Rio Mearim (Brazil): "*At times, the* *downstream flow resumed after passage of the bore for another 30 seconds before the flow again surged upstream.*"; these observations were based upon measurements at 0.7 m above the bottom. KJERFVE and FERREIRA (1993) reported further an early flow reversal: "*the current began changing directions 1 min ahead of arrival of the bore*". Further field studies highlighted some unusual mixing processes. CHANSON (2011c) observed some transient intrusive fronts behind the tidal bore in Bay of Mont Saint Michel (France), inducing further secondary currents and vertical circulation. The front arrived typically a couple of minutes after the bore front and lasted several minutes.

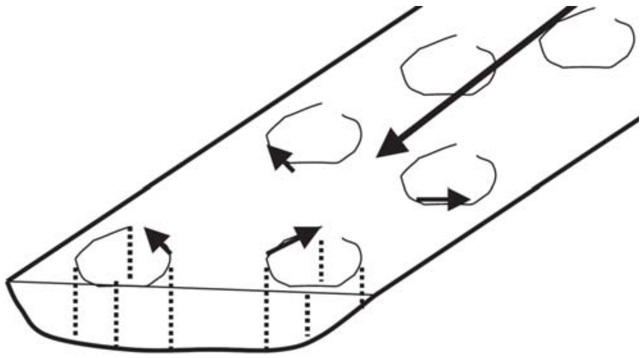
These observations demonstrate unequivocally the complicated flow features and turbulent mixing associated with tidal bore propagation. Large energetic vortical structures are characteristic features of tidal bores, as well as spilling breaking waves (NADAOKA et al. 1989). It is thought that these are induced by some secondary current motion and enhanced in the natural, three-dimensional, non-prismatic irregular and meandering channels (Fig. 9). The measurements of large transverse and vertical velocity fluctuations behind the tidal bore implied the existence of transient secondary currents behind the bore front, associated with some unsteady transverse shear pattern (Fig. 9A). Detailed measurements of the turbulent characteristics have been performed in natural rivers and experimental facilities. WOLANSKI et al. (2001) presented field studies on the sediment dynamics of the two arms of Cambridge Gulf, tropical Western Australia., highlighting the recent existence of tidal bores in this river. This phenomenon only appeared due to successive human interventions, leading to significant changes in the tidal dynamics and bathymetry of the estuary. WOLANSKI et al. (2004) presented field measurements undertaken in the Daly River (Australia) and observed a three-minute duration patch of macro-turbulence that occurred 20 minutes after the undular bore front (Fig. 9B). SIMPSON et al. (2004) studied tidal bores propagating in the tidally energetic estuarine channel of the Dee River (UK). They observed a high degree of variability in bore intensity, this unpredictable aspect being characteristic of many tidal bores in natural channels. The bore front involved an almost instantaneous injection of turbulent kinetic energy, resulting in large turbulent kinetic energy levels which rapidly dissipated. The large bottom shear stresses also generated large turbulent kinetic energy levels in the strong flood currents (1.5 m/s). For comparison, the ebb flow ([1]) was found to be relatively tranquil with maximum speed of 0.5 m/s, thus inducing smaller turbulent kinetic energy production rates.

[1] A tidal bore is only observed during the flood tide. No bore is observed during the ebb tide.

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).



(A) Near-bed turbulence and secondary currents in a tidal bore propagating in a rectangular channel - Top right: secondary flow motion in the corner



(B) Surface macro-turbulence and scars advected upstream behind the undular tidal bore of the Daly River (Australia) and observed 20 min after the bore passage (after WOLANSKI et al. 2004)
Fig. 9 - Macro-turbulence generated during tidal bore propagation

The Reynolds stresses characterise a transport effect resulting from turbulent motion induced by velocity fluctuations with its subsequent increase of momentum exchange and of mixing. Physical data generally showed large normal and tangential Reynolds stresses beneath the bore front. A comparison between undular and weak surge data suggested some basic difference (KOCH and CHANSON 2009). In breaking surges, large stresses are observed in regions of high velocity gradients, while some unsteady flow recirculation are recorded next to the bed. In undular surges, the largest Reynolds stresses are recorded in the lower flow region including next to the bed, and maximum normal and tangential stresses are observed beneath the wave crests behind the advancing front. Experimental measurements show large turbulent stresses and turbulent stress fluctuations, below the bore front and ensuing flow. Beneath the positive surge with roller, large normal and tangential Reynolds stresses were observed in the upper water column (CHANSON 2010b, CHANSON and DOCHERTY 2012). The Reynolds stress magnitudes are significantly larger than before the surge passage at all vertical elevations. In the undular surge, the largest normal and tangential stresses are observed beneath the wave crests and just before each crest (KOCH and CHANSON 2008, CHANSON 2010b).

Both MOUAZE et al. (2010) in the Bay of Mont Saint Michel (France) and CHANSON et al. (2011) in the Garonne River (France) found that the Reynolds stress measurements indicated some large and rapid fluctuations during the tidal bore and flood flow. The Reynolds stress magnitudes were significantly larger than during the ebb tide, and some substantial normal and tangential stress fluctuations were observed. This was confirmed by REUNGOAT et al. (2012) showing that the turbulent stress magnitudes were larger than during the ebb tide. The time-variations of shear stresses highlighted a drastic increase by nearly one order of magnitude in shear stress levels during the flow reversal itself associated with the bore motion.

CHANSON (2011b) showed the effect of channel constriction and bridge piers on the propagation of undular bores. The data illustrated the major impact on the free-surface properties, as some strong macro-scale turbulence was produced when the tidal bore propagated through the constriction, and further vorticity was produced by and advected behind the bore front. This is consistent with in situ observations. The effects of bed roughness were shown by CHANSON (2010b), CHANSON and DOCHERTY (2012) and DOCHERTY and CHANSON (2012). For an undular bore, the bed roughness induced a strong attenuation of the oscillating free-surface flow pattern effect on the longitudinal and vertical velocity components next to the bed, although this quasi-periodic pattern was still seen close to the free-surface. In the breaking bore, the longitudinal velocity data suggested a longer transient recirculation next to the invert on the rough bed. The height and duration of the transient were a function of the bed roughness, with a higher and longer recirculation region above the rough bed. The vertical velocity data presented some positive, upward motion during the bore passage, with increasing maximum vertical velocity with increasing distance from the bed. The transverse velocity data showed some large fluctuations after the roller passage, which highlighted some intense secondary motion advected behind the bore. Such a recirculation pattern is significant because it may contribute to very intense bed scouring beneath the tidal bore in presence of coarse bed materials and bed forms.

CHANSON et al. (2012) argued that all experimental studies conducted in laboratories are based upon a Froude similitude, but with Reynolds numbers about one to two orders of magnitude smaller than in most natural estuarine systems. Further all physical arrangements in laboratory did not reproduce the 'true' tidal bore motion observed in a natural estuary.

The structure of the flow field still has to be detailed in field surveys, and no visualisation technique was implemented to illustrate the coherent structures detected by some field and numerical studies. Scale effects may occur, but have still to be quantified. Some studies indicate that bed roughness affects the tidal bores, but systematic studies still have to show the effect on the structure of the flow. Moreover, the transition between undular and breaking tidal bores has to be investigated. Overall all the data sets present instantaneous turbulent stresses larger than the onset of sediment motion for cohesive and non-cohesive sediment materials, and the observations are consistent with the evidences of major sedimentary processes in tidal bore affected estuaries. Instantaneous Reynolds stress data highlight large turbulent stress magnitudes and turbulent stress fluctuations during the passage and behind the bore front at all vertical elevations. Hence bed erosion may take place during the surge front passage, and the eroded material and other scalars are advected in the "whelps" and wave motion behind the tidal bore front. These would be consistent with very-strong turbulent mixing observed in tidal bore affected estuaries, associated with accretion and deposition in the upper estuarine zones.

Sedimentary processes in bores propagating upriver

A bore induces a strong turbulent mixing which can affect both estuarine and river eco-systems. KJERFVE and FERREIRA (1993) reported that "*in shallow areas, the water boiled violently after passage of the bore and became brownish-black in color and heavily sediment-laden due to turbulent scouring and resuspension of bottom sand and mud.*" TESSIER and TERWINDT (1994) showed a major role played by tidal bores in the estuarine zone of the Bay of Mont Saint-Michel. Large sedimentary structures undergo large deformations during tidal bores passages. CHEN (2003) analysed some surface water samplings under a 0.6 m-high breaking bore: the sediment concentrations taken in the bore front was up to 15.92 kg/m^{-3}; two hours later the sediment concentration was down to 2.50 kg/m^{-3}, illustrating the stronger turbulent bore capacity to carry a large amount of sediments. WOLANSKI et al. (2004) observed a time lag between the passage of an undular bore and resuspension, as accelerating flood tide currents resuspended the sediment two minutes after the bore front. For comparison, the resuspension of sediments under many tidal bores are generally quasi-instantaneous (WOLANSKI et al. 2001, SIMPSON et al. 2004, MOUAZE et al. 2010, CHANSON et al. 2011, FURGEROT et al. 2012). The tidal bores do impact onto the estuarine eco-system (DONNELLY and CHANSON 2005). Tidal bores are turbulent flows, associated with strong mixing and bed material scouring. As the bore propagates, air is entrained in the roller of the breaking bore and the river flows upstream, advecting suspended matters. DONNELLY and CHANSON (2005) argued that undular tidal bores have some potential to scour the channel bed. Upward flow motion between troughs and subsequent crests advects bed material towards the free-surface. The rapid velocity redistributions, associated with the long-lasting chaotic wave motion, contribute to maintain sediment suspension which is advected upstream with the bore and eventually deposited in intertidal zones. A comparison between undular and weak surge data suggested two main mechanisms of sediment scour and scalar transport (KOCH and CHANSON 2009). In weak surge flows, the data indicate some rapid flow separation beneath the surge front. Flow separation and large transverse velocities enable scour and erosion of unconsolidated bed materials that are subsequently mixed in the developing shear region of the roller and advected by large coherent structures behind the roller. In undular surges, maximum Reynolds stresses are observed beneath and just before each wave crest. Bed erosion may take place beneath each wave crest, and the eroded material and other scalars are advected in the "whelps" and wave motion behind the first wave crest. The long lasting impact of the free-surface undulations is a key feature of undular tidal bores in natural systems (CHANSON 2010b,c).

The macro-turbulent eddies observed in natural rivers "*are important in the transport of fine sediment because, […] they essentially double the suspended sediment concentration*" (WOLANSKI et al. 2006). In the Sélune River, the passage of the bore and the ebb flow was characterised by large suspended sediment concentrations (MOUAZE et al. 2010). In the Graonne River, some unusually high suspended sediment concentration about 100 s after the tidal bore front, this event lasting for more than 10 minutes (CHANSON et al. 2011). It has been speculated that the tidal bore passage scoured the bed and convected upwards the bed material, reaching the free-surface after the bore passage: "*behind the tidal bore, the net sediment flux magnitude was 30 times larger than the ebb tide net flux and directed upstream. A striking feature of the data set was the intense mixing and suspended sediment motion during the tidal bore and following flood tide.*" REUNGOAT et al. (2012) observed that, "*the suspended sediment flux data indicated a downstream positive suspended sediment flux during the end of the ebb tide prior to the tidal bore. After the passage of the bore, the net sediment mass transfer per unit area was negative (i.e. upriver) and its magnitude was 1.5 to 2 times larger than the ebb tide net flux.*" In the Qiantang River (China), "*sediment concentration rapidly and substantially increased from roughly 0 kg.m^{-3} to greater than 70 kg.m^{-3} at the Ershigongduan station and rose from roughly 2 kg.m^{-3} to 20 kg.m^{-3} at the Ershiergongduan station*" (PAN and HUANG 2010). Concerning the tidal bore influence in the Qiantang river (China), FAN et al. (2012) stated: "*the tidal bore and subsequent rapid flood flows take a leading role in shaping estuarine morphology and depositional strata, even though they only account for about one tenth of a single semidiurnal tidal cycle*."

CHANSON and TAN (2010, 2011) illustrated the turbulent mixing capacity of tidal bores and longitudinal dispersion of fish egg particles. The large turbulent structures present under tidal bores were responsible for the vertical water mixing as a tidal bore propagates upstream in an estuary. These large-scale eddies were also responsible for the rapid longitudinal dispersion of the fish eggs, also seen in the field (RULIFSON and TULL 1999). Some form of preferential motion seemed to depend upon the particle's vertical elevation. A key result was the comparative observations suggesting that undular bores induced a larger particle mixing compared to breaking bores, especially in the upper flow region.

KHEZRI and CHANSON (2012a, b) studied the inception of sediment motion and transient sediment transport beneath an unsteady tidal bore flow, both theoretically and physically. A key result is the identification of the dominant contribution of the longitudinal pressure gradient force to sediment inception beneath the breaking bore. The sediment particles are de-stabilized by the roller toe passage beneath the breaking bore front and advected upstream by bed load motion. A transient recirculation next to the bed leads to a delayed drag force contribution acting in the upstream direction and adding to further transport of the particles. The undular bore had a negligible effect on gravel particle movement, likely linked with the large sediment size (KHEZRI and CHANSON 2012b). Under a breaking bore, the magnitude of negative transient longitudinal velocity close to the bed was greater on fixed bed than on mobile bed, indicating some damping effect of the movable gravel bed (KHEZRI and CHANSON 2012c).

Simply tidal bores do have a significant impact in terms of sediment processes on an estuarine system, and this was evidenced during tsunami-induced bores.

Discussion

Tidal bores are sometimes presented as a proxy to tsunami-induced river bores, although some limitations must be clearly stated. A tidal bore is a predictable event induced by the tides, which are caused by the gravitational influences of the moon and sun. The tides and tidal waves are most pronounced in narrow bays or in rivers along the coast. On the other hand a tsunami is not related to tides: it occurs when some unpredictable, highly-energetic and rapid event disturbs the ocean, although the impact of a tsunami could be influenced by the tidal level when it reaches the shoreline. Tsunamis and tidal bores have different length and time scales. The time scale of a tidal bore is 12 h 25 min or 24h 50 min for semi-diurnal and diurnal tidal regimes respectively, while the time scale of a tsunami-induced bore may vary from a few minutes to more than 1 hour. A tidal bore is simply a true tidal wave and it is not to be confused with a tsunami, which is a large ocean wave travelling primarily on the open ocean.

Some similarities between tidal bores and tsunamis propagating in rivers can also be highlighted. Both flow motions are similar, with massive volumes of water rushing upriver. Both types of bores are neither solitons nor progressive waves, but rather look like large walls of water that keeps coming from the sea. In both cases, there is a net flux of mass and momentum during the bore passage. Tidal bores and tsunamis are not solitary waves (MADSEN et al. 2008), although solitary waves are known for having some interesting properties: e.g., symmetrical form with a single hump, uniform velocity without changing form. The tide does not consist of a single wave, and there is now clear evidence that tsunamis are not solitary waves (MADSEN et al. 2008).

Both tidal bores and tsunamis originate from the ocean. The wave generated by a sudden and energetic event may travel for thousands of kilometres across the ocean until it reaches the coastlines. While it propagates in the ocean, the wave height is only the order of a metre or less, and the wave length can be more than several hundred kilometres, making it difficult to detect. In shallow waters, the energy is concentrated by shoaling and often tunnelling due the bathymetry, inducing some drastic wave steepening. Tides in the open ocean are also usually of much smaller amplitude than those along the coast, partly because of amplification by reflection and resonance. When approaching an inlet whose shape focuses the tidal wave energy, the funnelling effect induced an increase of tide height. More generally the tidal wave is shoaling into shallower water, its celerity decreases, and both tide height and tidal current strength increase accordingly. Basically both tidal bores and tsunamis are more spectacular when they arrive in funnel-shaped shallow water areas. The celerity of the bore is comparable for similar initial flow conditions and Froude numbers. For example, upriver tsunami celerities observed during the 2011 Tohoku tsunami (ADITYAWAN et al. 2012b) were close to some observations of the Qiantang River bore propagation speed (CHYAN and ZHOU 1993). Tidal bores can reach large heights (e.g. Amazon River), they are able to of overtop dikes and levees (e.g. Qiantang River) and can modify drastically the bed morphology (CHANSON 2011a). In the Sélune River (France), CHANSON (2011a) reported "*the formation of a new main channel by the tidal bore on 31 August 2008*"; "*The tidal bore cut a channel meander*"; "*The channel incision event was followed by intense bed form motion processes and standing waves during the early flood tide flow*" (Fig. 10). Figure 10 illustrates the leading edge of the bore cutting a new channel in the Bay of Mt St Michel (France).

Both flows need some converging paths to propagate far upstream in the river. The mouth shape of the estuary is critical to facilitate the focusing of energy. If the shape is too narrow, both tidal waves and tsunamis will dissipate the energy by breaking. Both types of bore can propagate under the form of undular or breaking bores in the rivers (TSUJI et al. 1991). Many video footages and photographs of tsunami propagation upriver during the 11 March 2011 Tohoku tsunami showed the formation of an undular bore. The formation of undular bores was observed during the 1983 Nihonkai-Chubu tsunami by SHUTO (1985), who reported that short waves of

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

the order 10-15 s were riding on top of the main tsunami, which was of the order 5-30 minutes (also MADSEN et al. 2008, MADSEN 2010). Tidal bores can reach long upstream distances (hundreds of kilometers) with a typical celerity ranging between 15 to 20 km/h. Tsunami-induced bores were reported to travel upstream rivers as fast as tidal bores (ROH et al. 2012).

Fig. 10 - Channel incision by the tidal bore of the Sélune River (France) on 31 August 2008 - The red arrow points to the bore front cutting a new channel - Bore propagation from background to foreground

A tidal bore is a natural and fragile phenomenon, which is of great importance for the ecology of an estuary, whereas a tsunami is a catastrophic event. The tidal bore is a very important phenomenon for the estuarine eco-system: e.g., turbulence, mixing capacity, sediment transport, remobilisation of particulates and pollutants. Tidal bore affected estuarine systems are known feeding and spawning grounds for various species. Carnivores and scavengers are common behind tidal bores. In the Amazon, piranhas gobble up fish and crabs. Crocodiles swim behind the Styx River bore in Queensland (Australia). The disappearance of several bores was reported to adversely impact onto the ecosystem, with elimination of fish species. Tidal bores also impact human industrial activities. For example, some sections of the Airbus A380 travel on barges on the Dee and Garonne River estuaries that are both affected by tidal bores. The impact on the ecology is acknowledged (CHANSON 2009,2011c). Tidal bores can tear vegetation like trees from their roots, while tidal bore affected estuarine systems are known feeding and spawning grounds for various species (RULIFSON and TULL 1999). Major modifications of tidal bores can lead to fish species' disappearance. Tidal bores are tourist attractions in many locations. Numerous places are known for surfers' gatherings. Meetings and cultural event are organised during spring tide periods to coincide with the occurrence of large tidal bores. People are often regrouped in associations interested with the observation of this natural phenomenon, and numerous web sites share the experiences of worldwide tidal bores. The tidal bore has become some fragile heritage: people can watch television shows and often read articles in magazines and daily newspapers concerning tidal bores.

Man-made interventions led to the disappearance of several bores: e.g., harbour facilities, bridges, locks, dams, dredging operations. The global climate change is also responsible for the modifications of the conditions of appearance of bores: variations of river flows and bathymetries, rise of water and sea levels, floods, etc. The famous tidal bore of the Seine River no longer exists following dike constructions and dredging operations in the 1960s.

Conclusion

The 26 December 2004 and 10 March 2011 tsunami disasters highlighted the rapid advances of the tsunami waters following rivers and canals causing massive damage deep inland. The leading edge of the tsunami formed a series of waves propagating upriver. In these rivers and shallow-water bays, the propagation of the bores is associated with strong mixing and massive sedimentary processes upriver. A number of tsunami-induced bore disasters were reviewed herein and the basic equations of tsunami propagation upriver were developed. A number of compelling evidences on the turbulent mixing and sediment processes induced by tsunami bores were presented based upon some recent field observations, as well as physical and numerical studies of tidal bores. It was shown that the propagation of the bore front modifies drastically the water column properties and the tsunami waters behind the front may carry a large amount of sediments, explaining some of the sedimentological and morphological changes observed after some recent disasters.

Tidal bores and tsunamis propagating upriver are two distinct phenomena, showing some interesting similarities when propagating upriver. Human activities can modify or even prevent the occurrence of tidal bores. The same may be considered to minimise the impact of tsunamis propagating upriver.

Acknowledgements

The authors thank both reviewers, Professor Hitoshi TANAKA (Tohoku University, Japan) and Dr Hubert BRANGER (IRPHE/Luminy, France). of their helpful comments. They acknowledge the discussions with their students and co-workers. The financial assistance of the Agence Nationale de la Recherche (Projet MASCARET 10-BLAN-0911-01) is acknowledged.

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

References

ABADIE, S., HARRIS, J. C., GRILLI, S. T., FABRE, R. (2012). "Numerical Modeling of Tsunami Waves generated by the Flank Collapse of the Cumbre Vieja Volcano (La Palma, Canary Islands): Tsunami Source and Near Field Effects." *Journal of Geophysical Research C: Oceans*, Vol. 117, No. 5, C05030.

ABE, K. (1986). "Tsunami Propagation in Rivers of the Japanese Islands." *Continental Shelf Research*, Vol. 5, No. 6, pp. 665-677.

ADITYAWAN, M.B., ROH, M., TANAKA, H., and FARID, M. (2012a). "The Effect of River Mouth Morphological Features on Tsunami Intrusion." *Proc. Annual International Conference organized by the International Institute for Infrastructure*, Renewal and Reconstruction (IIIRR), Kumamoto, Japan, August 24 - 26, pp. 75-83.

ADITYAWAN, M.B., ROH, M., and TANAKA, H. (2012b). "Investigation of tsunami Propagation Characteristics in River and on Land Induced by the Great East Japan Earthquake 2011." *Journal of Earthquake and Tsunami*, Vol. 6, No. 3, Paper 1250033, 22 pages (DOI: 10.142/S1793431112500339).

BAPTISTA, M. A., HEITOR, S., MIRANDA, J. M., MIRANDA, P., and MENDES VICTOR, L. (1998). "The 1755 Lisbon Tsunami; Evaluation of the Tsunami Parameters." *J. Geodynamics*, Vol. 25, No. 2, pp. 143-157.

BAPTISTA, M. A., MIRANDA, J. M., OMIRA, R., and ANTUNES, C. (2011). "Potential Inundation of Lisbon Downtown by a 1755-Like Tsunami." *Nat. Hazards Earth Syst. Sci.*, Vol. 11, pp. 3319–3326.

BAZIN, H. (1865). "Recherches Expérimentales sur la Propagation des Ondes." ('Experimental Research on Wave Propagation.') *Mémoires présentés par divers savants à l'Académie des Sciences*, Paris, France, Vol. 19, pp. 495-644 (in French).

BOMBARDELLI, F., and CHANSON, H. (2009). "Progress in the Observation and Modeling of Turbulent Multi-Phase Flows." *Environmental Fluid Mechanics*, Vol. 9, No. 2, pp. 121-123 (DOI: 10.1007/s10652-009-9125-8).

BUKREEV, V. I. (2004). "On the Critical Velocities and Depths in a Nonuniform Steady Flow in an Open Channel." *Vodnye Resursy*, Vol. 31, No. 1, pp. 40–45. (English translation: *Water Resources*, 2004, Vol. 31, No. 1, pp. 35-40.)

CAPUTO, J.-G., and STEPANYANTS, Y. A. (2003). "Bore Formation, Evolution and Disintegration into Solitons in Shallow Inhomogeneous Channels." *Nonlinear Processes in Geophysics*, Vol. 10, pp. 407–424.

CARTWRIGHT, J.H.E., and NAKAMURA, H. (2009). "What Kind of a Wave is Hokusai's *Great Wave off Kanagawa*?" *Notes & Records of the Royal Society*, Vol. 69, pp. 119-135.

CHANSON, H. (2004). "Environmental Hydraulics of Open Channel Flows." *Elsevier-Butterworth-Heinemann*, Oxford, UK, 483 pages.

CHANSON, H. (2005). "Le Tsunami du 26 Décembre 2004: un Phénomène Hydraulique d'Ampleur Internationale. Premier Constats." ('The 26 December 2004 Tsunami: a Hydraulic Engineering Phenomenon of International Significance. First Comments') *Journal La Houille Blanche*, No. 2, pp. 25-32 (in French).

CHANSON, H. (2009). "Current Knowledge in Hydraulic Jumps and Related Phenomena. A Survey of Experimental Results." *European Journal of Mechanics B/Fluids*, Vol. 28, No. 2, pp. 191-210.

CHANSON, H. (2010a). "Coastal Observations: Tsunami Warning Signs on the Enshu Coast of Japan." *Shore & Beach*, Vol. 78, No. 1, pp. 52-54.

CHANSON, H. (2010b). "Unsteady Turbulence in Tidal Bores: Effects of Bed Roughness." *Journal of Waterway, Port, Coastal, and Ocean Engineering*, ASCE, Vol. 136, No. 5, pp. 247-256 (DOI: 10.1061/(ASCE)WW.1943-5460.0000048).

CHANSON, H. (2010c). "Undular Tidal Bores: Basic Theory and Free-surface Characteristics." *Journal of Hydraulic Engineering*, ASCE, Vol. 136, No. 11, pp. 940-944 (DOI: 10.1061/(ASCE)HY.1943-7900.0000264).

CHANSON, H. (2011a). "Tidal Bores, Aegir, Eagre, Mascaret, Pororoca: Theory and Observations." *World Scientific*, Singapore, 220 pages (ISBN 9789814335416).

CHANSON, H. (2011b). "Undular Tidal Bores: Effect of Channel Constriction and Bridge Piers." *Environmental Fluid Mechanics*, Vol. 11, No. 4, pp. 385-404.

CHANSON, H. (2011c). "Current Knowledge in Tidal bores and their Environmental, Ecological and Cultural Impacts." *Environmental Fluid Mechanics*, Vol. 11, No. 1, pp. 77-98.

CHANSON, H. (2012). "Momentum Considerations in Hydraulic Jumps and Bores." *Journal of Irrigation and Drainage Engineering*, ASCE, Vol. 138, No. 4, pp. 382-385 (DOI 10.1061/(ASCE)IR.1943-4774.0000409).

CHANSON, H., and DOCHERTY, N. (2012). "Turbulent Velocity Measurements In Open Channel Bores." *European Journal of Mechanics B/Fluids*, Vol. 32, pp. 52–58.

CHANSON, H., and TAN, K.K. (2010). "Turbulent Mixing Of Particles Under Tidal Bores: An Experimental Analysis." *Journal of Hydraulic Research*, Vol. 48, No. 5, pp. 641–649.

CHANSON, H., and TAN, K.K. (2011). "Dispersion of Fish Eggs under Undular and Breaking Tidal Bores." *Fluid Dynamics & Materials Processing*, Tech Science Press, Vol. 7, No. 4, pp. 403-418.

CHANSON, H., REUNGOAT, D., SIMON, B., and LUBIN, P. (2011). "High-Frequency Turbulence and Suspended Sediment Concentration Measurements in the Garonne River Tidal Bore." *Estuarine Coastal and Shelf Science*, Vol. 95, No. 2-3, pp. 298-306 (DOI 10.1016/j.ecss.2011.09.012).

CHANSON, H., LUBIN, P., and GLOCKNER, S. (2012). "Unsteady Turbulence in a Shock: Physical and Numerical Modelling in Tidal Bores and Hydraulic Jumps." in "Turbulence: Theory, Types and Simulation", Nova Science Publishers, Hauppauge NY, USA, Ed. R.J. MARCUSO, Chapter 3, pp. 113-148 (ISBN 978-1-61761-735-5).

CHEN, S. (2003). "Tidal Bore In The North Branch Of The Changjiang Estuary." International Conference on Estuaries and Coasts, November 9-11, Hangzhou, China.

CHYAN, S., and ZHOU, C. (1993). "The Qiantang Tidal Bore." *Hydropower Publ.*, Beijing, China, The World's Spectacular Sceneries, 152 pages (in Chinese).

DELWAR, H.S.M. (2001). "Hydrodynamic Characteristics of the Coastal Areas of Bangladesh." *Proc. Intl Seminar on Quaternary Development and Coastal Hydrodynamics of Ganges Delta Bangladesh*, Khorshed-Alam-A-K-M and Khairul-Islam-M Editors, Geological Survey of Bangladesh Publ., Dhaka, Bangladesh, pp. 69-85.

DIDENKULOVA, I., and PELINOVSKY, E. (2011). "Runup of Tsunami Waves in U-Shaped Bays." *Pure Appl. Geophys.*, Vol. 168, pp. 1239–1249.

DOCHERTY, N., and CHANSON, H. (2012). "Physical Modeling of Unsteady Turbulence in Breaking Tidal Bores." *Journal of Hydraulic Engineering*, ASCE, Vol. 138, No. 5, pp. 412-419 (DOI: 10.1061/(ASCE)HY.1943-7900.0000542).

DONNELLY, C., and CHANSON, H. (2005). "Environmental Impact of Undular Tidal Bores in Tropical Rivers." *Environmental Fluid Mechanics*, Vol. 5, No. 5, pp. 481-494 (DOI: 10.1007/s10652-005-0711-0).

FAN, D.D., CAI, G.F., SHANG, S., WU, Y.J., ZHANG Y.W., and GAO, L. (2012). "Sedimentation Processes and Sedimentary Characteristics of Tidal Bores along the North Bank of the Qiantang Estuary." *Chinese Science Bulletin*, Vol. 57, No.13, pp. 1578-1589.

FINKL, C. W., PELINOVSKY, E. N., and CATHCART, R. B. (2012). "A Review of Potential Tsunami Impacts to the Suez Canal." *Journal of Coastal Research*, Vol. 28, No. 4, pp. 745–759.

FRITZ, H., PETROFF, C., CATALA, P., CIENFUEGOS, R., WINCKLER, P., KALLIGERIS, N., WEISS, R., BARRIENTOS, S, MENESES, G., VALDERAS-BERMEJO, C, EBELING, C., PAPADOPOULOS, A., CONTRERAS, M., ALMAR, R., DOMINGUEZ, J.-C., and SYNOLAKIS, C. (2011). "Field Survey of the 27 February 2010 Chile Tsunami." *Pure Appl. Geophys.*, Vol. 168, pp. 1989–2010.

FURGEROT, L., MOUAZE, D., TESSIER, B., and BRUN-COTTAN, J.C. (2012). "Tidal Bore: Eulerian Velocities and Suspended Sediment Concentration Measurements." *Proc. Intl Conf. on Fluvial Hydraulics River Flow 2012*, San Jose, Costa Rica, 8 pages (CD-ROM).

FURUYAMA, S., and CHANSON, H. (2010). "A Numerical Solution of a Tidal Bore Flow." *Coastal Engineering Journal*, Vol. 52, No. 3, pp. 215-234.

HENDERSON, F.M. (1966). "Open Channel Flow." *MacMillan Company*, New York, USA.

HOKUSAI, K. (1826-1833). "*Thirty-Six Views of Mount Fuji*." Japan.

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.

KAYANE, K., TANAKA, H., and ADITYAWAN, M.B. (2012). "Influence of River Bed Slope for Tsunami Propagation into Rivers." *Journal of Japan Soc. of Civil Engineers*, Series B2 (Coastal Engineering), Vol. B2-68, 5 pages.

KHEZRI, N., and CHANSON, H. (2012a). "Sediment Inception under Breaking Tidal Bores." *Mechanics Research Communications*, Vol. 41, pp. 49-53 & 1 vide movie (DOI 10.1016/j.mechrescom.2012.02.010).

KHEZRI, N., and CHANSON, H. (2012b). "Inception of Bed Load Motion beneath a Bore." *Geomorphology*, Vol. 153–154, pp. 39–47 & 2 video movies (DOI: 10.1016/j.geomorph.2012.02.006).

KHEZRI, N., and CHANSON, H. (2012c). "Undular and Breaking Bores on Fixed and Movable Gravel Beds." *Journal of Hydraulic Research*, Vol. 50, No. 4, pp. 353–363(DOI: 10.1080/00221686.2012.686200).

KJERFVE, B. and FERREIRA, H.O. (1993). "Tidal Bores: First Ever Measurements." *Ciência e Cultura (Journal of the Brazilian Association for the Advancement of Science)*, Vol. 45, No. 2, pp. 135–138.

KOCH, C., and CHANSON, H. (2008). "Turbulent Mixing beneath an Undular Bore Front." *Journal of Coastal Research*, Vol. 24, No. 4, pp. 999-1007.

KOCH, C., and CHANSON, H. (2009). "Turbulence Measurements in Positive Surges and Bores." *Journal of Hydraulic Research*, IAHR, Vol. 47, No. 1, pp. 29-40.

KOSHIMURA, S., MATSUOKA, M., MATSUYAMA, M., YOSHII, T., MAS, E., JIMENEZ, C., and YAMAZAKI, F. (2011). "Field Survey of the 2010 Tsunami in Chile." *Proceedings of the 8th International Conference on Urban Earthquake Engineering*, Tokyo Institute of Technology, Japan, 7−8 March.

LACOMBE, H. (1952). "Quelques Aspects du Problème des Marées Fluviales et de la Formation du Mascaret." ('Some aspects of the Problem of Tides in Rivers and the Formation of a Tidal Bore.') *Bulletin d'information*, Comité Central d'Océanographie et d'Études des Côtes (COEC), France, Vol. 4, No. 6, June, pp. 228-254 (in French).

LIGGETT, J.A. (1994). "Fluid Mechanics." *McGraw-Hill*, New York, USA.

LIGHTHILL, J. (1978). "Waves in Fluids." *Cambridge University Press*, Cambridge, UK, 504 pages.

LUBIN, P., GLOCKNER, S., and CHANSON, H. (2010a). "Numerical Simulation of a Weak Breaking Tidal Bore." *Mechanics Research Communications*, Vol. 37, No. 1, pp. 119-121.

LUBIN, P., CHANSON, H., and GLOCKNER, S. (2010b). "Large Eddy Simulation of Turbulence Generated by a Weak Breaking Tidal Bore." *Environmental Fluid Mechanics*, Vol. 10, No. 5, pp. 587-602.

MADSEN, P. A., SIMONSEN, H. J. and PAN, C.-H. (2005). "Numerical Simulation of Tidal Bores and Hydraulic Jumps." *Coastal Eng.*, Vol. 52, pp. 409-433.

MADSEN, P. A., FUHRMAN, D. R., and SCHÄFFER, H. A. (2008). "On the Solitary Wave Paradigm for Tsunamis". *J. Geophys. Res.*, Vol. 113, C12012, doi:10.1029/2008JC004932.

MADSEN, P. A. (2010). "On the Evolution and Run-up of Tsunamis." *Journal of Hydrodynamics*, Vol. 22, No. 5 (Suppl. 1), pp. 1-6.

MONTES, J.S. (1998). "Hydraulics of Open Channel Flow." *ASCE Press*, New-York, USA, 697 pages.

MORI, N., TAKAHASHI, T., YASUDA, T., and YANAGISAWA, H. (2011). "Survey of 2011 Tohoku earthquake tsunami inundation and run-up." *Geophysical Research Letters*, Vol. 38, L00G14, 6 pages.

MOUAZE, D., CHANSON, H., and SIMON, B. (2010). "Field Measurements in the Tidal Bore of the Sélune River in the Bay of Mont Saint Michel (September 2010)." *Hydraulic Model Report No. CH81/10*, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 72 pages (ISBN 9781742720210).

NADAOKA, K., HINO, M., and KOYANO, Y. (1989). "Structure of the Turbulent Flow field under Breaking Wave in the Surf Zone." *Journal of Fluid Mechanics*, Vol. 204, pp. 350-387.

OSHIKI, H., CHIBA, S., IWASE, H., FUJIMA, K., and MATUI, K. (2008). "Numerical Simulation of Tsunami Run-up on the Yoneshiro River by the 1983 Nihonkai-chubu Earthquake." *Annual Jl of Coastal Eng.*, JSCE, Vol. 55, No. 1, pp. 241-245 (in Japanese).

PAN, C., and HUANG, W. (2010). "Numerical Modeling of Suspended Sediment Transport Affected by Tidal Bore in Qiantang Estuary." *Jl of Coastal Research*, Vol. 26, No. 6, pp. 1123-1132.

CHANSON, H. and LUBIN, P. (2013). "Mixing and Sediment Processes induced by Tsunamis propagating Upriver" in "Tsunamis: Economic Impact, Disaster Management and Future Challenges." *Nova Science Publishers*, Hauppauge NY, USA, T. CAI Editor, Chapter 3, pp. 65-102 (ISBN 978-1-62808-682-9) (ISBN 978-1-62808-686-7 ebook).

PELINOVSKY, E. N., and RODIN, A. A. (2011). "Nonlinear Deformation of a Large¬ Amplitude Wave on Shallow Water." *Doklady Physics*, Vol. 56, No. 5, pp. 305–308.

POINCARÉ, H. (1910). "Leçons de Mécanique Céleste. Tome 3. Théorie des Marées." ('Lectures on Celest Mechanics. Volume 3. Theory of Tides.') *Gauthier-Villars*, Paris, France (in French).

RAO, G., and LIN, A. (2011). "Distribution of Inundation by the Great Tsunami of the 2011 M_w 9.0 Earthquake off the Pacific Coast of Tohoku (Japan), as Revealed by ALOS Imagery Data." *International Journal of Remote Sensing*, Vol. 32, No. 22, pp. 7073-7086.

RAYLEIGH, Lord (1908). "Note on Tidal Bores." *Proc. Royal Soc. of London, Series A containing Papers of a Mathematical and Physical Character*, Vol. 81, No. 541, pp. 448-449.

REUNGOAT, D., CHANSON, H., and CAPLAIN, B. (2012). "Field Measurements in the Tidal Bore of the Garonne River at Arcins (June 2012)." *Hydraulic Model Report No. CH89/12*, School of Civil Engineering, The University of Queensland, Brisbane, Australia, 121 pages (ISBN 9781742720616).

ROH, M., TANAKA, H., ADITAYWAN, M.B., MANO, A., and UDO, K. (2012)." Evaluation of Celerity and Velocity for Tsunami Propagation into Rivers." *Proc. 33rd Intl. Conf. on Coastal Eng.*, Santander, Spain, P. LYNETT and J. McKEE SMITH Editors, 10 pages.

ROWBOTHAM, F. (1983). "The Severn Bore." *David & Charles*, Newton Abbot, UK, 3rd edition, 104 pages.

RULIFSON, R.A., and TULL, K.A. (1999). "Striped Bass Spawning in a Tidal Bore River: the Shubenacadie Estuary, Atlantic Canada." *Transactions of the American Fisheries Society*, Vol. 128, pp. 613-624.

SHUTO, N. (1985). "The Nihonkai-Chubu Earthquake Tsunami on the North Akita Coast." *Coastal Eng. in Japan*, Vol. 20, pp. 250-264.

SIMPSON, J.H., FISHER, N.R., and WILES, P. (2004). "Reynolds Stress and TKE Production in an Estuary with a Tidal Bore." *Estuarine, Coastal and Shelf Science*, Vol. 60, No. 4, pp. 619-627.

SOMMER, A., and MOSLEY, W.H. (1972). "East Bengal Cyclone of November 1970. Epidemological Approach to Disaster Assessment." *Le Lancet*, Vol. 299, No. 7759, Sat. 13 May, pp. 1029-1036.

TANAKA, H., ISHONO, K., NAWARATHNA, B., NAKAGAWA, H., YANO, S.-I., YASUDA, H., WATANABE, Y. and HASEGAWA, K. (2008). "Field Investigation Of Disasters In Sri Lankan Rivers Caused By Sumatra Earthquake Tsunami." *J. Hydraulics, Hydrology and Environment*, JSCE, 26(1), 91-112.

TANAKA, H., TINH, N.X., and DAO, N.X. (2011). "Field Measurement and Numerical Studies on the Tsunami Propagation into Upstream Rivers." *Proc. 34th IAHR World Congress*, Brisbane, Australia, 26 June-1 July, Engineers Australia Publication, Eric VALENTINE, Colin APELT, James BALL, Hubert CHANSON, Ron COX, Rob ETTEMA, George KUCZERA, Martin LAMBERT, Bruce MELVILLE and Jane SARGISON Editors, pp. 1317-1324.

TANAKA, H., NGUYEN, X.T., UMEDA, M., HIRAO, R., PRADJOKO, E., MANO, A., and UDO, K. (2012a). "Coastal and Estuarine Morphology Changes Induced by the 2011 Great East Japan Earthquake Tsunami." *Coastal Engineering Journal*, Vol. 54, No. 1, paper 1250010, 25 pages (DOI: 10.1142/S0578563412500106).

TANAKA, N., YAGISAWA, J., and YASUDA, S. (2012b). "Characteristics of Damage due to Tsunami Propagation in River Channels and Overflow of their Embankments in Great East Japan Earthquake." *International Journal of River Basin Management*, Vol. 10, No. 3, pp. 269-279.

TINH, N.X., TANAKA, H., HIRAO, R., PRADJOKO, E., MANO, A., and UDO, K. (2012)." Morphology Change caused by the 2011 Great Tohoku Tsunami Wave - Mechanism of Recent Closure and Breaching of the Nanakita River Mouth." *Proc. 33rd Intl. Conf. on Coastal Eng.*, Santander, Spain, P. LYNETT and J. McKEE SMITH Editors, 10 pages.

TSUJI, Y., YANUMA, T., MURATA, I., and FUJIWARA, C. (1991). "Tsunami Ascending in Rivers as an Undular Bore." *Natural Hazards*, Vol. 4, pp. 257-266.

TESSIER, B., and TERWINDT, J.H.J. (1994). "An Example of Soft-Sediment Deformations in an intertidal Environment - The Effect of a Tidal Bore". *Comptes-Rendus de l'Académie des Sciences*, Série II, Vol. 319, No. 2, Part 2, pp. 217-233 (in French).

WIJETUNGE, J. J., WANG, X., and LIU, P. L.-F., (2008). "Indian Ocean Tsunami on 26 December 2004: Numerical Modeling of Inundation in Three Cities on the South Coast of Sri Lanka." *Journal of Earthquake and Tsunami*, Vol. 2, No. 2, pp. 133-155.

WIJETUNGE, J. J. (2009a). "Field Measurements and Numerical Simulations of the 2004 Tsunami Impact on the East Coast of Sri Lanka." *Pure Appl. Geophys.*, Vol. 166, pp. 593–622.

WIJETUNGE, J. J. (2009b). "Field Measurements and Numerical Simulations of the 2004 Tsunami Impact on the South Coast of Sri Lanka." *Ocean Engineering*, Vol. 36, pp. 960–973.

WOLANSKI, E., MOORE, K., SPAGNOL, S., D'ADAMO, N., and PATTIERATCHI, C. (2001). "Rapid, Human-Induced Siltation of the Macro-Tidal Ord River Estuary, Western Australia." *Estuarine, Coastal and Shelf Science*, Vol. 53, pp. 717-732.

WOLANSKI, E., WILLIAMS, D., SPAGNOL, S., and CHANSON, H. (2004). "Undular Tidal Bore Dynamics in the Daly Estuary, Northern Australia." *Estuarine, Coastal and Shelf Science*, Vol. 60, No. 4, pp. 629-636.

WOLANSKI, E., WILLIAMS, D., and HANERT, E. (2006). "The Sediment Trapping Efficiency of the macro-tidal Daly Estuary, Tropical Australia." *Estuarine, Coastal and Shelf Science*, Vol. 69, pp. 291-298.

YASUDA, H., WATANABE, Y., and FUJIMA, K. (2004). "Report on River Propagation of Tsunami Generated by the Tokachi-Oki Earthquake on 26 September, 2003." *J. Hydraulics, Coastal and Environment Engineering*, JSCE, No. 768/11-68, 209-218 (in Japanese with English abstract).

YASUDA, H. (2010). "One-Dimensional Study on Propagation of Tsunami Wave in River Channels." *Jl of Hydraulic Engineering*, ASCE, Vol. 136, No. 2, pp. 93-105.

YEH, H., TOLKOVA, E., JAY, D., TALKE, S., and FRITZ, H. (2012). "Tsunami Hydrodynamics in the Columbia River." *Journal of Disaster Research*, Vol.7, No. 5, pp. 604-608.

The manuscript was peer-reviewed by Professor Hitoshi TANAKA (Tohoku University, Japan) and Dr Hubert BRANGER (IRPHE/Luminy, France).