

TIDAL BORE PROCESSES IN THE BAIE DU MONT SAINT MICHEL (FRANCE): FIELD OBSERVATIONS AND DISCUSSION

HUBERT CHANSON

Dept of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia
(Tel: +61-7-3365-4163, Fax: +61-7-3365-4599, e-mail: h.chanson@uq.edu.au)

Abstract

The occurrence of tidal bore has a significant impact on estuarine systems. Evidences of tidal bores in the Baie du Mont Saint Michel are detailed herein. In the Baie, tidal bores may spread over more than 1 km width before entering river mouths where the bores propagate more than 10 km inland. The tidal bore passage is associated with major sediment scour beneath the surge front and next to the banks, as well as with scour beneath bore front propagating over dry tidal flats. The Baie du Mont Saint Michel is a distinctive illustration of tidal bore impact on eco-systems. But the bore existence relies upon a fragile hydrodynamic balance which may be easily disturbed by changes in boundary conditions and freshwater inflows.

Keywords : Tidal bores; Field observations; Baie du Mont Saint Michel; Scour; Mixing; Ecology.

1. INTRODUCTION

A tidal bore is a positive surge propagating upstream as the tidal flow turns to rising (Chanson 2001). Its inception and development is commonly predicted using the method of characteristics and Saint-Venant equations (e.g. Henderson 1966, Chanson 2004). After formation, the flow properties immediately upstream and downstream of the bore front must satisfy the continuity and momentum principles. A tidal bore process impacts significantly on estuarine systems. Mixing and dispersion of matters is drastically enhanced by the bore. Bed erosion and scour take place beneath the bore while suspended matters are then advected upstream with the tidal bore (Donnelly and Chanson 2002). However tidal processes remain poorly understood today because of a lack of field observations and comprehensive studies.

In this paper, the occurrence of tidal bores in the Baie du Mont Saint Michel (48°40'N, 1°35'W) is documented based upon new field observations (Fig. 1, 2 & 3, Table 1), complemented by a laboratory study. A particular emphasis is placed on the bore impacts on the intertidal zones. The results bring new evidences on the hydrodynamic and ecological significance of the events.

1.1 BAIE DU MONT SAINT MICHEL : PRESENTATION

The Baie du Mont-Saint-Michel (France) in the English Channel, is known for the abbey built on Mont Saint Michel (¹), its very large tidal range, and fast advancing flood tide. The Baie is an UNESCO World Heritage site since 1979. It is drained by three main rivers : the Couesnon, the Sélune and the Sée (Fig. 1). The hydrodynamics and sedimentology of the Baie, including the access to the Mont Saint Michel, were most affected by the strong flows of the Couesnon and Sélune rivers. Up to 1863, the Couesnon river was uncontrolled and it flowed past both sides of Mont Saint Michel. A non-submersible digue to the Mont Saint Michel was completed in 1879 and the river has been flowing West of the Mont since. In 1969, the Couesnon river was further impacted by the construction of a barrage to reduce salt intrusion in the catchment. It will be also affected by major works in 2004-2009 with the destruction of part of the digue and of the barrage (e.g. Lefeuvre and Bouchard 2002). The Sélune river is 70 km long with a catchment area of 1,010 km². It was partially controlled around 1860 after the completion of a digue redirecting the river Northwards. The river was further affected by the completion of two dams (La Roche Qui Boit, 1920; Vezins, 1931) with spillway capacities in excess of 300 m³/s. Today it constitutes the most significant freshwater inflow into the Baie today. At its mouth, the river joins the Sée river, and the waters merge at low tides.

During spring tides, the Couesnon, Sélune and Sée rivers are subjected to tidal bore processes, but the occurrences of bores was seldom documented in the Baie du Mont Saint Michel. Larssonneur (1989) mentioned briefly a tidal bore near Pointe du Grouin du Sud propagating at about 2.5 m/s. Tessier and Terwindt (1994) discussed shortly the effect of tidal bore on sediment transport downstream of the Sée and Sélune river mouths.

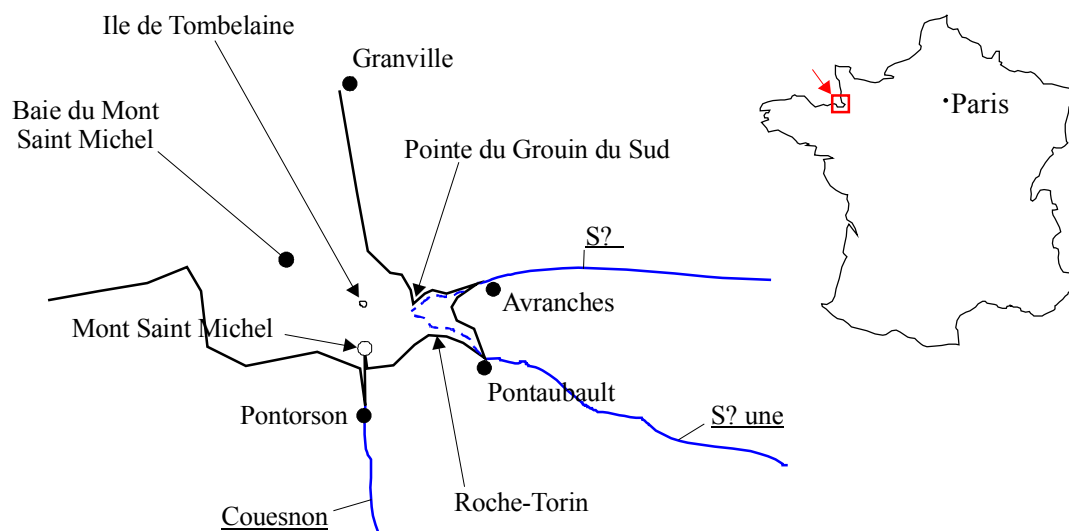


Fig. 1 Map of the Baie du Mont Saint Michel - The name of the rivers is underlined

¹The sanctuary dates back to AD 708 when the mount was called Mont Tombe.

2. FIELD OBSERVATIONS

Although the tidal bore of the Couesnon river almost disappeared after construction of an upstream barrage in 1969, a small bore is still visible during spring tides. The bore arrives about 1h 45 min. to 1h 30 min. before high tide at Mont Saint-Michel and it may propagate up to the township of Pontorson. Smaller tidal bores are also observed in numerous smaller channels of the Baie (Fig. 2). For example, Fig. 2 shows a small bore in a shallow water channel East of Mont Saint Michel digue that was observed about 15 min. after the Couesnon river tidal bore. These smaller bore events are not spectacular but the front propagation on dry flats is often associated with significant bed scouring.

The tidal bore of the Sée and Sélune rivers develops first in the Baie du Mont Saint Michel where it may have a few kilometres width, before entering the river mouths (Fig. 1). The tidal bore process spans over more than 14 km and it can be powerful at spring tides. Between 2003 and 2004, tidal bore occurrences were regularly investigated during spring tides (Table 1). One event is detailed below.

On 7 April, the writer observed the Sélune river tidal bore at Roche-Torin and Pontaubault, about 90 min. and 30 min. respectively before the high tide at Mont Saint-Michel (Fig. 1 and 3). The tidal range was 13.75 m and it was the largest tides in the Baie du Mont Saint Michel for 2004. At Roche-Torin, the writer heard the rumble of the tidal bore about 25-30 min. before the bore front arrived. The bore was first visible between Ile de Tombelaine (2) and Pointe du Grouin du Sud (Fig. 3A). The front was more than one kilometre wide before entering the Sée and Sélune river channels. The advancing front entered the Sélune river mouth with a celerity of about 2.7 to 3.1 m/s (Fig. 3B). The freshwater flow was negligible and the advancing bore height was about 0.3 to 0.6 m, although the bore constantly evolved in shape in response of changes in channel topography. In front of Roche-Torin, the middle section of the bore was an undular bore in the deep water channel, while breaking bores were observed in the shallower waters and sometimes advanced on dry flats. At one stage, the undular bore disappeared briefly on the channel centreline, possibly because of a deeper water hole, although the breaking bores were clearly seen elsewhere moving upstream of Roche-Torin. About 50 min. later, the tidal bore reached Pontaubault, about 8 km upstream of Roche-Torin (Fig. 3C). A group of kayakists was following the bore for a few kilometres. The bore celerity was about 2.5 to 2.7 m/s, the freshwater flow velocity before bore arrival was around 0.1 m/s while the advancing bore front was roughly 0.4 to 0.6 m high. The bore then flowed beneath a 15th century stone bridge, called Pont Aubaud. The bore passage between the piers was extremely turbulent. Note that the bridge piers were shaped with knife-edges to cut the tidal bore flow

²The Ile de Tombelaine is also called Mont Tombelaine.



Fig. 2 Photograph of a small tidal bore East of Mont Saint Michel digue on 7 March 2004 about 80 min. before high tide - (Left) Advancing bore propagating in shallow waters (right) and on dry bed (left), bore direction from left to right. (Right) view from Mt St Michel looking South (upstream) at the channel at low tide

Table 1. Tidal flow conditions at Mont Saint Michel (France) during field observations

Day	Local time		Height (m)		Remarks
	Low	High	Low	High	
(1)	(2)	(3)	(4)	(5)	(6)
20 March 2003	03:18	08:41	0.51	14.96	Coeff. 114
	15:41	21:04	0.35	14.65	Coeff. 113
7 March 2004	--	07:38		13.70	Coeff. 93.
	14:35	20:02	1.40 m	13.65	Coeff. 97.
7 April 2004	04:07	09:29	0.90 m	14.55	Coeff. 107. Highest tide of 2004.
	16:27	21:49	0.85 m	14.30	Coeff. 105.
31 August 2004	03:39	09:04	1.05 m	14.05	Coeff. 103.
	15:58	21:20	1.19 m	14.50	Coeff. 104.

3. PHYSICAL MODELLING

New experiments were performed in two tilting flume to study tidal bore flows under controlled flow conditions. One channel was 0.25 m wide and 20 m long, made of glass panels. The second channel was 0.5 m wide and 12 m long. It was made of smooth PVC bed and glass walls. A tainter gate was located next to the downstream end. Its controlled and rapid closure induced a positive surge propagating upstream. The water discharge was measured with bend meters, calibrated in-situ with a large V-notch weir. The percentage of error is expected to be less than 2%. In steady flows, the water depths were measured using a rail mounted pointer gauge. The surge celerity and unsteady water depth were measured using several digital video-cameras with high-shutter speed (shutter: up to 1/10,000 s).



(A)



(B)



(C)

Fig. 3 Photographs of a major tidal bore in Baie du Mont Saint Michel on 7 April 2004 ; (A) Sée-Sélune river tidal bore - Looking at the advancing tidal bore in front of Ile de Tombelaine - The tidal bore front was more than 1 km wide; (B) Sélune river tidal bore in front of Roche-Torin - Note the undular bore in the deep channel section, the breaking bores in shallower waters and the bore advancing over dry bed in background; (C) Sélune river tidal bore at Pontaubault, about 45 min. later - Advancing tidal bore (mascaret) downstream of Pont Aubaud with some kayaks - Note the banks undercut by the bore in background

In both flumes, the inflow was uncontrolled and uniform equilibrium flow conditions were established prior to the downstream gate closure. After gate closure (partial or complete), the travelling bore propagated upstream against the uniform equilibrium flow over the full channel length. Experiments were repeated systematically for different gate closures, inflow conditions and bed slopes.

3.1 EXPERIMENTAL RESULTS

Undular bores were observed for surge Froude numbers less than 1.40. For surge Froude numbers between 1.40 and 1.50, some wave breaking was seen at the first wave crest, but the free-surface profile remained undular. For $Fr > 1.50$, the surge front was breaking and no undular wave was seen. For all experiments with undular surges, visual observations showed that the undular bore was basically two-dimensional ($Fr < 1.4$). For an observer moving with the surge front, the free-surface profile appeared stationary. The observations were identical for both channels and they were similar to previous experiments performed in rectangular channels (e.g. Treske 1994). In a downward-sloping channel, the bore appearance changed

progressively as it lost energy. In some rare cases, with supercritical inflow conditions, a weak undular bore would stop before the upstream end of the fume and became an undular hydraulic jump. The transition from an undular bore to an undular jump was a slow, progressive process associated with the development of three-dimensional flow features that were not investigated to date.

Present laboratory experiments demonstrated the effects of inflow conditions and gate closure on the undular bore formation. Undular surges were observed only for a narrow range of inflow conditions and gate closure conditions. Small changes in gate closure conditions or inflow conditions would lead to the formation of a breaking bore or to a gentle free-surface slope without free-surface discontinuity (i.e. no bore). Basically the experiments under controlled flow conditions demonstrated that an undular bore results from a delicate, fragile balance between initial and new flow conditions, and that this balance can be too easily disturbed by external factors.

In Nature, the bore development is closely linked with the tidal range and river mouth shape. Once formed, the bore existence relies upon the exact momentum balance between the initial and new flow conditions. A small change in boundary conditions and river flow may affect adversely the bore existence. In the Baie du Mont Saint Michel, tidal bores may appear and disappear in response to changes in channel topography and freshwater flux. For example, no tidal bore was observed in the Sée river at Pointe du Grouin du Sud on 20 March 2003 with a tidal range of 14.3 m possibly because of a too-deep channel, although a tidal bore was seen there in 2002 and 2004 for smaller tidal ranges. Dredging and river training can cause the disappearance of several tidal bores : the mascaret of the Seine river (Fra.) no longer exists, the Colorado river bore (Mex.) is drastically smaller. Although the fluvial traffic gained in safety in each case, the ecology of the estuarine zones were adversely affected. Wind conditions may also affect the bore formation. At Turnagain and Knik Arm inlets, strong and winds (opposing the flood tide) were seen to strengthen the bore. In Bangladesh, tidal bores were experienced during storm surges, when strong winds exert a drag onto the water surface and increase the tidal range, causing major damage to already flooded low-lands.

4. DISCUSSIONS

The occurrence of tidal bore processes has a significant impact on the Baie du Mont-Saint-Michel. The bore passage is associated with intense bed shearing, and the sudden rise in water level produces a very-rapid increase in pore pressure, resulting in liquefaction of channel bottom, bed erosion and scour. Further the bore breaks in the shallow waters next to the banks where it undercuts the banks and resuspends sediments (e.g. Fig. 3C). This contributes to the channel widening and migration continuously observed in the Baie du Mont Saint Michel. Advancing bores on dry tidal flats were observed in numerous occasions particularly in the smaller channels (fig. 2 & 3B). In each case, the advancing flow had a very dark colour, evidence of significant bed scour, sediment loading and migration.

Tidal bores can be significant tourism attractions. Near Hangzhou, the Qiantang river bore attracts more than 300,000 people each year for the Moon festival. The tidal bore of the

Turnagain inlet, Alaska is a feature of many organised tours. In the Bay of Fundy, Canada, thrill-seekers ride over the bore in inflatable dinghies (e.g. Shubenacadie river). In Europe, the Dordogne and Severn rivers are the sites of bore surfing competitions. During the early 1960s, the mascaret of the Seine river attracted more than 20,000 people during week-ends. However tidal bores may be dangerous. Dozens of people were killed by flooding caused by the Hangzhou bore: e.g., in June 2000. Bores affect shipping and navigation, as in Papua New Guinea (Fly and Bamu rivers), Malaysia (Benak at Batang Lupar) and India (Hoogly bore). In the past, the Seine river bore had a sinister reputation: more than 220 ships were lost between 1789 and 1840 in the Quilleboeuf-Villequier section (Malandain 1988). Similarly the bores of the Petitcodiac river (Bay of Fundy, Canada) and Colorado river (Mexico) were feared. In the Baie du Mont-Saint-Michel, the tidal bores are surprisingly not a major tourist attraction, while tourist walks in the Baie at low tide are not warned of the danger of incoming tidal bores.

The impact of tidal bores on the ecology is acknowledged. In the Amazon river, piranhas eat matter in suspension after the passage of the bore (Cousteau and Richards 1984). At Turnagain Arm inlet, bald eagles and seagulls were seen fishing behind the bore, while beluga whales were observed playing in the bore as it formed near the mouth of the arm (Bartsch-Winkler and Lynch 1988, Molchan-Douthit 1998). In the same estuary, a moose tried unsuccessfully to outrun the bore; he was caught and disappeared (MOLCHAN and DOUTHIT 1998). In the Baie du Mont Saint Michel, sheep have been outrun and drowned by tidal bores. In Alaska and France, it is believed that the animals were panicked by the rumbling noise of the bores and lost their direction sense. In Australia, sharks and saltwater crocodiles were seen swimming, and fishing, behind tidal bores at Broadsound (Queensland) and in the Daly river (Northern Territory) respectively. In the Dordogne river, fishermen caught a lot of fish at low tide before and immediately after the bore arrival. In winter times, locals caught lamproie (*Petromyzon*) fish, and mule (mulet) and silure (catfish) fish during the warmer months. The writer observed them on 21 Feb. 2004. In the Severn river, the bore impacted on sturgeons in the past and on elvers (young eels) today (Witts 1999, Jones 2003). In the Bay of Fundy, Morris et al. (2003) suggested that juvenile striped bass (*Morone saxatilis*) follow the tidal bore front during tidal exchanges and may reside in mid-reach freshwater area. Hence nursery grounds are farther upstream of the mouth in freshwater habitats.

5. CONCLUSIONS

A tidal bore is a very fragile process and it results from a fragile balance between topography, tidal condition, freshwater runoff and meteorological conditions. It is the writer's opinion and experience that tidal bores have a significant impact on river mouths and estuarine systems. In the Baie du Mont Saint Michel, a wide tidal bore front may be observed during spring tides before the bore enters the Sée and Sélune river channels. Significant scour take place by bed erosion, bank undercutting and dry tidal flat runup, while suspended matters are carried upwards in the ensuing wave motion. The process is most intense in the

intermediate and upper intertidal zones, and it contributes to significant sediment transport with deposition in upstream intertidal areas. It is hoped that this contribution will alert the community of the significance of tidal bore processes in the unique environment of the Baie du Mont-Saint-Michel.

ACKNOWLEDGMENTS

The writer thanks Mr and Mrs Jacques Chanson, and Mr and Mrs Claude Roquet for their assistance with field observations, and Dr Eric Jones for his advice.

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