Large Amplitude Undular Tidal Bore Propagation in the Garonne River, France

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ABSTRACT

We present new observations on the dynamics of spring tides propagating in the Gironde estuary and the Garonne River up to 160 km from the estuary mouth. The amplification and distortion of the tide lead to the formation, in the Garonne River, of well-developed undular tidal bores, which propagate over more than 30 km. New results about the structure and the dynamics of the secondary wave field associated with tidal bores are presented.

KEY WORDS: undular bore; breaking; estuary; mascaret; long wave; tsunami; Boussinesq-type equations.

INTRODUCTION

A tidal bore is a positive surge propagating upstream that may form when a significant amplitude rising tide enters shallow, gently sloping and narrowing rivers. Tidal bores have been widely observed worldwide in estuaries and rivers in regions with large tidal amplitudes (*e.g.* Tricker, 1965, Lynch, 1982, Simpson *et al.*, 2004, Wolanski *et al.*, 2004). The study of this surge wave phenomenon is motivated by its significant impact on the river ecosystem behavior, and also because tidal bores present analogies with tsunami-induced river bores (Higman *et al.*, 2004). Such tsunami bores can cause tremendous damage when propagating up rivers (*e.g.* Tsuji *et al.* (1991) and Tanaka *et al.* (2008)). Even if the physical mechanisms controlling the formation of tidal bores and tsunami bores are different, their propagation up rivers shows many similarities. In both cases, the surge wave can evolve into a large range of bore types, from undular non-breaking bore to purely breaking bores. The complex competition between energy dissipation, nonlinear and dispersive effects, which govern bore dynamics, makes the prediction of their evolution a challenging task for numerical models. Contrary to tsunamis, tidal bores are mainly related to a predictable phenomenon that is the astronomical tide. Thus, to analyze large amplitude bore propagation in the field, we conducted in 2010 two intensive field experiments devoted to tidal bore propagation in the Garonne River (see Bonneton *et al.*, 2011b) that revealed that, in this river, tidal bores were ubiquitous as observed for a large majority of tides. In the present paper, we focus our discussion on the propagation of large amplitude tidal bores (named *mascaret*) which occur during spring tides and low fresh water discharge periods.

FIELD SITE

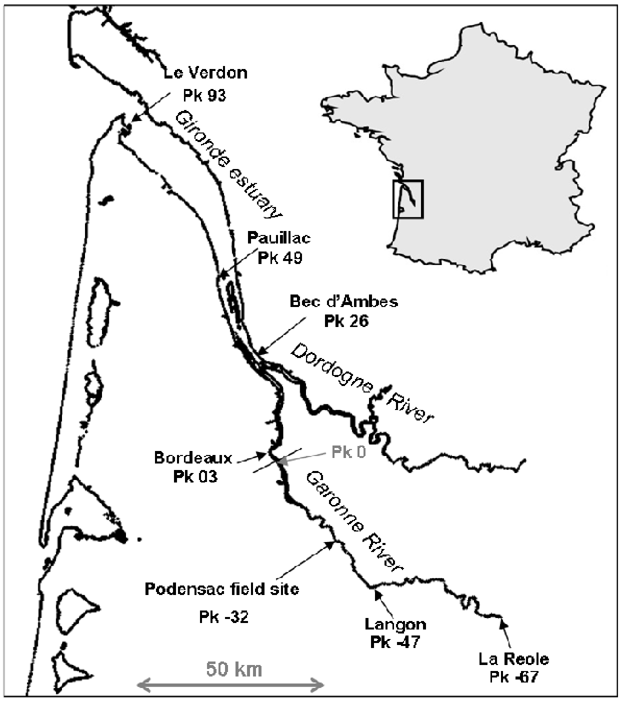

Fig. 1 Location map of the Gironde estuary and the Garonne River. Tide propagates in the estuary from Le Verdon to Bec d'Ambes and continues in the Garonne and Dordogne rivers. Well-developed bores (*mascarets*) propagate in the Garonne River between Bordeaux and Langon. PK: distance expressed in kilometers from *Pont de pierre* (south of Bordeaux).

The Gironde estuary is located in the Bay of Biscay, on the southwest coast of France and is formed from the meeting of the rivers Dordogne and Garonne (see Fig. 1). The estuary shows a regular funnel shape of 75 km. In the Gironde mouth, the mean neap tidal range and mean spring tidal range is 2.5 m and 5 m, respectively. As the tide propagates upstream a marked ebb-flood asymmetry occurs in the upper reaches of the estuary and the wave is amplified (Castaing and Allen, 1981). This large-amplitude tidal wave propagates in the Garonne River (the same applies for Dordogne River) up to La Réole, 160 km from the estuary mouth. During spring tides and low fresh water discharge periods, large amplitude undular tidal bores (named *mascarets*) form in the two rivers (Parisot *et al*., 2010). In the Garonne River, *mascarets* occur approximately between Bordeaux and Langon (see Fig. 1). They correspond to Froude numbers larger than about 1.1. Bonneton *et al.* (2011b) showed that low Froude number tidal bores, less readily apparent than *mascaret*, frequently occur in the Garonne River. Tidal bores form for a large majority of tides, with an occurrence percentage of 90% for low flow discharges and 65% for large flow discharges.

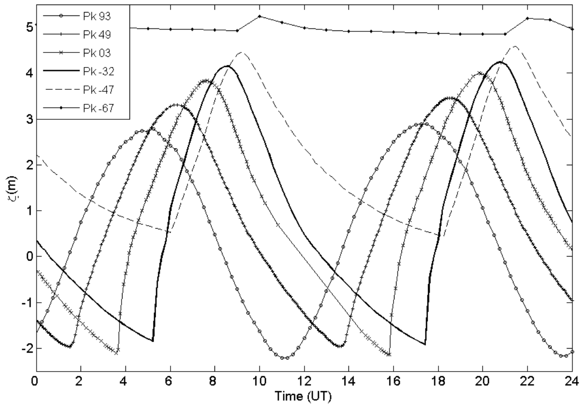

Fig. 2 Time series of tide elevation (altimetry NGF-IGN69 system) the 10th of September 2010 in different locations of the Gironde estuary and the Garonne River. PK93, Le Verdon; PK 49, Pauillac; PK 03, Bordeaux; PK -32, Podensac field site; PK -47, Langon; PK -67, La Réole.

In order to observe tidal bores for a large range of tidal amplitudes and contrasting degree of river discharge, two field campaigns were conducted in 2010 around the spring and autumn equinox. The field site was located in the Garonne River (France) at Podensac located 140 km upstream from the estuary mouth. This site was selected owing to the presence, during spring tide, of well-developed undular tidal bores. The first campaign (Parisot *et al.* 2010), took place between the 24th of February and the 15th of April, for large fresh water discharges (around 700 m^3/s) and the second one (Bonneton *et al.* 2011b), between the 1st of September and the 22nd of October, for low water discharges (around 125 m^3/s). In the present paper, we analyze the propagation of a large amplitude tidal bore (*i.e. mascaret*) on the 10th of September, for one of the largest tide observed during the campaigns. This analysis is based, on the combination of tidal gauge measurements and aerial observations along the estuary and the Garonne River and, more locally, on video observations and high-frequency pressure measurements at Podensac field site. A detailed description of the field experiment is given in Bonneton *et al.* (2011b).

Fig. 3 Aerial photographs on the 10th of September 2010 of the different *mascaret* types of the Garonne River. The Froude number increases from panel (a) to panel (d). a, Cambes, PK -16, 16h47 UT; b, Podensac field site, PK -32, 17:31 UT; c, Pont de Beguey, PK -33, 17:37 UT; d, east Arcins river branch, PK -6, 16:15 UT.

Fig. 4 Tidal bore refraction around La Lande island, PK -12, in the Garonne River, the 10th of September 2010, 16:37 UT.

RESULTS

The evolution of water levels, over two tidal cycles on the 10th of September 2010, at different locations of the Gironde estuary and the Garonne River is presented in Fig. 2. The tidal wave in the lower estuary (Le Verdon) is fairly symmetric. As the tide propagates upstream, the wave is deformed and a marked ebb-flood asymmetry occurs in the central estuary (Pauillac) and subsequently intensifies in the Garonne River (Bordeaux and Podensac). At Podensac, the time of level rise is 3h20min and the time of level fall is 9h. In the Gironde estuary, the effect of tidal wave convergence as tide progresses up the funneled estuary is larger than frictional dissipation effects (see Allen *et al.*, 1980). This imbalance leads to an increase of the tidal range, T_R, from 5.0 m at the estuary mouth to a maximum of 6.3 m at Podensac. Slightly further Podensac, the tidal range starts to decrease with a value of 4.9 m at Langon and 0.4 m at la Réole. At Bordeaux and Podensac, the moment where the tide flow turns to rising is characterized by a sudden and intense increase of the water level, which can be associated with the occurrence of a tidal bore. Aerial and boat observations showed that well-formed tidal bores (*i.e. mascaret*) occur in the Garonne area where tidal asymmetry and amplitude reach maximum intensities, that is between Arcins island (PK-6) and Cadillac (PK-35). During the propagation, both the intensity and the shape of the tidal bore are strongly dependent on the local river bathymetry. A *mascaret* may disappear in areas of deeper water and subsequently reform in shallow areas. It is worthwhile to note that *mascaret* disappearing is not necessary due to the absence of a tidal bore at rising tide, but to the fact that below a Froude number of about 1.1, tidal bores are readily apparent (see Bonneton *et al.*, 2011b) except indirectly from some boundary layer turbulent structures generated by the bore at the river banks.

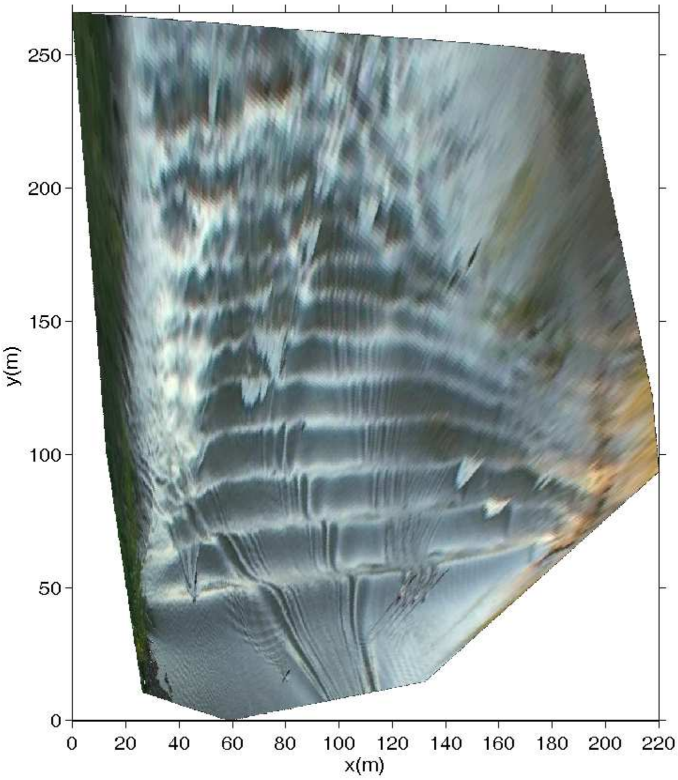

Fig. 5 Rectified image (video system) of the undular tidal bore at the Podensac field site (PK -32), the 10th of March 2010 (17:30 UT).

Aerial photographs of the main types of Garonne *mascarets* are shown in Fig. 3. The most frequently observed *mascaret* is a non-breaking undular bore (see Fig. 3a). Very localized breaking areas can be observed on the river banks. A more intense undular bore is illustrated in Fig. 3b. The surge Froude number, based on cross-section mean water depth is 1.17 and the mean jump is 0.9 m. If the first three secondary waves are non-breaking, excepted on the river banks, the next waves can locally break outside the river banks. Reflection of the first wave at the banks is clearly visible in fig. 3b. The interaction between secondary waves and the shallow mid-slope river banks leads to the modulation of the secondary wave field into a triangular shape. This wave pattern is similar to those observed in trapezoidal channel by Treske (1994) for the same range of Froude number. The highest *mascaret* observed during the aerial survey is presented in Fig. 3c and corresponds to a Froude number of about 1.2 and a mean jump of about 1 m. It is an undular breaking bore with a breaking front which expands along a large part of the river cross-section. Atypical undular breaking bores with larger Froude numbers, but with much smaller bore jump (about 0.5 m), can be observed in a narrow and shallow Garonne branch along the Arcins island (see Fig. 3d).

Strong refraction processes occur along river meanders and around islands. Fig. 4 shows a spectacular example of undular bore refraction around La Lande island. The *mascaret* splits into two parts propagating separately in each branch of the river. In the deeper branch (on the right side of fig. 4), the bore propagates faster than in the other branch and is strongly refracted at the branch outlet. After the island, two bores propagate one behind the other. The second one moves faster than the other and finally the two bores merge in one undular bore.

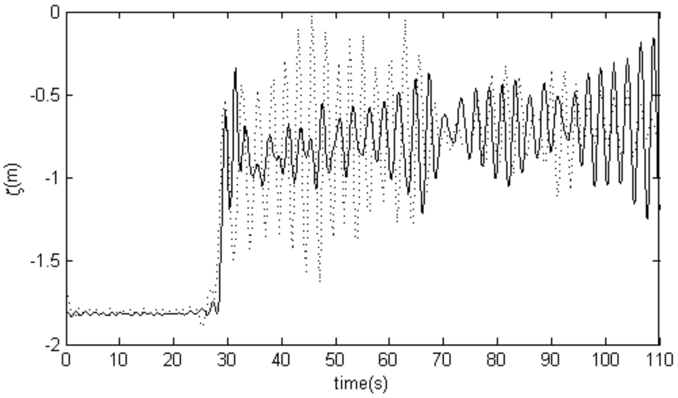

Fig. 6 Water elevation time series (altimetry NGF-IGN69 system) the 10th of March 2010 (17:30 UT), when the tide flow turns to rising at the Podensac field site (PK -32). Tidal range: T_R=6.3 m. Comparisons between two pressure sensors along a river cross-section transect. Dashed line: elevation in the deeper part of the transect (3.1 m water depth at low tide); continuous line: elevation close to the river bank (1.3 m water depth at low tide).

To analyze in more details the spatial structure of the undular bore wave field, a video system (2 HDV cameras, SONY HDR-HC9E) was set up on the west bank of the Podensac field site. Image coordinates were rectified to ground projected coordinates using a direct linear transformation calibrated on ground control points. The pixel footprint ranges from less than 20 cm near the camera to about 2 m at 250 m from the camera. The wave field observed the 10th of September 2010 is presented in fig 5. In agreement with the aerial view (fig. 3b), we can observe intense breaking along the river banks and the modulation of the secondary wave field into a triangular shape. The bore celerity is equal to 5.2 m/s and the first wavelength, measured in the river axis, is equal to 18.5 m. We observe a decrease of the secondary wavelength from the river axis to the river banks. After the first four waves, secondary waves locally break outside the river banks. Pressure measurements were performed synchronously with the video observations and converted to water depth (see fig. 6). Due to strong non-hydrostatic effects associated to well-developed tidal bores, a non-hydrostatic correction, based on linear theory, was applied to the data. This method has been validated by comparing its results with direct acoustic surface tracking measurements. In fig. 6 we compare two synchronized pressure sensors moored along a river cross-section, in low tide water depths of 1.3 m (close to the west river bank) and 3.1 m (deeper part of the cross-section). We observe that the 0.9 m mean jump and the first secondary wave crest are almost uniform across the river section. On the other hand, the next secondary waves have an amplitude much smaller close to the banks than in the middle of the river. This is in agreement with the triangular shape of the secondary wave field previously described in Fig.5. We also note a low frequency amplitude modulation of the wave field, with a maximum wave height of 1.64 m occurring for the 6th wave. This observation is in agreement with the breaking occurrence observed in Fig.5. At given times, for instance between t=65s and 90s, wave elevations measured at the two sensors are very similar.

CONCLUSIONS

We present in this paper a unique field database describing the complex formation and propagation of a large amplitude undular tidal bore over more than 30 km. The main types of undular bores, the breaking occurrence, and the refraction around an island are described from aerial and rectified video images. We underline the complex interactions between secondary waves and shallow mid-slope river banks. Our study provides a unique database to improve and validate nonlinear, non-hydrostatique models (*e.g.* Bonneton *et al*., 2011a, Tissier *et al*., 2011), for the simulation of bore propagation for both tide and tsunami applications.

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