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A novel method to generate tidal-like bores in the laboratory

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ABSTRACT

Laboratory experiments are reported where the analogue of a tidal bore is generated with a centimeter-scale local tidal range in a water channel. A discussion of the hydraulic regimes allows to set the experimental conditions to observe the bore. Temporal measurements of the free surface deformation with an acoustic sensor display an analogue of the tidal asymmetry met in nature between the ebb and the flood. Spatial measurements of the free surface deformation are performed with a laser sheet which delineates the interface thanks to the fluorescent re-emission of fluoresceine diluted in water. Afterwards, a parameter space is provided for the observation of a mini-bore with different hydrodynamical regimes (undular, undular–breaking, breaking) by showing the influence of the analogue local tidal range on the shape of the tidal wave. Finally, flow visualizations reveal the inner structure of the velocity profile of the mini-bore in the undular–breaking regime characterized by flow reversals.

A tidal bore is a tidal phenomenon in which the leading edge of an incoming tide forms a front/wave (or a train of waves) of water that travels up a river or narrow bay against the direction of the river or bay's current [1–7]. Tidal bores are generated by an abnormal local tide that is a tidal wave which has suffered from distortion by non-linearities during its propagation in the estuary. In particular, it has been known since a long time that the quasi-sinusoidal shape of the incoming tide is deformed and becomes non-linear when propagating upstream the river [8–15]. According to historical references like in the following quotation of Brownlie [12], "we discern two abnormal local tidal conditions: (1) the ebb is exceedingly long and slow; (2) the flood is exceedingly short and swift. These conditions are totally different from the usual tidal conditions in the Ocean at the river mouth, therefore they are wholly local; but both are necessary towards the formation of the bore". The shape of the tidal wave is asymmetric between the ebb and flood durations. Nowadays, the terminology "ebb–flood asymmetry" is used to characterize such a behavior. Moreover, the tidal bore often occurs when the wave ascending in a narrowing channel meets in its generation with a bank of sand or elevated bed, which becomes an obstacle to its passage [9–11] since the first waves are caught up by the following waves because of the retardation induced by the obstacle. Here, we report experiments where we create, for the first time, a tidal-like bore with conditions to generate it similar to the ones present in the field namely an ebb–flood asymmetry and the presence of an obstacle at the river entrance albeit without a reduction of the river cross section. We present first the experimental setup and procedures used. Then, we discuss our experimental observations before exploring possibilities for future investigations.

1. The experimental setup

The re-circulating water channel (see Fig. 1) of the Pprime Institute is 6.8 m long. It is characterized by a rectangular cross-section. Its width is $W = 0.39$ m and the water level can be set up to 0.5 m. The flow rate per unit width $q = Q/W$ ranges up to 0.172 m^2/s and is controlled by a PCM Moineau pump featuring an eccentric bearing, an endless screw and a speed controller. It generates a current which passes through a honeycomb and a 3D convergent chamber where the fluid is accelerated by a double constriction in both width and height to suppress vortices at the entrance of the channel and boundary layer effects. The resulting velocity profile at the end of the convergence chamber is almost flat in the vertical direction. Then, the fluid flows along the channel and visualizations are made through the transparent side windows. An exit chamber is located at the very end of the channel where the fluid is re-injected into the pump, and a sluice gate is placed at its entrance in order to control the water depth and flow regimes. In our experiments, the sluice gate is set in the lowest position such

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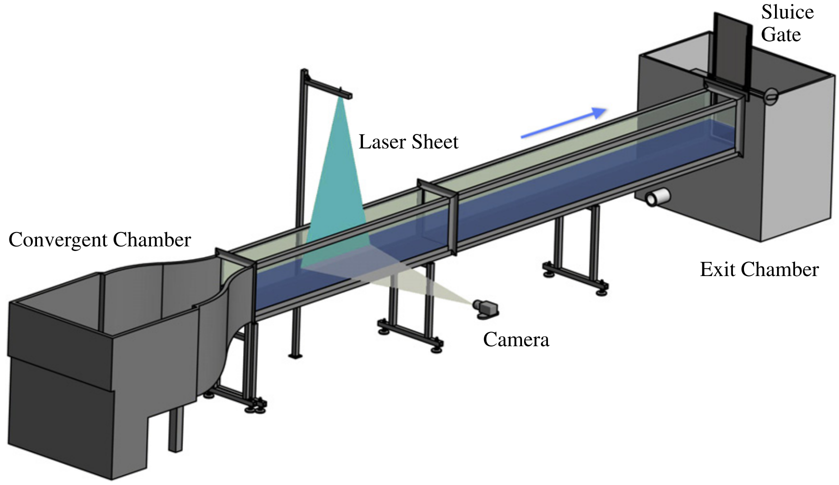

Fig. 1. A sketch of the experimental setup with the laser sheet and the side camera. The arrow indicates the direction of the water current: the bore propagates in the reverse direction.

that the water level is free: depending on the regime, a spillway is generated or not and the water depth adapts itself.

To visualize free surface deformations, an Argon LASER (Spectra Physics 2W) is used with a light fiber and a cylindrical lens in order to produce a vertical laser sheet with a thickness of 2.5 mm whose trace is located on the middle of the channel width. The laser trace on the flat free surface is centered at 1.5 m from the channel entrance (namely the convergent exit) and extends on 3 m. We diluted 50 g of fluoresceine in the water channel with a static depth of 0.24 m initially. The laser intensity is set such that the sheet only penetrates on a small depth typically of a few mm, thanks to the absorption by the fluorescent dye. A CCD black and white camera (Pulnix RM-4200CL 2048p^2) records the laser trace of the free surface through the channel side window on roughly 1 m along the longitudinal direction of the bore. An additional digital camera (Canon Powershot SX40 HS) is used for colored pictures and movies. In addition, an acoustic sensor (Microsonic mic+24/IU/TC) with a resolution of 0.1 mm measures the water depth at a given place. As its position was varied in the course of experiments, the acoustic sensor is not represented in the setup scheme contrary to the laser sheet which was fixed.

2. The hydraulic regimes and procedures to generate the bore

Concerning the terminology, we will call the static (dynamical) depth h_0 (h_d), the water depth in absence (presence) of a flow. The water depth $h(x, t)$ is both a function of space and time in presence of the bore. By varying the initial static water depth, the sluice gate position and the flow rate of the pump, we can generate different hydraulic regimes with specific flow currents and corresponding dynamical water depths. Since the seminal experiments by George Bidone in 1825 [16] and in order to reproduce a propagating bore in the laboratory [1,17–19], a second sluice gate (not represented in Fig. 1) is placed upstream of the regulation gate and operates as a "guillotine". The gate moves downwards from a initial upper position before being stopped at a given height below the water level. It can be closed partially or completely and then, it blocks the flow. In practice, there is always a small leaking stream below the gate in order that the closing gate does not deteriorate the bottom of the water channel. This closing process creates a sudden rise in the water level and generates a tidal-like body of water which propagates against the flow direction [16,1,17–19]. This procedure is qualified as the "classical" one. In the same vein, sudden changes of the discharge in canals (due to a valve for example) have been studied since the time of Darcy and Bazin and produces similar surges that do not differ from the closing ones [20–23]: they are often described as positive surges from downstream in treatise on hydraulics [24]. Now, a new "natural" procedure mimicking the effect of a tidal wave entering a river is introduced. Of course, it is impossible to reproduce a true tide in the laboratory but it will be shown how to use the hydraulic regimes of the water channel (see the Appendix for details) in order to produce an analogue of the ebb–flood asymmetry encountered in tidal rivers.

The following procedure was chosen to create a laboratory bore with tidal-like conditions. Let us illustrate it with a practical example. First, the static water height is set at $h_0 = 25$ mm; then, the pump is fixed at a given flow rate (for example $q_0 = 0.0215$ m^2/s); the dynamical water depth increases and then stabilizes in a state of equilibrium: one observes a small negative mean slope on the entire channel length due to head losses (mainly because of viscous dissipation); the dynamical water height reaches roughly $h_d = 50$ mm. Now the crucial point: we turn off the pump. The flow rate does not go to zero instantaneously but with a time evolution depending on the pump characteristics and the water channel geometry. It is outside the scope of the paper to understand the precise dynamics of this "closed water system" with the associated equilibrium between the water bodies formed by both chambers and the channel. The dynamical water level in the channel drops rapidly with time as measured with the acoustic sensor (see Fig. 2 (bottom)): it is the analogue of time series of tide elevation.One recovers the typical ebb–flood asymmetry as observed in the field (see the recent survey by Bonneton et al. [4,7] and the often ignored older papers [8–15]) where a long ebb is followed by a short flood at the foot of which the bore is generated. We do believe that this is the main signature of the tidal-like bore formation which makes us believe in the "naturalness" of our laboratory procedure.

The decreasing water depth reaches a minimum (at a given time that we call the time of reversal t_r, here 30 s for $h_0 = 15$ mm in Fig. 2 (bottom)) which is lower than the static and initial water depth h_0 and where the slope suddenly changes its sign. This height at reversal that we denotes h_r is a function (data not reported here) of the static water depth h_0 and one has always $h_r < h_0$: for the case of Fig. 2 (bottom) corresponding to $h_0 = 15$ mm, the minimum water depth is $h_r = 11.5$ mm. The time at reversal t_r increases with the initial flow rate. Then, a sudden rise follows this very long diminution of height. We can explain this behavior by considering that the analogue of the local tidal range in our natural procedure is the parameter $h_0 - h_r$ whereas the global tidal range would be $h_d - h_0$ recalling that h_d is a function of both the initial