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Criteria for the Transition from a Breaking Bore to an Undular Bore

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ABSTRACT

Field data on undular and breaking bores observed in a coastal zone and river estuaries were collected. The existing criteria of distinction of these two regimes of bores, which depend on the ratio between the bore height and unperturbed water depth, are applied to the collected data. It is shown that criterion $H/h > 1.5$ (where H is bore height measured from the bottom and h is unperturbed depth of reservoir) is sufficient for the rough separation of the bores by their type.

KEY WORDS: breaking bore; undular bore; shallow water theory; field data

INTRODUCTION

In the coastal zone wind waves are often presented as asymmetrical waves and their crests are separated by extended troughs. From the point of view of the shallow water theory (Korteweg-de Vries equation or a system of Boussinesq) [Zakharov et al., 1980, Newell, 1985, Lamb, 1983; Kudriashov, 2008], such waves are called cnoidal and when the distance from the crests is large enough, cnoidal waves consist of a sequence of solitary waves called solitons. Frequently they can be observed when a tidal bore enters a river estuary and transforms into a braking bore (hydraulic jump) or an undular bore.

Wonderful photos of such bores are collected in the book [Chanson, 2012] and a few of them are shown in Fig. 1.

Fig.1 Wave forms in the coastal zone

However, in addition to undular bores (represented by a set of solitons) in shallow water breaking bores can exist naturally as well. Frequently, they are found close to each other in one place, as illustrated in Fig. 2.

Undular bores propagate in the center of bays where depths are greater, and a change in regime is clearly seen closer to the coasts of the bay where the formation of the breaking bore occurs. The formation of both types of bore is clear from physical considerations, in particular, when a tidal wave or tsunami enters the river.

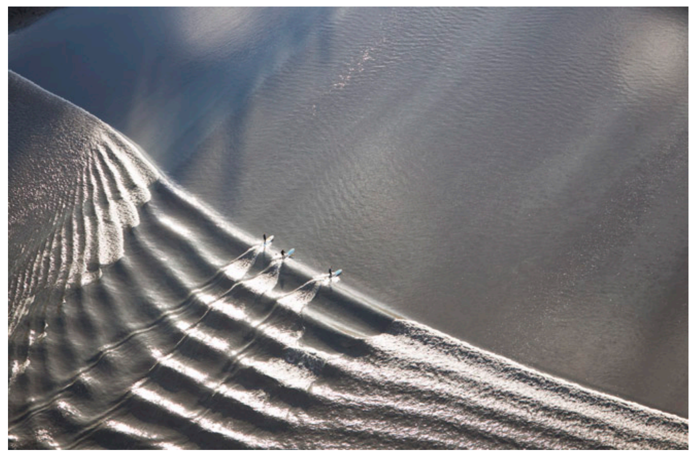

Fig. 2 Photograph of the bore in the Cook Gulf, Alaska (Credit: Scott Dickerson, www.surfalaska.net).

If the nonlinearity of such a wave is sufficiently weak, dispersion prevents breaking of the tidal wave and facilitates the formation of undulating oscillations over the body of the long wave, which later transform into a series of solitons. This process is qualitatively well described by the well known solution of the Korteweg - de Vries equation [Zakharov et al., 1980]. If nonlinearity is strong, dispersion cannot prevent the rapid steepening of the wave front and its breaking. This process has also been well studied within the hyperbolic shallow water system [Stocker, 1959, Pelinovsky, 1972]. Unfortunately most of the known applied numerical models of wave dynamics in the coastal zone cannot take into account both these effects together. In the most widespread shallow water equations for the description of the tidal and tsunami waves, the smoothing of the wave front is performed by the introduction of horizontal viscosity (diffusion). In realistic basins, the spatial step appears sufficiently large so that nonlinear wave deformation is not clearly seen [Zahibo et al. 2006]. On the contrary, in the new models of nonlinear dispersion theory (the Boussinesq equations of different order), the formation of the undular bore has been well described, in particular, during the tsunami in the Indian Ocean in 2004 [Dao & Tkalich, 2007], wave breaking is not observed. Nonlinear dispersion models do not have a significant performance, and therefore they are rarely used. In this relation one would like to have a simple criterion to judge the validity of application of one or another model to describe a real situation. Such criteria are known from the results of numerous laboratory experiments in the ideal conditions of a one dimensional flow [Stocker, 1959, Docherty & Chanson, 2010; Favre, 1935; Nakamura, 1973; Teles Da Silva & Peregrine, 1990]. However, to our knowledge, these were not verified by the field observations of the wave processes in the coastal zone. The goal of this paper is to analyze field data that will allow us to judge the applicability of criteria obtained under laboratory conditions. This will help us to perform a preliminary zoning of the water basins by the type of the waves that propagate in these basins.

FIELD DATA

Unfortunately, photos of different tsunami forms are rare. They are frequently fragmentary and do not contain any information about the depth of the place and wave height. At the same time, a sufficiently large collection of tidal bores exist, which are formed when a tide enters a river estuary. The classical tidal bore is the bore on the Severn River in England, which has a height of more than two meters during spring tides downstream from Gloucester. Tidal bores, unlike tsunami or the waves formed by the breaking of a dam, have a very useful property: the periodicity of their appearance, which makes possible to accumulate a large amount of data relatively quickly. Many of them are described in the book [Chanson, 2011], where quantitative parameters are also given. Therefore, tidal bores were selected to analyze the types of shallow water wave breaking regime. We used different sources to collect field data of recorded tidal bores in the mouths of rivers from the entire globe. They are presented in Table 1.

Table 1. Field data of tidal bores (Brealing - B, undular -U)

№	River, date	h, m	H, m	H/h	Bore type	Reference
1	Seine River, France	1	1.9	1.9	B	[Chanson, 2008]
2	Sélune River, France, 24/09/10	0.38	0.72	1.89	B	[Mouaze et al., 2010]
3	Sélune River, France, 25/09/10	0.33	0.74	2.25	B	[Mouaze et al., 2010]
4	Garonne River, France, Podensac, 10/09/10	3.1	4.2	1.35	U	[Bonneton et al., 2011]
5	Garonne River, France, Podensac, 4/09/10	1.85	2.1	1.13	U	[Bonneton et al., 2011]
6	Qiantang River, China, October 2007	1	4	4	B	[Cun-Hong and Hai-Yan, 2010]
7	Rio Mearim, Brazil, 30/01/91	1.8	2.7	1.5	U/B	[Kjerfve and Ferreira, 1993]
8	Dee river, Great Britain, 15/05/2002	0.8	1.05	1.3	U	[Simpson et al., 2004]
9	Garonne river, France, Arcins channel, 10/09/10	1.74	2.3	1.32	U	[Simon et al., 2011]
10	Dee river, Great Britain, 22/09/72	1	1.8	1.8	U	[Chanson, 2009]
11	Dordogne river, France, 26/04/90	1.12	1.602	1.43	U	[Chanson, 2011]
12	Daly river, Australia, 2/06/2003	1.5	1.78	1.19	U	[Chanson, 2011]
13	Qiantang River, China, 19/09/09	7.12	7.90	1.1	U	[Zhu, 2011]
14	Garonne River, France, 7/06/12	2.65	3.17	1.2	U	[Reungoat et al., 2014]
15	Garonne River at Arcins, France, 19/10/13	2.05	2.35	1.15	U	[Reungoat et al., 2014]
16	Dee River, Great Britain, 6/09/03	0.72	1.17	1.63	B	[Simpson et al., 2004], [Reungoat et al., 2014]
17	Sée River, France, 7/05/12	0.9	1.46	1.62	U	[Reungoat et al., 2014], [Furgerot et al., 2013]

All records were selected so that there are no repeated data, for example, where measurements were made at the same place and in close time periods, where indicators are approximately the same. The type and height of the bore relative to the bottom (H) and also the depth of the basin before the bore front (h) are input parameters. The total number of cases in Table 1 is 17; five of them are cases of a breaking bore, eleven are related to an undular bore, and one type is intermediate. To some extent, we can speak about the available data as a statistically representative sampling.

CRITERIA OF TRANSITION FROM AN UNDULAR TO A BREAKING BORE

The available data are based on different parameters of wave flux; the simplest of them use the ratio of the bore height calculated from the bottom (H) to unperturbed depth of the basin (h). For example, the following simple criterion is given in [Favre, 1935]: if $H/h > 1.75$ the bore is breaking (hydraulic jump); in the intermediate situation, undular bores are observed with the effects of breaking ones. The author of [Stocker, 1959] gives a more general criterion: if $H/h < 1.5$, the bore is considered undular; if $H/h > 1.5$ the bore is breaking. Stoker's criterion is supplemented in experimental work [Nakamura, 1973] by one more condition: if $H/h > 9$ a parabolic wave is realized (as in the wave occurring after the breaking of a dam).

Favre's criterion is generalized in [Teles Da Silva & Peregrine, 1990]. In this paper, a similar parameter (Δ) is responsible for the change in the regime of the bore, which is determined as $\Delta=(H-h)/h$. If $\Delta \geq 0.7$ the bore has a breaking front. If the values of parameter Δ are intermediate, both effects are observed: breaking and dispersion decomposition. If we reduce the values of parameter Δ to the previous case, the intervals of our criterion shift: the undular bore should appear at $H/h < 1.3$, and the breaking bore is considered to occur if $H/h > 1.7$. At the same time, in some publications [Docherty & Chanson, 2010] a transition criterion of the bore was related to the Froude number based on the bore motion in the rivers and laboratory tanks. The undular regime of the bore appeared at the value Fr < 1.8 ($H/h < 1$). If Fr > 1.8 (or $H/h < 1$), the bore transfers to the breaking regime. Field data in Table 1 can be tested whether they satisfy the criteria (Fig. 3).

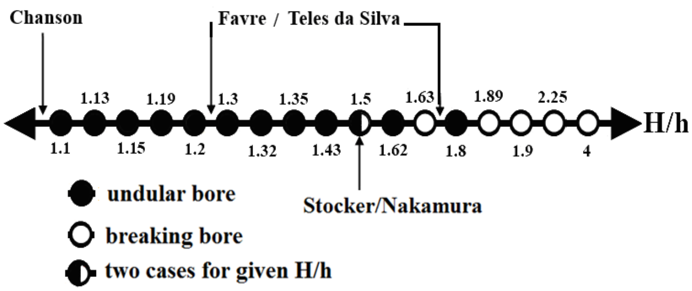

Fig. 3 Distribution of the data of observations by parameter *H*/*h*

One can see that undular and breaking bores are well separated by the threshold value $H/h = 1.5$ excluding one case with $H/h = 1.8$, which is on the threshold of the Favre–Teles da Silva interval. In general, criterion $H/h = 1.5$ can be used as a rough estimate of the type of wave motion and correspondingly for the selection of the appropriate numerical model to describe long wave dynamics.

CONCLUSIONS

Thus, collected data of observations of tidal bores confirm that the criteria of the bore character regime presented here are satisfied practically in all cases, while the most dangerous breaking bores (with a large height difference) occur in such rivers as Seine, Selune, Dee, Quintang, and Mearim. On the basis of the field data, criterion *H*/*h* can be used as a rough estimate of the wave motion type and correspondingly for the selection of the appropriate numerical model to describe long wave dynamics.

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