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A wave-by-wave analysis for the evaluation of the breaking-wave celerity

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ABSTRACT

The paper gives an overall description of the breaking-wave celerity on the basis of a wave-by-wave analysis that has been performed by using field data collected during the ECORS Project (Truc Vert Beach, France, 2008). Data coming from two pressure sensors have been analyzed with the aim to correlate, after a zero-crossing analysis, each wave of both signals. The method is based on a first correlation between 10′ time windows of both signals and, then, on the individuation of the correct time lag for each wave. Such data, which reveals a quasi-gaussian behavior of the breaking wave celerity, have also been used to relate the wave celerity with suitable wave characteristics, and comparisons are made with the most common formulas that can be found in the literature. The wave-by-wave method, validated by means of suitable laboratory test data, gives good results in the evaluation of the celerity, especially when it is made to depend on both a velocity scale and the wave non-linearity parameter. Further, a comparison with literature models used for the prediction of breaking wave celerity suggests good performances of both solitary-wave (correlation coefficient $R^2 = 0.79$) and shock-wave ($R^2 = 0.71$) theories, that give results well matched to the field data.

1. Introduction

Although the celerity of breaking waves is fundamental for the description of nearshore waves, especially in the development of both wave-averaged and wave-resolving numerical models (e.g. Boussinesq-type models), a satisfactory theory for its prediction is not available as yet. Whereas the celerity of non-breaking waves is well known, wave breaking and the related energy and momentum transformations introduce so much uncertainty in the representation of the wave flow that a complete description of wave celerity is still missing.

Only few studies on this topic are available, such as [21], that is the fundamental work that compares results of field experiments and linear-theory predictions, Tissier et al. [22] (hereinafter TI11), who analyzed field data using a cross-correlation 10′-averaged approach for the evaluation of both breaking-wave celerity and nonlinear predictors, or [8], who analyzed the video measurements performed in the nearshore region to predict the beach evolution from the breaking wave celerity. Other works, e.g. [4,7,19,20], aimed at investigating the main characteristics of breaking waves by performing laboratory experiments. Svendsen et al. [20], starting from the continuity and momentum equations and using both a constant-form wave and a constant water depth, obtained an important formula for the description of the phase speed of breaking waves, also validated by experimental tests. Such a model, known as the “classical” bore model, neglects turbulent effects and Stive [19] compares his own experimental data with Svendsen et al.'s formula [20], also taking into account turbulence, finding a good agreement. On the other hand, linear theory largely underestimates the propagation speed of surf-zone waves. More recently, Catálan and Haller [4] compared some of the most common analytical models for the prediction of the wave celerity with experimental results, obtained in a large wave flume by means of a video technique. Such a technique, also applied by Almar et al. [1], enables to recognize when a wave breaks and what is its celerity by means of images (time stacks) that are built using video recordings and represent the time evolution of the water level along a cross section of the nearshore. Further, Grue and Jensen [7] analyzed the kinematics of deep-water breaking waves in terms of local variables, like the local wave slope and the local phase speed, the latter being estimated from the nonlinear dispersion relation. They also compared their findings with the field data collected by Romero and Melville [16].

Moreover, other works that are, more generally, focused on the wave-breaking phenomenon, also investigate the celerity of breaking waves. As an example, [2] are interested in the analysis of the breaking initiation of solitary waves and, for this purpose, they compare the results of their numerical model with experimental data. They also studied the case of bore-front propagation speed overcoming a critical phase speed, that is used for the individuation of the breaking initiation. When this condition is satisfied, such a speed represents the breaking-wave celerity. Also, Okamoto

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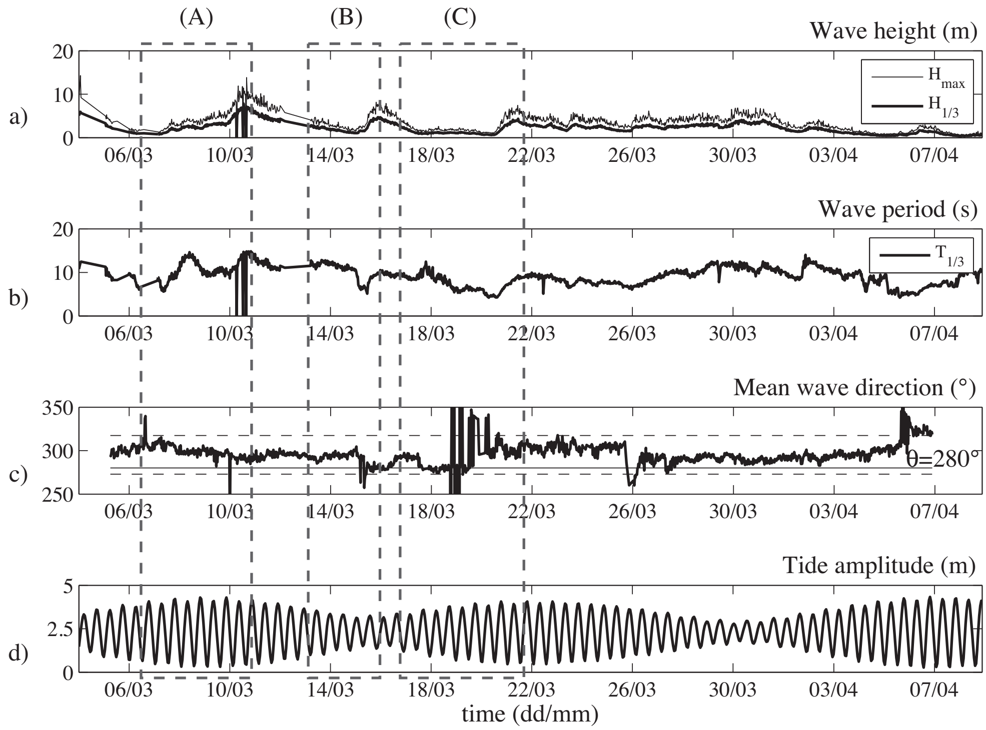

Fig. 1. Wave and tide characteristics. The three boxed areas, (A), (B) and (C), represent the recorded intervals. From top to bottom: (a) significant ($H_{1/3}$) and maximum (H_{max}) wave height; (b) significant wave period ($T_{1/3}$); (c) mean wave direction ($\theta = 280°$ is the shore normal); (d) tide amplitude.

and Basco [13] aimed at recognizing the initiation of wave breaking using the "Relative Trough Froude Number", defined as $RTFN = (|u_{trough}| + c)/\sqrt{gd_{trough}}$, where u_{trough} is the trough velocity, c the wave celerity and d_{trough} the water depth at the trough. They correlated the particle velocity at the wave crest with the phase speed of the wave, which is the breaking-wave celerity when the former is larger than the latter. The RTFN has also been implemented in FUNWAVE, which is a numerical, depth-averaged model, based on the Boussinesq equations and developed by Kirby et al. [9].

Knowledge of the breaking-wave celerity (c_b) is particularly important for both wave-averaged and wave-resolving models. In the former models terms like mass flux, energy flux and dissipation are averaged over a wave period T, that is used, together with c_b, for the evaluation of the breaking location. On the other hand, in typical Boussinesq-type models (see, for example, [18]), that are wave-resolving, the celerity of breaking waves is parameterized using the linear, shallow water celerity ($c_{lin} = \sqrt{gh}$) and adapting it to real-life conditions through a calibration coefficient (e.g. $c_b = 1.3\sqrt{gh}$), even if this is neither the best approximation of what actually happens in the surf zone, nor a theoretically solid approach. Further, a correct prediction of the breaking wave celerity is fundamental for the application of remote sensing techniques, especially when they are used to operate a depth inversion, i.e. to reconstruct, given a sea state, the beach morphology (for more details, see [4]).

Literature studies concerning the breaking-wave celerity of real sea waves are very few, hence we dedicate the present work to this topic. The innovative approach used here is that of evaluating the breaking-wave celerity by means of a wave-by-wave analysis, that leads to the individuation of the actual celerity related to each breaking wave that is directly measured in the field. This purpose has been undertaken starting from the work of TI11, who analyzed the same field data using a 10′-averaged procedure and treating a number of waves as a group characterized by the same celerity. The novelty of our work, which we regard as complementary to that of TI11, is the analysis of each wave, that enables to find its actual celerity rather than an averaged one. In fact, TI11's approach may lead to neglect some important information about all the waves that travel and, eventually, evolve between two points that are used to estimate the breaking wave celerity. Beyond the novel procedure for the evaluation of c_b, a comparative analysis is made to assess which of the available literature formulas best represents our field data and which is the best to be used within the mentioned wave-resolving and wave-averaged models.

The paper is organized as follows. Section 2 describes the experimental set-up of the field experiments. Section 3 details the method used for the analysis of the acquired data, while Section 4 illustrates results derived from the wave-by-wave method and compares them with some analytical models. Finally, Section 5 closes the paper.

2. Experimental set-up

In a six-week period during March–April 2008 a multi-institutional campaign of nearshore field experiments was performed at the Truc Vert beach, that is about 60 km far from Bordeaux, along the southern part of the French Atlantic coast. The beach is natural, i.e. with minimal impact of human activities. The main features are those of the 100 km sandy coast located between the Gironde Estuary (on the North) and the Arcachon inlet (on the South). The morphological activity is very intense, because of both a large tide range (about 3.70 m) and high-energy wave conditions (wave heights up to 14 m in winter), and a double-barred system protects the emerged beach and limits the inshore wave height (see also TI11).

Fig. 1 shows an example of the main wave properties recorded by a wave buoy located offshore of the Truc Vert beach, in a 54 m water depth. During the experiments the significant wave height ($H_{1/3}$) ranged, in general, between 1 m and 8 m. Four storms occurred in the period of interest, including a storm characterized by a maximum wave height larger than 10 m.