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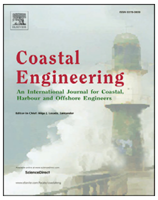

Breaking of ship bores in a Boussinesq-type ship-wake model

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ABSTRACT

A numerical study of ship-induced bores is carried out with a focus on soliton generation in different supercritical regimes, and the transition from breaking solitons to a pure bore measured in Gourlay's (2001) laboratory experiments. The fully nonlinear Boussinesq model, FUNWAVE-TVD, with appropriate dissipation schemes, is able to simulate ship-induced broken bores with amplitudes and periods consistent with the measured data. Two breaking dissipation schemes with different breaking criteria (a viscosity dissipation scheme with the surface slope breaking criterion, and a shock-capturing dissipation scheme with the wave height or surface elevation breaking criteria) are examined in a series of numerical experiments. It is found that both models predict soliton generation and the general trend of the transition from breaking solitons at lower Froude numbers to a pure bore at higher Froude numbers. Some differences are identified between the two different breaking schemes, including breaking locations, soliton propagation speed, amplitudes of wakes behind the ship, and the critical Froude number for the transition from a broken undular bore to a pure bore. In general, the viscosity-type breaker with the surface slope criterion performs more consistently with the laboratory observation compared with the shallow water equation-based shock-capturing breaker.

1. Introduction

A ship traveling in a channel around the critical speed can generate smooth solitons, broken solitons, bores, and steady supercritical flow (Gourlay, 2001). The critical speed of a ship is defined as the natural speed of long waves in shallow water, i.e., $\sqrt{gh}$, where g is the gravitational acceleration and h is the still water depth. The depth-based Froude number $F_r = U_v/\sqrt{gh}$, where U_v is the ship speed, is commonly used for describing subcritical and supercritical regimes related to traveling at different vessel velocities.

Generation of solitons by moving disturbances has been studied by a number of authors, especially from the 1980s, when the nonlinear theory of solitons of different types was developed. Wu (1987) pointed out that the physical significance of soliton generation can be attributed to a well-balanced interplay between wave nonlinearity and dispersion. In the transcritical speed range ($F_r \sim 1$), the wave in front of a moving disturbance accumulates energy gained from the forcing disturbance. When the wave reaches a certain threshold magnitude, the phase speed, which increases with growing amplitude, becomes significant enough to make the wave separate from the disturbance as a new solitary wave. The process is then repeated, resulting in a packet of solitons propagating ahead of the disturbance. It was found that this type of soliton generation is highly sensitive to the channel width. Solitons in such a case behave more like 1-D waves without much transverse variation. The dominant parameter for the generation of solitons is the blockage coefficient – the ratio of the maximum cross-sectional area of the ship and the cross section of the channel (Gourlay, 2001).

Theoretical and experimental studies have shown that pure solitons no longer exist when F_r is greater than about 1.2 (e.g., Huang et al., 1982; Ertekin et al., 1986; Lee et al., 1989). In theory, there is a range of Froude numbers where the steady flow cannot satisfy continuity without violating the Bernoulli equation. In other words, the regime in this Froude number range only exists when wave dissipation occurs.

Gourlay (2001) carried out laboratory experiments to examine various flow regimes under supercritical conditions. The experiments verified that there exists a gradual transition from breaking solitons at lower Froude numbers to a bore at higher Froude numbers, and then to a steady supercritical wave system at even higher Froude numbers. A simple theoretical model was then proposed for predicting the form of the bores and the transition to steady supercritical flow. No comprehensive numerical studies have been reported in conjunction with the experimental data.

Boussinesq-type equations are often used to simulate ship-induced

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solitons and bores, but cannot directly model the ship waves at depth-based Froude numbers greater than about 1.2 (Wu, 1987) if artificial energy dissipation is not included in the model. A great amount of effort has been devoted to the development of explicit expressions for wave breaking effects in Boussinesq-type models in the 1990s and early 2000s (Kirby, 2016), including roller models (Schäffer et al., 1993), vorticity models (Veeramony and Svendsen, 2000), and eddy-viscosity models (Zelt, 1991; Kennedy et al., 2000). More recently, hybrid shock-capturing approaches for modeling breaking wave dissipation have become widely used in Boussinesq models. The approach used a finite-volume method as the dominant computational scheme and thus naturally adopted the shock-capturing capabilities for the nonlinear shallow water equations (SWE) (Toro, 2009). Wave breaking is modeled by switching the dispersive Boussinesq equations to nonlinear shallow water equations at grid points where a breaking criterion is reached. There are several breaking criteria used in the shock-capturing type Boussinesq models such as the Froude number criterion (Tonelli and Petti, 2009), the momentum gradient criterion (Roeber and Cheung, 2012), a local surface elevation criterion (Shi et al., 2012a), as well as a more sophisticated two-step splitting method (Tissier et al., 2012). Regardless of what type of breaking criterion is the most appropriate, the shock-capturing breaking scheme gives reasonable results as long as it is calibrated by experimental and field data in applications of surfzone waves, solitary wave breaking, and runup. The question is: are those breaking criteria also appropriate for modeling ship-induced breaking bores?

In this study, we use a fully nonlinear Boussinesq wave model, FUNWAVE-TVD (Shi et al., 2012a), with different wave breaking schemes and breaking criteria to model the generation of solitons and bores in various flow regimes presented in Gourlay (2001) laboratory experiments. The gradual transition from breaking solitons to a pure bore was verified against the experimental data. Special emphasis is placed on examining the performance of different wave breaking criteria and dissipation schemes in simulating generation of ship-bores and wakes in different flow regimes.

In Section 2, the different breaking criteria and dissipation schemes employed in Boussinesq-type wave models are briefly reviewed. Section 3 illustrates the Boussinesq equations and the source function used for ship-wake simulations in this study. In Section 4, results from different breaking schemes are compared with measured data. Some discussion is given in Section 5. Findings from this numerical study are summarized in Section 6.

2. Modeling breaking in Boussinesq models

2.1. Existing breaking schemes in Boussinesq-type wave models

Wave breaking in a Boussinesq-type model can be modeled by a number of techniques, ranging from the simple prescribed artificial eddy-viscosity models and roller models, to reasonably detailed calculations of the generation and transport of vorticity or turbulent kinetic energy under the breaking wave crest. Most recently the shock-capturing breaking schemes were used in the hybrid numerical models. Regardless of what kind of dissipation schemes are used, the breaking criterion which determines the onset and cessation of breaking is believed to be crucial. The breaking criteria may not be universal in terms of different breaking mechanisms, such as modulational instability, dispersive focusing, wind forcing, and wave-current interaction. In a review of breaking waves in deep and intermediate waters, Perlin et al. (2013) classified wave breaking into three categories, i.e., geometric, kinematic and dynamic breaking criteria. Although those criteria were not found to be robust, as pointed out by the authors and other recent reseachers (e.g., Banner et al., 2014), they have been widely used in various breaking regimes. For a Boussinesq model, similar criteria can be implemented based on those categories. However, because of the two-dimensional description of the model equations, more empirical or semi-empirical approaches to account for wave breaking are usually applied.

The surface slope criteria, or the geometric criteria, use the limiting steepness associated with incipient wave breaking as a critical parameter for the prediction of breaking-onset in a Boussinesq model. Although the limiting steepness parameter can take on a large range for different scenarios, such as regular waves, wave groups, solitary wave, as well as effects of three-dimensionality, wind, and current effects, the geometric criteria are simple and relatively straightforward to apply (Perlin et al., 2013). Schäffer et al. (1993) directly used the slope of the water surface as a breaking criterion in their Boussinesq model with a roller model. Similar criteria can be found in Zelt (1991) and Kennedy et al. (2000), who used the time derivative of the surface elevation η_t, representing implicitly the surface slope in their eddy-viscosity dissipation models. Two critical values of η_t are specified to determine the onset and cessation of breaking. Zelt chose this criterion to have constant critical values, while Kennedy et al. used a parameter which involves a time history, in order to allow the slope of the breaking wave crest to relax after the onset of breaking.

The Froude number-based criterion is based on the analogy between bores and spilling breakers (Peregrine and Svendsen, 1978). A bore with a jump between two uniform levels h_1 and h_2, with h_1 as the upstream depth, as shown in Fig. 1 (a), starts breaking as the upstream Froude number exceeds a threshold. Based on Peregrine (1983), the Froude number can be denoted by

$$F_r = \sqrt{1 + \frac{3}{2}\frac{H}{h_1} + \frac{1}{2}\left(\frac{H}{h_1}\right)^2}, \tag{1}$$

where H is the wave height. Tonelli and Petti (2009) used $F_r = 1.60$ as the wave breaking threshold and derived the corresponding value of $H/h_1 = 0.82$ as the breaking criterion in their model. Note that the wave height is measured from the wave trough to the wave crest as shown in Fig. 1 (a). A similar breaking criterion based on the Relative Trough Froude Number (RTFN) was implemented in the previous FUNWAVE code by Okamoto and Basco (2006). They provided a theoretical analysis and model/data comparisons to demonstrate that the RTFN theory works

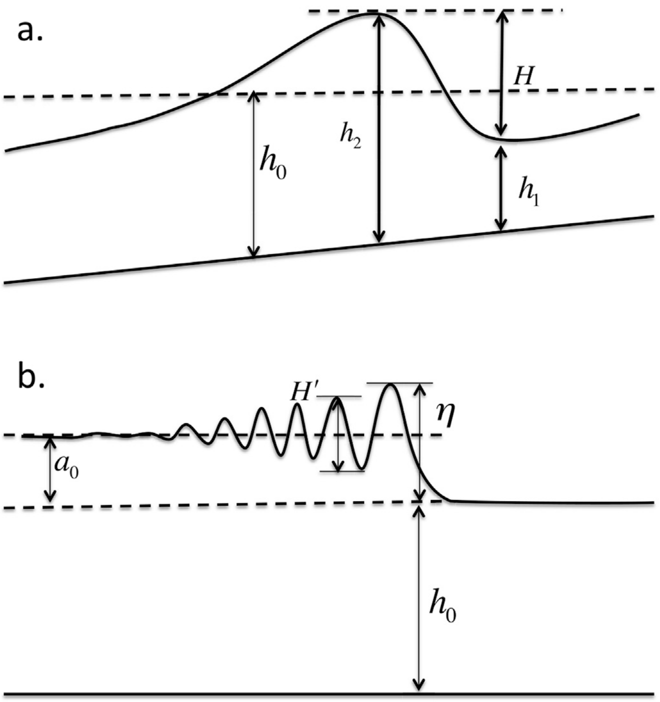

Fig. 1. Geometries of different types of waves and measures for breaking criteria. (a) Wave height H can be measured from the wave trough h_1 to the wave crest h_2. (b)Undular bore with representative parameters: a_0 - the bore amplitude, η - the surface elevation of the front bore, and ‘wave height’ H' used in model tests. h_0 - the still water depth.