Coastal Engineering 95 (2015) 4–19

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Breaking characteristics and geometric properties of spilling breakers over slopes

Mayilvahanan Alagan Chella [a,*], Hans Bihs [a], Dag Myrhaug [b], Michael Muskulus [a]

[a] Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway
[b] Department of Marine Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 16 July 2014
Received in revised form 12 September 2014
Accepted 15 September 2014
Available online 12 October 2014

Keywords:
Breaking waves
Wave profile asymmetry
Spilling breakers
Numerical modeling
Breaker indices

ABSTRACT

A two-phase flow CFD model based on the Reynolds-Averaged Navier–Stokes (RANS) equations coupled with the level set method (LSM) and $k-\omega$ turbulence model is used to simulate spilling breakers over a sloping bed. In order to validate the present numerical model, the simulated results are compared with the experimental data measured by Ting and Kirby (1996). The simulated horizontal velocities and free surface elevations are in good agreement with the experimental measurements. Moreover, the present model is able to model the prominent features associated with the breaking process such as the motion of air pockets in the water, formation of a forward moving jet, the splash-up phenomenon and the mixing of air and water in the breaking region. The numerical model has been utilized to study the influences of three important environmental parameters; water depth, offshore wave steepness and beach slope on the characteristics and geometric properties of spilling breakers over slopes. A total of 39 numerical experiment cases are performed to investigate the characteristics of breaking waves such as breaking location, incipient breaker height and water depth at breaking, incipient breaker indices and geometric properties with different offshore wave steepnesses at different water depths over a wide range of beach slopes. The geometric properties associated with breaking waves in shallow water are described using the wave steepness and asymmetry factors introduced by Kjeldsen and Myrhaug (1978). The computed results appear to give reasonable predictions and consistency with previous studies.

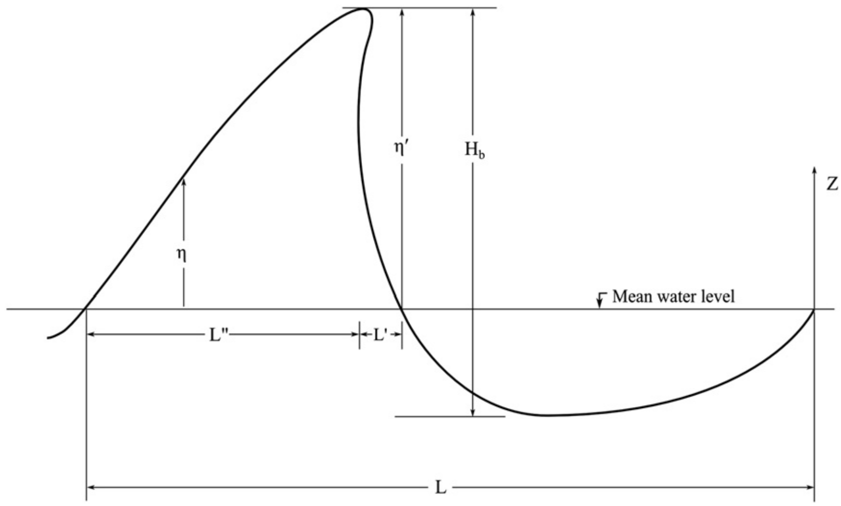
1. Introduction

Wave breaking is a natural process involving transformation of wave energy into turbulent energy leading to a violent transformation of the free surface, that exerts massive hydrodynamic loads on marine structures (Cokelet, 1977). During wave breaking for shoaling waves, the dissipation of energy takes place in order to approximately balance the increase in the local wave energy due to shoaling. However, the wave breaking process is primarily responsible for the creation of the surface turbulence and is increasing the turbulent kinetic energy, that plays an important role in the vertical mixing of momentum through the water column (Craig, 1996; Ting and Kirby, 1996). Massel (2007) gives a wide perspective of the breaking of both regular and random waves and how this is linked with the aerosol production and air-sea gas interaction. Based on the steepness of the wave and the seabed slope, breaker types can be categorized into four different types, namely spilling, plunging, surging and collapsing (Galvin, 1968). The breaking process depends on many physical parameters; water depth, wave height, wave length and seabed slope. Breaking waves are three-dimensional (3D) due to the interaction with waves, current or wind in a real sea environment. Moreover, e.g. in a wave tank waves always begin to propagate down the tank as undisturbed two-dimensional (2D) waves and reach the critical point at which the unstable water front evolves into a 3D flow. Therefore, 2D models can capture most of the wave breaking characteristics up to the breaking point, where 3D effects are minimal.

A symmetrical wave can be expressed by the wave steepness. As it propagates over a plane slope, the wave starts to deform and the wave front moves forward, thus the shape of the wave profile is not symmetric anymore. Several studies have been carried out to investigate the geometric properties of breaking waves in deep water (Babanin et al., 2010; Bonmarin, 1989; Kjeldsen and Myrhaug, 1978; Lader, 2002). Although a considerable amount of literature has been reported on wave steepness and asymmetry factors of shallow water waves (Adeyemo, 1968; Ippen and Kulin, 1954; Iwagaki and Sakai, 1972; Miller and Zeigler, 1964), there have been limited studies on the geometrical asymmetry associated with breaking waves on slopes in shallow water. A definition sketch of the wave asymmetry profile at breaking in shallow water is shown in Fig. 1. The breaking asymmetry profile parameters can be related to breaking wave forces on coastal structures, which influence the global design of a structure (Adeyemo, 1968). Much uncertainty still exists about the relationship between the wave asymmetry profile parameters and the breaking wave forces,

* Corresponding author.
E-mail address: acm@ntnu.no (M. Alagan Chella).

http://dx.doi.org/10.1016/j.coastaleng.2014.09.003
0378-3839/



$$\varepsilon = \frac{\eta'}{L'} \qquad \delta = \frac{\eta'}{L''} \qquad \lambda = \frac{L''}{L'} \qquad \mu = \frac{\eta'}{H_b}$$

Fig. 1. Definition sketch of local wave geometry parameters following (Kjeldsen and Myrhaug (1978).

suggesting a need to understand the geometric properties of breaking waves on slopes in shallow water and the effect of breaking wave forces on coastal structures. The maximum wave height governs the critical design condition for coastal structures, which is greatly influenced by the wave breaking process.

The wave transformation over a sloping bed, such as shoaling, overturning and onset of wave breaking can be described theoretically or numerically by classical potential flow theory. However, this disregards the influence of viscosity and turbulence production, which plays a vital role in wave breaking, especially for waves over sloping beds. The first numerical computation of breaking waves in deep water was performed by Longuet-Higgins and Cokelet (1976) by applying a mixed Eulerian–Lagrangian formulation (MEL) with the boundary integral method based on potential theory and a conformal mapping of physical plane limited to a periodic domain in deep water. Vinje and Brevig (1981) applied the same method in the physical plane, and they extended the application to finite water depth. Most recent MEL based models are capable of modeling both arbitrary waves and water depths. The MEL method is able to model the breaking waves until breaking but cannot model the interface reconnection phenomenon that occurs during the breaking process (Chen et al., 1999). Other models based on the Boussinesq approximation have been used to simulate only the wave deformation. This method cannot be used directly to model the wave breaking (Christensen, 1998), but the model can be used to calculate the wave transformation in the surf zone together with a model for the dissipation of energy. The description of the breaking process is highly demanding due to unsteady non-linear viscous flow, the complex air-water interface, small scale free surface turbulence transport and dissipation process. Moreover, the theoretical description of the entire process is only possible with gross simplifications and assumptions (Cokelet, 1977). Thus, most of the studies on breaking waves are limited to field and laboratory experiments. Many theories and formulas to predict the breaking wave characteristics have been proposed based on the physical experiments (Goda, 2010; Iwagaki and Sakai, 1972; Tsai et al., 2005). Due to the complexity in describing the wave breaking process, most of the existing formulas are empirical and semi-empirical, and thus subjected to the experimental conditions and scale effects. However, none of the relationships have been established globally for obtaining the breaking wave properties for practical engineering applications (Southgate, 1993).

An efficient model based on Computational Fluid Dynamics (CFD) can describe the wave breaking process without specifying breaking criteria. The prominent features of the physical process can be obtained in detail without much simplifications, assumptions and approximations in the fluid flow properties (Christensen, 1998). CFD solves the fundamental fluid dynamic equations including the air-water interface. The small scale free surface turbulence transport and dissipation process can be represented by a suitable turbulence model. Hence, the method is capable of determining the detailed information concerning fluid flow properties such as velocities, turbulence, interface deformation etc. A number of numerical studies based on viscous computations attempted to simulate the breaking process with a single phase model such as Lin and Liu (1998), Bradford (2000) and Zhao et al. (2004). Since a single phase model ignores the motion of the air over the free surface and the density variation across the interface, which are primarily responsible for the surface deformation phenomenon, the complete description of the breaking process is still not fully represented. Hence, all the previously mentioned models have some significant discrepancies compared with the experimental data. Other studies such as Chen et al. (1999), Hieu et al. (2004), Christensen (2006), Jacobsen et al. (2012) used a two-phase flow model to describe the wave breaking process. Detailed literature reviews on the methods and results can be found in Lin and Liu (1998), Chen et al. (1999), Zhao et al. (2004), Hieu et al. (2004) and Bradford (2000). Christensen (2006) studied the undertow profiles and turbulence levels in breaking waves with a Navier–Stokes solver and the volume of fluid method (VOF). The Large Eddy Simulation (LES) technique was used to model the turbulence in the breaking waves. The predicted turbulence levels and the wave heights at breaking were higher than in the experiments. Jacobsen et al. (2012) presented the application of OpenFOAM to model spilling breaking waves using the Reynolds-Averaged Navier–Stokes (RANS) equations, coupled with the VOF method. They compared the numerical results with the experimental data by Ting and Kirby (1996) using a geometric cut-off (i.e. a significant modification at the end of the tank). Moreover, their model slightly over-predicted the wave crest height before the breaking point and under-predicted the wave crest height in the surf zone. These studies proposed to model the undertow profiles, turbulence levels and turbulent characteristics for different types of breakers. However, uncertainty still exists about the relationship between the environmental parameters, characteristics and geometrical properties of wave breaking on slopes.

The purpose of the present work is to investigate the effects of water depth, offshore wave steepness, and beach slope on the characteristics and geometric properties of spilling breakers over slopes. A 3D two-phase flow CFD model solving the RANS equations is applied in a 2D