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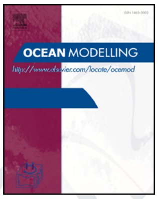

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Hydrodynamic characteristics and geometric properties of plunging and spilling breakers over impermeable slopes

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ABSTRACT

The two-phase flow CFD model REEF3D has been used for modeling waves breaking over a sloping seabed for a spilling and a plunging breaker. This model is based on Reynolds-averaged Navier–Stokes (RANS) equations with the level set method (LSM) for the free surface and k–ω model for turbulence. First, the characteristics and geometric properties of plunging breaking waves with different offshore wave steepnesses over slopes are examined and discussed. The study further explores the hydrodynamic characteristics of spilling and plunging breakers in terms of the wave height evolution and attenuation, horizontal and vertical velocity, free surface profile evolution, and the geometric properties during the development of the breaking process. The numerical results show a good agreement with experimental data in terms of free surface elevation and horizontal and vertical velocity for the spilling and plunging breakers. Results of numerical simulations describing the physical flow characteristics such as the formation of the forward overturning water jet, air pocket, splash-up, and the secondary wave during the breaking process are presented for both cases. For both cases, the physical flow process is found to have similar flow features, but the breaking process occurs at significantly different scales.

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1. Introduction

Wave breaking is a two-phase flow process composed of air and water, which transforms the large scale deterministic irrotational flow into rotational flow resulting in turbulence and vortices of different types and scales. The wave breaking process in shallow waters naturally influences many physical processes such as wave energy dissipation, air–sea interaction, wave–structure interaction, rip current, cross-shore and along-shore currents, sediment transport, shoreline evaluation. Breaking waves are strongly influenced by the local wave parameters and seabed slope, and are described by four different types: spilling, plunging, collapsing and surging (Galvin, 1968). Breaking waves exert significant hydrodynamic loading on offshore platforms and foundations of offshore wind turbines in intermediate and shallow water. A recent feasibility study on the deployment of offshore wind turbines on Thornton bank outside the Belgian coast shows that hydrodynamic forces from plunging breaking waves govern the design criteria of a truss substructure (Alagan Chella et al., 2012). Understanding the breaking process remains a challenge since both measurements and simulations are extremely intricate.

Svendsen et al. (1978) divided the surf zone from inception to broken waves into three regions: outer, inner and run-up region. In the outer region, waves undergo drastic changes in the shape and the flow features, i.e. the flow pattern changes from irrotational flow to rotational flow. As the wave propagates farther shoreward, the wave motion becomes turbulent with low frequency components leading to the formation of wave rollers in the inner region. The region closest to the shore is the run-up region. The two-dimensional effects and longitudinal variations are more pronounced when waves approach the breaking point. On the other hand, the three-dimensional effects become more significant just after breaking and the flow becomes highly turbulent where waves undergo drastic changes in the deterministic flow characteristics. Therefore, three-dimensional effects and the surface tension effects need to be considered for a better description of air entrainment during the breaking process and the turbulent flow characteristics in the surf zone. The present study focuses on the physical process up to the inner breaking region where the three-dimensional effects are minimal, i.e. the large-scale changes in

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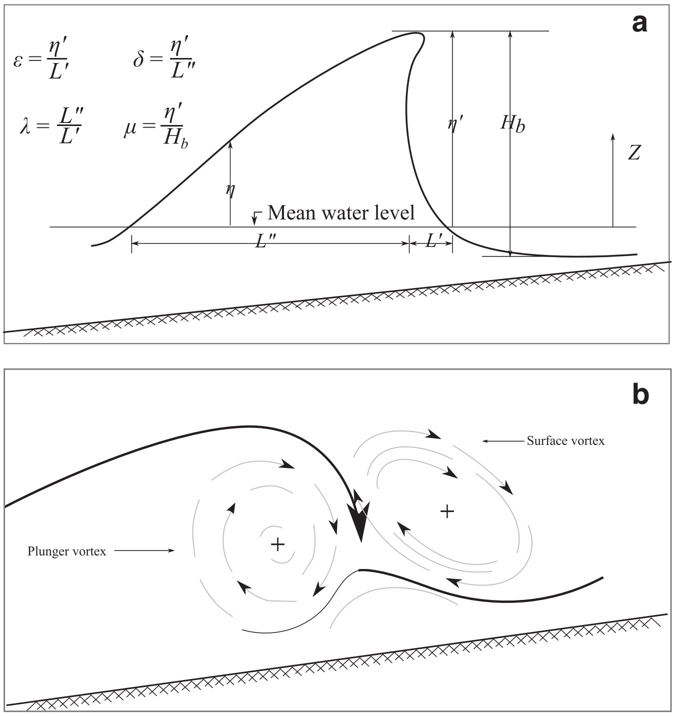

Fig. 1. (a) Definition sketch of local steepness and asymmetry parameters following Kjeldsen and Myrhaug (1978). (b) Schematic of formation of plunger vortex and surface vortex during breaking following Basco (1985).

the incident deterministic flow pattern. The wave breaking process primarily depends on the following parameters: local water depth (d), offshore wave steepness (H_0/L_0, where H_0 and L_0 are wave height and wave length, respectively in deep water) and sea bed slope (m). The wave characteristics and the seabed slope are key factors in determining the breaker type (Iversen, 1952; Galvin, 1968; Battjes, 1974). Battjes (1974) described the breaker types based on the surf similarity parameter ($\xi_0 = \frac{m}{\sqrt{H_0/L_0}}$), which is a function of the wave steepness in deep water (H_0/L_0) and the seabed slope (m). For $\xi_0 < 0.5$, spilling breakers develop for waves of high steepness over mild slopes with the formation of white water foam or a small overturning water jet at the wave crest. For $0.5 < \xi_0 < 3.3$ corresponding to waves of low steepness propagating over moderate seabed slopes, waves break as plunging breakers with the larger forward overturning jet at the wave crest. Surging or collapsing breakers occur for $\xi_0 > 3.3$. Many laboratory experiments have been performed to obtain more insights into the breaking wave geometric, kinematic, dynamic and turbulent characteristics in deep and shallow waters, such as Kjeldsen and Myrhaug (1978), Adeyemo (1968), Stive and Wind (1982), Miller (1987), Nadaoka et al. (1989), Smith and Kraus (1990), and Ting and Kirby (1994). Kjeldsen and Myrhaug (1978) proposed steepness and asymmetry parameters from zero-downcross analysis to describe the prominent asymmetry features of a wave that approaches breaking: crest front steepness (ε), crest rear steepness (δ), the vertical asymmetry factor (λ) and the horizontal asymmetry factor (μ) as defined in Fig. 1(a). A detailed experimental study by Ting and Kirby (1994, 1995, 1996) investigated the dynamics of surf zone turbulence under waves breaking over a sloping seabed using fibre-optic laser-Doppler anemometer (LDA) technique. They addressed the basic differences in the turbulent characteristics and turbulence production mechanisms between spilling and plunging breakers. A number of studies have reviewed the wave evolution, flow properties and physical characteristics of waves breaking in deep and shallow water Cokelet (1977), Peregrine (1983), Basco (1985), Banner and Peregrine (1993), and Perlin et al. (2013). Importantly, most numerical studies have addressed the deformation of solitary waves during the breaking process in shallow waters including Emarat et al. (2012) and Mo et al. (2013). Though a very few numerical studies have investigated the periodic waves breaking in shallow waters.

The wave transformation process in the surf zone is well represented by the Navier–Stokes equations and a direct solution of these equations is extremely complicated (Lemos, 1992). With the advancements in the development of computational fluid dynamics (CFD), a numerical model that solves the Navier–Stokes equations coupled with a free surface capturing scheme is capable of solving the complex free surface flow problem and details of the fluid flow properties can be obtained. The first numerical investigation of free surface flows by directly solving the Navier–Stokes equations was demonstrated by Harlow and Welch (1965). A class of computational methods based on the Reynolds-averaged Navier–Stokes (RANS) equations was first proposed by Lemos (1992) together with the volume-of-fluid method (VOF) and the k–ϵ turbulence model to simulate breaking waves in shallow water. Several studies attempted to model the breaking process using a single-phase flow model (Lin and Liu, 1998; Bradford, 2000; Zhao et al., 2004; Christensen and Deigaard, 2001). The major inadequacies of the single-phase flow models to represent the complete wave breaking process are that they do not account for the air phase, the constant pressure assumption in air and the associated boundary conditions at the free surface. Therefore, this model cannot represent the complex air–water interaction, which has a prominent role in the process. Hence, two-phase flow models are crucial to model the wave breaking process, such as Hieu et al. (2004), Christensen (2006), Lubin et al. (2006), Moraga et al. (2008), Wang et al. (2009), Shi et al. (2010), Ma et al. (2011), Jacobsen et al. (2012), Xie (2013), Alagan Chella et al. (2015a) and Alagan Chella et al. (2015b). Alagan Chella et al. (2015a) used the present numerical model to simulate spilling breakers over slopes. The authors compared the numerical results to the experimental data for the spilling breaker case in order to validate the numerical model. Moreover, the main aim of the study was to investigate the effects of water depth, offshore wave steepness, and beach slope on the characteristics and geometric properties of spilling breakers over slopes.

The present numerical study uses the incompressible Reynolds-averaged Navier–Stokes equations based numerical wave tank. Unlike most of the previous numerical studies on breaking waves, in the current numerical model, different approaches have been proposed for describing the computational grid architecture and discretization schemes. The employment of the Cartesian grid facilitates to implement higher order spatial and temporal discretization schemes that provide very good numerical accuracy and stability. Particular attention has been given to achieve a more accurate representation of free surface waves in order to avoid the unrealistic damping at the free surface. Several numerical studies that are aimed at modeling the surf zone hydrodynamics have shown quite good results, but far too little attention has been paid to investigate the evolution of the free surface profile and the prominent flow features during the breaking process. In the hydrodynamic load assessment point of view, the evolution of free surface profiles, wave height and changes in velocities and geometric properties associated with the initial breaking process are important for the modeling of breaking wave forces. Meanwhile, there have been limited studies on these hydrodynamic characteristics relevant to the load assessment parameters in shallow waters.

The main purpose of the present paper is to investigate the hydrodynamic and geometric properties of plunging breakers over slopes with the two-phase flow CFD model REEF3D and compare them with the spilling breakers (Alagan Chella et al., 2015a). Comparison with similar results obtained for spilling breakers in Alagan Chella et al. (2015a) are also discussed. First, the study assesses the characteristics and geometric properties of plunging breaking waves of different offshore wave steepnesses over different slopes. This has been accomplished by examining the breaking characteristics such as breaker

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