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Numerical modelling of wind effects on breaking solitary waves

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HIGHLIGHTS

- Contribute to the understanding of breaking waves under the influence of wind.
- A two-phase flow model is presented and validated against experimental data in the absence of wind.
- Wave pre-breaking, overturning, post-breaking processes are captured.
- Provide insights of wind effects on the wave breaking process.

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ABSTRACT

Wind effects on breaking solitary waves are investigated in this study using a two-phase flow model. The model solves the Reynolds-averaged Navier–Stokes equations with the $k - \epsilon$ turbulence model simultaneously for the flows both in the air and water, with the air–water interface calculated by the volume of fluid method. First, the proposed model was validated with the computations of a breaking solitary wave run-up on a 1:19.85 sloping beach in the absence of wind, and fairly good agreement between the computational results and experimental measurements was obtained. Further, detailed information of the water surface profiles, velocity fields, vorticity, turbulent stress, maximum run-up, evolution of maximum wave height, energy dissipation, plunging jet and splash-up phenomena is presented and discussed for breaking solitary waves in the presence of wind. The inclusion of wind alters the air flow structure above water waves, increases the generation of vorticity and turbulent stress, and affects the solitary wave shoaling, breaking and run-up processes. Wind increases the water particle velocities and causes water waves to break earlier and seaward, which agrees with the previous experiment.

1. Introduction

Wave breaking plays an important role in the air–sea interactions, surf zone dynamics, nearshore sediment transport and wave-structure interactions. Over the last three decades, significant advances have been made in the theoretical, experimental and numerical studies of the characteristics of breaking waves (see [1–4] for reviews). However, little attention has been paid to investigate breaking waves under the influence of wind, either by experimental measurements or numerical simulations. When the wind is blowing over water waves, it cannot only enhance the exchanges of heat, mass and momentum on the air–water interface, but also affect the wave breaking process.

When the wind is absent, many research works have been done in the past to maturate the understanding of breaking waves. Much of our knowledge of breaking waves comes from laboratory measurements. Several systematic studies have been carried out for steady breaking waves [5], quasi-steady breaking waves [6], unsteady deep-water breaking waves [7–11], and breaking waves in the laboratory surf zone [12–14].

With the development of the numerical methods for the Navier–Stokes equations and free surface flows [15], several numerical studies have been performed to further our understanding of breaking waves. In order to track or capture the interface, several techniques have been employed, such as the marker-and-cell (MAC) method [16,17], surface tracking method [18,19], volume of fluid (VOF) method [20–23], level set method [24,25], and the density function method [26]. In addition, there are some meshless methods such as the moving particle semi-implicit (MPS) method [27], smoothed particle hydrodynamics (SPH) method [28–30], and Meshless Local Petrov–Galerkin method based on Rankine source solution (MLPG_R) method [31]. It is noted that most models are based on one-phase flow, in which only the flow in water is considered in the computation, the pressure in the air is taken as a constant, and the boundary conditions are specified at the free surface. When the wind is present, the pressure in the air is no longer a constant and the previously used boundary conditions are not valid at the interface. In order to take

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the air into account for wave breaking, recently, several two-phase flow models (for example [21,24,25,32–38]), in which both flows in the air and water are solved, have been developed to study the details of breaking waves and the air entrainment during wave breaking. However, the effect of wind on breaking waves has not been explored in their studies.

Most flows in breaking waves are turbulent and therefore need different treatment for the turbulence. In most engineering applications, the Reynolds-averaged Navier–Stokes (RANS) approach is often employed as it requires less computational effort when compared to direct numerical simulation and large-eddy simulation. In RANS modelling, the k–ϵ model is one of the most widely used two-equation turbulence models. It has been tested over a large variety of flow situations and therefore its limitations, as well as its successes, have become well understood [39]. The k–ϵ turbulence model has been successfully applied for a wide range of hydraulic problems [40] and surf zone dynamics [20,22]. Recently, it has also been employed in two-phase flow models within CFD codes Fluent [41] and OpenFOAM [42] to study turbulent surf and swash zone wave motions and coastal engineering processes, respectively.

Some important effects of the wind on the breaking waves have been discussed in [43–46]. Banner and Phillips [47] have considered the effect of a thin laminar wind drift layer in reducing the maximum wave height for deep-water breaking waves and found the 'micro-breaking', which is important in the energy and momentum transfer from the wave to near surface turbulence and currents. Through the laboratory measurements for steady and unsteady breaking waves, Banner [48] investigated the influence of wave breaking on the surface pressure distribution in wind–wave interaction and found that the form drag and wind stress increase during wave breaking. In addition, a logarithmic wind profile was found over water waves. Ward et al. [49] conducted a series of physical model tests to study the effects of onshore wind on run-up elevations. It was suggested that low wind speeds have little effect on run-up, but higher wind speeds significantly increase run-up elevations. Feddersen and Veron [50] carried out a laboratory study of wind effects on shoaling wave shape over a steep beach (slope 1:8) in a laboratory wind–wave tank and found that wind increases the shoaling wave energy and has a significant effect on the wave shape (e.g. changes wave skewness and asymmetry). Douglass [51] has experimentally investigated the influence of local wind on nearshore breaking waves in a laboratory wind–wave flume and found that wind has significant effects on the breaker location, geometry and type. Onshore winds cause waves to break earlier and in deeper water further from shore; offshore winds cause waves to break later and in shallower water closer to shore. He found that the wind effect on breaker depth is significant while on breaker height is slight. Douglass [51] indicated that the primary mechanism for wind affecting breaking waves appears to be shear, not normal stress and concluded that

> 'Surf zone dynamics models that ignore wind or include wind only as a surface shear may be missing a very important effect of the wind—its effect on the initiation and mechanics of wave breaking.'

Recently, in order to investigate the influence of wind on water waves, very few numerical studies have been carried out. Chen et al. [52] implemented the parameterised wind stress into Boussinesq wave models to investigate the nearshore wave propagation and horizontal circulation. Kharif et al. [53] applied an empirical wind pressure distribution on the free surface using Jeffreys sheltering theory [54] in their potential flow model, to calculate the influence of wind on extreme wave events. Yan and Ma [55] used a potential flow model combined with a commercial software package to investigate the interaction between wind and 2D freak waves.

The solitary wave, which can represent many characteristics of water waves and tsunamis, is often used to study water wave propagation and tsunami hazards. Synolakis [56] carried out laboratory measurements to study the run-up of non-breaking and breaking solitary waves on a 1:19.85 sloping beach. Li [57] experimentally investigated the splash-up of breaking solitary waves on a 1:15 sloping beach and vertical walls. A theory and an asymptotic result for the run-up of non-breaking solitary waves on plane beaches have been presented by Synolakis [58]. Several numerical simulations for the breaking solitary wave run-up have also been done based on different models [28,59–62]. However, only the flow in the water is solved in these models; therefore, they might have limitations for providing all the detailed information during wave breaking such as the development of the plunging jet and splash-up phenomenon. In addition, the wind effect is neglected in these studies.

Thus, the objective of the present study is to investigate wind effects on breaking solitary waves and provide detailed information during wave breaking. A recently developed two-phase flow model [37], which solves the flow in the air and water simultaneously, is adopted here to study breaking solitary waves on a sloping beach under the influence of wind. The description of the mathematical model and numerical method for the two-phase flow is presented in Section 2. A breaking solitary wave run-up on a beach without wind [56] is used to validate the present method in Section 3. After that, wind effects on breaking solitary waves run-up on a beach are calculated in Section 4. Detailed computational results of the water surface profiles, velocity fields, vorticity, turbulent stress, maximum run-up, evolution of maximum wave height, and energy dissipation are shown and discussed. Finally, conclusions are drawn in Section 5.

2. Mathematical model and numerical method

2.1. Geometry

Wind effects on a two-dimensional breaking solitary wave running up a uniform sloping beach of angle β are considered in this study. The schematic of this problem is shown in Fig. 1, where the origin of the coordinate system is where the still water surface meets the beach slope, x and z are the horizontal and vertical coordinates respectively, D is the still water depth, H is the solitary wave height, $\eta(x,t)$ is the solitary wave profile, t is the time, and x_L is the initial centre of the solitary wave. x_0 is the toe location of the beach, $h(x)$ is the local still water depth, U is the wind speed and R is the maximum run-up, which is defined as the highest position the wave can reach on the slope.

2.2. Governing equations

The governing equations for incompressible Newtonian fluid flow are the Reynolds-averaged Navier–Stokes equations. Mass conservation is described by the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0, \tag{1}$$

where ρ is the density and $\boldsymbol{u} = (u, w)$ is the velocity vector.

If we assume that the fluid is incompressible ($\mathrm{d}\rho/\mathrm{d}t = 0$), then the continuity equation can be simplified to

$$\nabla \cdot \boldsymbol{u} = 0. \tag{2}$$

The momentum conservation is expressed as

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u}) = -\nabla p + \nabla \cdot [(\mu + \mu_t)(\nabla \boldsymbol{u} + \nabla^{\mathrm{T}} \boldsymbol{u})] + \rho \boldsymbol{g}, \tag{3}$$