Coastal Engineering 83 (2014) 36–48

Contents lists available at ScienceDirect

Coastal Engineering

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

Non-hydrostatic modeling of surf zone wave dynamics

Pieter Smit [a,*], Tim Janssen [b], Leo Holthuijsen [a], Jane Smith [c]

[a] Environmental Fluid Mechanics Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] Theiss Research, 30 Portola Ave, El Granada, CA 94018, USA
[c] U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA

ARTICLE INFO

Article history:
Received 11 July 2013
Received in revised form 20 September 2013
Accepted 23 September 2013
Available online 22 October 2013

Keywords:
Nonlinear
Wave statistics
Non-hydrostatic
Wave breaking
Wave model
SWASH

ABSTRACT

Non-hydrostatic models such as Surface WAves till SHore (SWASH) resolve many of the relevant physics in coastal wave propagation such as dispersion, shoaling, refraction, dissipation and nonlinearity. However, for efficiency, they assume a single-valued surface and therefore do not resolve some aspects of breaking waves such as wave overturning, turbulence generation, and air entrainment. To study the ability of such models to represent nonlinear wave dynamics and statistics in a dissipative surf zone, we compare simulations with SWASH to flume observations of random, unidirectional waves, incident on a 1:30 planar beach. The experimental data includes a wide variation in the incident wave fields, so that model performance can be studied over a large range of wave conditions. Our results show that, without specific calibration, the model accurately predicts second-order bulk parameters such as wave height and period, the details of the spectral evolution, and higher-order statistics, such as skewness and asymmetry of the waves. Monte Carlo simulations show that the model can capture the principal features of the wave probability density function in the surf zone, and that the spectral distribution of dissipation in SWASH is proportional to the frequency squared, which is consistent with observations reported by earlier studies. These results show that relatively efficient non-hydrostatic models such as SWASH can be successfully used to parametrize surf zone wave processes.

1. Introduction

In the nearshore region and surf zone, ocean waves undergo a dramatic transformation mostly due to nonlinear wave–wave interactions and breaker dissipation. These dynamics play a central role in nearshore circulation and transport processes, e.g. by controlling wave setup (e.g. Longuet-Higgins and Stewart, 1964), driving nearshore currents (e.g. Longuet-Higgins, 1970; Longuet-Higgins and Stewart, 1964; MacMahan et al., 2006; Svendsen, 1984), and causing morphodynamic evolution (e.g. Hoefel and Elgar, 2003). Understanding these processes and the development of predictive models is important for both scientific research and engineering in the coastal zone. Since most coastal and coastline processes take place on much longer scales than that of the individual waves, predictive models are generally used to estimate wave statistics (e.g. significant wave height, mean period) and variations therein. However, modeling wave statistics in the nearshore is complicated both by the strong influence of nonlinear processes and an incomplete understanding of dissipation of wave energy in shoaling and breaking waves.

Stochastic (or phase-averaged) wave models for coastal applications are usually based on some form of energy (or action) balance equation (e.g. Komen et al., 1994; The WAMDI Group, 1988; Wise Group, 2007), which assumes that the wave field is (and remains) quasi-homogeneous and near-Gaussian. However, due to nonlinearity, surf zone wave statistics are generally strongly non-Gaussian, and apart from variance, higher cumulants (e.g. skewness and kurtosis) are required to completely describe the wave statistics. This poses high demands on the model representation of the nonlinear and non-conservative dynamics. In particular, for statistical models, the representation of nonlinearity invariably requires some form of closure approximation and involves evolution equations for higher-order correlations, both of which generally render the model considerably more complicated and computationally intensive (e.g. Herbers and Burton, 1997; Herbers et al., 2003; Janssen, 2006; Smit and Janssen, 2013).

Deterministic (and phase-resolving) wave models can generally incorporate nonlinearity more easily, and naturally include full coupling to the wave-induced nearshore circulations. However, although a model based on the Reynolds-averaged Navier–Stokes (RANS) equations can model surface wave dynamics in great detail, and resolve very small scales of motion (e.g. Torres-Freyermuth et al., 2007), the computational cost can become prohibitive, even for small-scale applications. For wave modeling of most coastal-scale applications, and in particular for coastal engineering, more approximate but efficient models, such as so-called non-hydrostatic models or models based on a Boussinesq approximation are generally more useable. Boussinesq-type wave models have evolved from weakly nonlinear and weakly dispersive models (see Peregrine, 1967), to nearly fully dispersive and highly nonlinear models (e.g. Madsen et al., 2002; Nwogu, 1993; Wei et al., 1995), at the expense however, of much increased complexity of the underlying model

* Corresponding author.
E-mail address: p.b.smit@tudelft.nl (P. Smit).

0378-3839/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coastaleng.2013.09.005

equations and numerical implementations. In contrast, non-hydrostatic models are essentially numerical implementations of the basic conservation equations for mass and momentum (e.g. Ma et al., 2012; Stelling and Zijlema, 2003; Yamazaki et al., 2009), which can be directly used for wave propagation problems if sufficient spatial resolution, in particular in the vertical, is provided. As a consequence, such models are relatively simple, and grid resolution can be readily adapted to a particular application and allow propagation of waves from deep to shallow water.

However, such non-hydrostatic models (and Boussinesq models for that matter), do not model all aspects of surf-zone waves. In particular, for the sake of efficiency, these models assume a single-valued representation of the free surface in the horizontal plane, which implies that processes such as overturning, air entrainment, and wave-generated turbulence are not resolved. Instead, integral properties of breaking waves (including energy dissipation rate) are estimated by treating the breaking wave as a discontinuity in the flow variables (free surface, velocities) and maintaining momentum (and mass) conservation across the discontinuity (Smit et al., 2013). Although this gives good results for the second-order bulk statistics (such as the significant wave height), it is not clear whether such an integral approach, where some of the details of breaking waves are treated as sub-grid processes, can actually resolve the nonlinear and dissipative processes in the surf zone, and thus predict the details of the spectral evolution and nonlinear statistics there.

In the present work we set out to study these issues by comparing simulations with the non-hydrostatic model Surface WAves till SHore (SWASH, Zijlema et al., 2011) to flume observations of random waves over a 1:30 planar beach (see Smith (2004)). The motivation behind this work is to assess whether an efficient non-hydrostatic model such as SWASH can be a viable tool to study surf zone dynamics and accurately capture the statistics of strongly nonlinear and breaking waves.

In Section 2 we present the model equations, numerical approximations, and breaker modeling in SWASH. The laboratory experiments and specific model settings are described in Section 3 and we present our results (model-data comparison) in Section 4. We discuss and sum up our principal findings and their implications in Sections 5 and 6.

2. Model description

The non-hydrostatic model SWASH (Zijlema et al., 2011), is an implementation of the Reynolds-averaged Navier–Stokes equations for an incompressible, constant-density fluid with a free surface. In the present work we use this model to study one-dimensional wave propagation in a flume. In Cartesian coordinates, with x and z the horizontal and vertical coordinate respectively, and with z measured up from the still-water level z_0, the governing equations can be written as

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial wu}{\partial z}+\frac{\partial wu}{\partial z}=-\frac{1}{\rho}\frac{\partial (p_h+p_{nh})}{\partial x}+\frac{\partial \tau_{xz}}{\partial z}+\frac{\partial \tau_{xx}}{\partial x}, \tag{1}$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial ww}{\partial z}=-\frac{1}{\rho}\frac{\partial p_{nh}}{\partial z}+\frac{\partial \tau_{zz}}{\partial z}+\frac{\partial \tau_{zx}}{\partial x}, \tag{2}$$

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0, \tag{3}$$

where t is time, $u(x,z,t)$ and $w(x,z,t)$ are the horizontal and vertical velocities, respectively, and ρ is the (constant) density. Further, the hydrostatic pressure $p_h = \rho g(\zeta - z)$ (with g being gravitational acceleration) and p_{nh} represents the non-hydrostatic pressure contribution. The turbulent stresses $\tau_{\alpha\beta}$ are obtained from a turbulent viscosity approximation (e.g. $\tau_{xz} = \nu\partial_z u$, with ν the kinematic eddy-viscocity) using a standard $k - \varepsilon$ model closure approximation (Launder and Spalding, 1974). The water column is vertically restricted by the (time-varying) free-surface $z = \zeta(x,t)$ and immobile bottom $z = - d(x)$. Here d is the still water depth and the location of the free surface ζ is found from continuity, expressed as

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}\int_{-d}^{\zeta} u\mathrm{d}z=0. \tag{4}$$

Eqs. (1)–(4) are solved for constant pressure at the free-surface (i.e. $p = 0$), while accounting for the kinematic free-surface and bottom boundary conditions,

$$w=\frac{\partial \zeta}{\partial t}+u\frac{\partial \zeta}{\partial x}\qquad (z=\zeta)\qquad \text{and}\qquad w=-u\frac{\partial d}{\partial x}\qquad (z=-d). \tag{5}$$

At the up-wave boundary, waves are generated by prescribing the horizontal velocity $u(z, t)$ at that location, whereas opposite of the wavemaker the boundary is formed by the moving shoreline.

Since the objective is to study surf zone wave dynamics, we need to include motions in the infragravity band, which are generated in the shoaling process and released during breaking. These low-frequency components are much longer than the primary waves and much more strongly affected by bottom friction. To incorporate this, we include a bottom stress at the bottom boundary assuming a logarithmic velocity profile (Launder and Spalding, 1974) and a typical roughness height d_r.

2.1. Numerical approximations

For non-breaking waves these equations describe nonlinear shoaling, and thus include the energy transfers across different length scales in the wave spectrum due to triad and higher-order nonlinearities. The accuracy with which these processes are represented in numerical models such as SWASH, depends on the numerical methods used to approximate the governing equations, and the spatial (horizontal and vertical) and temporal resolutions used in the simulation. Moreover, when extending such models to the surf zone, careful attention must be paid to the conservation properties (in particular of momentum) of the numerical method (see Zijlema et al. (2011) for a more general discussion of the numerical methods used in SWASH).

To accurately resolve wave motion in a phase-resolving model, the horizontal resolution Δx must be a fraction of the shortest wave length L that needs to be resolved, i.e. $L/\Delta x = O(10)$. Similarly, the timestep Δt is usually a fraction of the shortest wave period T, i.e. $T/\Delta t = O(10)$. To allow for accurate, undamped propagation over long distances, SWASH uses a staggered horizontal grid combined with a second-order (in space and time), explicit, finite-difference method that is neutrally stable (no numerical damping) for small amplitude (linear theory) waves. The vertical resolution, and numerical approximations of the vertical pressure gradient, determines how well the model approximates the linear dispersion relation for surface gravity waves $\omega(k) = \sqrt{gk\ \tanh(kd)}$, which strongly affects propagation and dispersive characteristics of the wave field.

Non-hydrostatic models often make use of a boundary-fitted vertical grid that divides the instantaneous water depth $h = (\zeta + d)$ in a constant number of layers N, with variable vertical mesh-size $\Delta z = h/N$. The required number of layers N then generally depends on the deepest parts of the domain, and increases with the vertical variability of the wave-induced velocity profile, for free-surface waves represented by the relative depth kd. Hence, in shallow water ($kd \ll 1$), a coarse resolution generally suffices, whereas in deep water ($kd \gg 1$) a vertical resolution similar to the horizontal resolution is required, $\Delta z/\Delta x = O(1)$ (at least near the surface). Traditionally, this has severely limited the application of these models to wave propagation, as the number of layers required to accurately capture dispersion (say a relative error smaller than 1%) at high kd ($O(10)$) can become very large ($N > 20$), resulting in excessive computational times. These constraints are significantly relaxed in SWASH due to the use of an edge-based vertical grid combined