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Non-hydrostatic modelling of infragravity waves under laboratory conditions

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ABSTRACT

The non-hydrostatic wave model SWASH is compared to flume observations of infragravity waves propagating over a plane slope and barred beach. The experiments cover a range of infragravity wave conditions, including forcing by bichromatic and irregular waves, varying from strongly dissipative to strongly reflective, so that model performance can be assessed for a wide range of conditions. The predicted bulk wave parameters, such as wave height and mean wave period, are found to be in good agreement with the observations. Moreover, the model captures the observed breaking of infragravity waves. These results demonstrate that SWASH can be used to model the nearshore evolution of infragravity waves, including nonlinear interactions, dissipation and shoreline reflections.

1. Introduction

As short-wave groups propagate towards the shore they force longer waves with periods ranging from 20 s to 250 s. Such low-frequency motions are commonly referred to as infragravity waves (ig-waves). IG-waves are found to be significant for harbour resonance (e.g. Bowers, 1977), moored vessel motions (e.g. Naciri et al., 2004), collapse of ice shelves (Bromirski et al., 2010) and dune erosion (e.g. van Thiel de Vries et al., 2008), which makes them an important subject for coastal and harbour engineers.

Two main mechanisms for the generation of ig-waves have been identified. Longuet-Higgins and Stewart (1962, 1964) proposed that groups of short waves force ig-waves through spatial gradients in the radiation stress. These ig-waves propagate with the velocity of the short-wave envelope and are known as bound ig-waves. Furthermore, Symonds et al. (1982) showed that the time variation of the breakpoint, induced by short-wave groups, generates a shoreward and seaward directed free ig-wave which propagate with the free wave celerity. The cross-shore propagation of ig-waves over an uneven bottom has been studied extensively by means of field experiments, laboratory experiments and numerical models. Such studies revealed that, as waves approach the shore, bound ig-waves grow with a rate greater than for energy conservative shoaling, due to weakly nonlinear interactions between short waves and bound ig-waves (e.g. Battjes et al., 2004; Janssen et al., 2003; List, 1992; Masselink, 1995). In the nearshore, because ig-waves are generally much longer than the short waves which generate them, ig-waves can lose energy due to bottom friction (Henderson and Bowen, 2002). This is particularly important in case of an extensive flat and shallow region, such as a coral reef (Pomeroy et al., 2012), but less significant on sloping beaches (e.g. Henderson et al., 2006; Van Dongeren et al., 2007). Once ig-waves enter the surf zone, the wave motion becomes strongly nonlinear, energy is exchanged rapidly between the short waves and the ig-waves (Henderson et al., 2006; Thomson et al., 2006) and strong dissipation can occur due to ig-wave breaking (Van Dongeren et al., 2007). Ruju et al. (2012) suggested that, based on a numerical study, nonlinear interactions are strongest in the outer surf zone, whereas – if it occurs – ig-wave breaking appears to be the dominant process in the inner surf zone. For weakly dissipative conditions, ig-waves (partially) reflect at the beach and subsequently propagate in seaward direction. Because the short-wave motion is mostly destroyed in the surf zone, such seaward directed waves are free waves, which may either propagate towards deeper water, known as leaky waves, or become trapped in the coastal region by refraction, known as edge waves. The simultaneous presence of incoming, and outgoing ig-waves can result in a (partially) standing ig-wave pattern near the surf zone.

The large difference in scales and the various physical phenomena (e.g. friction, wave-breaking) involved in the evolution of ig-waves places stringent demands on numerical models. In the surf-zone, a full representation of the ig-wave dynamics not only involves resolving the wave groups, but also the individual waves, including small scale processes due to wave breaking. Resolving all relevant scales over relatively short temporal and spatial scales is now within reach of Reynolds-averaged Navier Stokes (RANS) type models (e.g. Lin and

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Liu, 1998), as is exemplified by the successful application of such a model to simulate low-frequency motions under laboratory conditions (e.g. Lara et al., 2011; Torres-Freyermuth et al., 2010). However, models applicable for larger scale engineering and scientific applications often do not explicitly resolve the short waves. Instead, a so called phase-averaged approach is often used, in which a model that accounts for the nearshore transformation of short waves, providing the forcing on the wave group scale, is combined with a model based on the shallow-water equations, which accounts for the nearshore transformation of ig-waves (e.g. Roelvink et al., 2009). These models have been applied to simulate ig-waves underfield conditions and obtained reasonable agreement between model results and field data (e.g. List, 1992; Reniers et al., 2002, 2006, 2010; Van Dongeren et al., 2003, 2013). However, because they invariably use linear theory for the evolution of the short waves, they are less accurate under strongly nonlinear conditions. Moreover, they usually only include a one way coupling, in which wave energy can be transferred from the short waves to the ig-waves, but not vice-versa.

Models based on a Boussinesq type formulation (e.g. Madsen et al., 1991; Nwogu, 1993; Wei et al., 1995) or based on the non-hydrostatic approach (e.g. Ma et al., 2012; Stelling and Zijlema, 2003) are an alternative to the RANS and phase-averaged approach. These models aspire to resolve both the individual waves, including all the relevant processes (e.g. shoaling, refraction, diffraction, and nonlinearity) and the bulk dissipation associated with wave breaking, but not the detailed breaking process itself (e.g. wave overturning). Compared to RANS models this allows them to efficiently compute free surface flows by considering the free surface as a single-valued function. Boussinesq type models, introduced for variable depths by Peregrine (1967), have been applied extensively to the cross-shore evolution of short-wave motions, including wave breaking (e.g. Cienfuegos et al., 2010; Kennedy et al., 2000; Schäffer et al., 1993; Tissier et al., 2012; Tonelli and Petti, 2012) and to a lesser extent to ig-motions (e.g. Madsen and Sørensen, 1993; Madsen et al., 1997). Non-hydrostatic models were introduced more recently and have shown great potential for resolving the short-wave dynamics, including wave-breaking (e.g. Ma et al., 2012; Smit et al., 2013; Zijlema and Stelling, 2008) and the nonlinear wave-dynamics in a surf zone (Smit et al., 2014). Similar to RANS models, non-hydrostatic models are essentially implementations of the basic conservation equations for mass and momentum, that by using a reduced vertical resolution (two to three layers) have a similar computational effort and accuracy compared with Boussinesq models, whereas their implementation is less complex thereby improving robustness and maintenance. However, thus far, at coarse vertical resolutions non-hydrostatic models have not been verified for ig-waves.

In this study we show the capabilities of SWASH (Simulating WAves till SHore, Zijlema et al., 2011), a non-hydrostatic type model, in reproducing the nearshore transformation of ig-waves. To include the generation of incident bound ig-waves, a wave-generating boundary condition – based on second order wave theory – has been implemented. Model results are compared with measurements of the flume experiment of Van Noorloos (2003) and Boers (1996).

The outline of this paper is as follows: §2 gives an overview of the governing equations of SWASH, including relevant details of its numerical implementation. In §3 we present the second-order boundary condition. The model validation for the Van Noorloos (2003) and Boers (1996) experiments is presented in §4 and §5, respectively. To conclude the paper, we discuss and summarise our main findings in §6 and §7.

2. Numerical model

2.1. Governing equations

The non-hydrostatic model SWASH (Zijlema et al., 2011) is a numerical implementation of the Reynolds-averaged Navier–Stokes equations for an incompressible fluid with a constant density and a free surface. In a two-dimensional framework that is bounded by the free surface $z = \zeta(x,t)$ and the bottom $z = -d(x)$, where t is time and x and z are Cartesian co-ordinates ($z = 0$ is located at the still water level), the governing equations read

$$\frac{\partial u}{\partial t}+\frac{\partial uu}{\partial x}+\frac{\partial wu}{\partial z}=-\frac{1}{\rho}\frac{\partial(p_h+p_{nh})}{\partial x}+\frac{\partial}{\partial x}\left(\nu^h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial z}\left(\nu^v\frac{\partial u}{\partial z}\right), \tag{1}$$

$$\frac{\partial w}{\partial t}+\frac{\partial uw}{\partial x}+\frac{\partial ww}{\partial z}=-\frac{1}{\rho}\frac{\partial(p_h+p_{nh})}{\partial z}+\frac{\partial}{\partial x}\left(\nu^h\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial z}\left(\nu^v\frac{\partial w}{\partial z}\right)-g, \tag{2}$$

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

where $u(x,z,t)$ is the horizontal velocity, $w(x,z,t)$ is the vertical velocity, ν^h and ν^v are the horizontal and vertical kinematic eddy viscosities, respectively, g is the gravitational acceleration, and p_h and p_{nh} are the hydrostatic and non-hydrostatic pressures, respectively. The hydrostatic pressure is expressed in terms of the free surface as $p_h = \rho g(\zeta - z)$ such that $\partial_z p_h = -\rho g$ (where ∂_z is short for $\partial/\partial z$) and $\partial_x p_h = \rho g \partial_x \zeta$. An expression for the free surface is obtained by considering the (global) mass balance for the entire water column

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

For waves propagating over intermediate distances (say $O(10)$ wave lengths), in the absence of strongly sheared currents, turbulence has only marginal effects on the wave motion and can – to a good approximation – be neglected. Furthermore, the above equations (excluding the turbulence terms) can be directly applied to estimate the overall characteristics of a quasi-steady breaking bore in the surf zone, without the need to resolve complex phenomena such as the wave generated turbulence. Therefore, turbulent stresses can be neglected in this study. However, to increase numerical stability and to allow the influence of bottom friction to extend over the vertical, we introduce some vertical mixing by means of the vertical exchange of momentum due to turbulent stresses with a constant $\nu^v (= 10^{-4} m^2/s)$.

Kinematic and dynamic boundary conditions are prescribed at the free surface and bottom, given by

$$\begin{aligned} w(x,z=\zeta,t) &= \frac{\partial \zeta}{\partial t}+u\frac{\partial \zeta}{\partial x}, \\ w(x,z=-d,t) &= -u\frac{\partial d}{\partial x}. \end{aligned} \tag{5}$$

These boundary conditions ensure that no particle leaves the surface and no particle penetrates the fixed bottom. At the free surface the dynamic boundary condition prescribes a constant pressure ($p_{nh} = p_h = 0$) and no surface stresses. At the bottom boundary a bottom stress term is added to the horizontal momentum Eq. (1) as bottom friction is important for the low-frequency motions, for which it is one of the mechanisms of energy dissipation. The bottom stress is based on a quadratic friction law $\tau_b = c_f \frac{U|U|}{h}$, where $h = d + \zeta$ is the total water depth, c_f is a dimensionless friction coefficient and U is the depth-averaged velocity. Feddersen et al. (2003) found that the friction coefficient is enhanced in the surf zone due to the presence of breaking waves. In this study we compute the friction coefficient based on the Manning-Strickler formulation, which reads $c_f = 0.015(d_r/h)^{1/3}$ where d_r is an (apparent) roughness value. Although this formulation was derived for slowly varying open-channel flows and not for rapidly varying flows such as in the surf zone, it gives increasing values of c_f for decreasing depths which