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Comparison between wave generation methods for numerical simulation of bimodal seas

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Abstract

This paper describes an investigation of the generation of desired sea states in a numerical wave model. Bimodal sea states containing energetic swell components can be coastal hazards along coastlines exposed to large oceanic fetches. Investigating the effects of long-period bimodal seas requires large computational domains and increased running time to ensure the development of the desired sea state. Long computational runs can cause mass stability issues due to the Stokes drift and wave reflection, which in turn affect results through the variation of the water level. A numerical wave flume, NEWRANS, was used to investigate two wave generation methods: the wave paddle method, allowing for a smaller domain; and the internal mass source function method, providing an open boundary allowing reflected waves to leave the domain. The two wave generation methods were validated against experimental data by comparing the wave generation accuracy and the variance of mass in the model during simulations. Results show that the wave paddle method not only accurately generates the desired sea state but also provides a more stable simulation, in which mass fluctuation has less of an effect on the water depth during the long-duration simulations. As a result, it is suggested that the wave paddle method with active wave absorption is preferable to the internal wave maker option when investigating intermediate-depth long-period bimodal seas for long-duration simulations.

Keywords: Wave modeling; Wave generation; RANS; Swell wave; Bimodal sea; Long-period waves

1. Introduction

Low-pressure storm systems in the deep ocean can generate waves with enough energy to enable them to travel away from the wave generation area and towards the shoreline. These waves, commonly known as swell waves, have the characteristics of long periods, low frequencies, and long wavelengths. Due to the longer wavelengths, swell waves have a greater runup and are therefore more likely to overtop coastal structures than others. This has significant impacts across the globe; flooding as a result of swell waves has been observed (Draper and Bownass, 1982; Turton and Fenna, 2008; Sibley and Cox, 2014). Occasionally extensive flooding occurs when a storm travels across an ocean at a sufficient velocity to maintain an input of energy into the longer-period wave group (Sibley and Cox, 2014). This was likely the case during the United Kingdom's winter storms of 2013–2014, when a successive run of severe low-pressure Atlantic storms caused extensive damage and flooding along the coastline. During cases of severe damage and flooding, wave periods greater than 20 s were observed (Slingo et al., 2014).

This paper examines the problem of generating bimodal swell waves in a numerical flume in order to further investigate their effects on coastal structures. A bimodal sea state occurs when both low-frequency swell waves and high-frequency local wind-generated waves are present at the same location. A significant problem when dealing with long-period waves is the increase of wavelength. This requires

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larger modeling domains, both in physical models and numerical simulations, to prevent reflected waves from the shoreline from reaching the wave generation region. For intermediate- to deep-water waves, the longer wavelengths mean that the wave can travel at a faster speed and can therefore be reflected more easily if the nearshore slope structure allows. Reducing the amount of reflection is important as it can affect the initial wave generation. In nature, an open boundary naturally occurs, which absorbs waves reflected by the coastal system. A wave flume is a closed system, and any reflected wave from the shoreline will be re-reflected in the wave generation area, thus altering the wave characteristics at the shoreline (Frigaard and Brorsen, 1995). Ideally, absorption measures need to be in place to ensure that re-reflection does not occur. The long-period waves investigated in this study make reflected waves more likely, thereby making absorption more difficult. In numerical flumes, the re-reflected wave can also cause an increase in the mean water level (Higuera et al., 2013; Torres-Freyermuth et al., 2010). During long-duration simulations this can become significant and will decrease the accuracy of the simulation.

In investigation of bimodal seas, the model running time is important. Sufficient time is required for the sea state to fully develop so as to ensure that all frequencies are represented in a test. This study used experimental data to compare the accuracy in wave generation with two different methods. The wave paddle method has been used extensively in numerical flume applications (e.g., Lin and Liu, 1998; Reeve et al., 2008; Jones et al., 2013; Zou et al., 2013), with good results. The internal mass source function method has also been used in numerical flume applications (e.g., Lin and Liu, 1999; Lara et al., 2010; Wei et al., 1999). To the best of the authors' knowledge there has been no comparison of the two in terms of generating bimodal seas with desired swell components and for long computational runs. Hafsia et al. (2009) provide a comparison between the wave paddle and mass source function methods, but only for solitary wave generation, finding that both methods perform equally well in comparison with experimental data. When the internal wave maker was developed for the NEWRANS model, Lin and Liu (1999) compared the generation of different wave types (i.e., irregular, second-order, and linear) and found good agreement with analytical solutions. However, the irregular wave test comprised the superposition of only three different wave frequencies, providing a very coarse representation of a full spectrum.

The aim of this study was to validate the NEWRANS model's capabilities in generating bimodal seas through comparison of simulated waves with experimental data. The long-duration simulations required allowed the effects of wave reflection to be analyzed through observation of increases in water level. This paper begins with a brief introduction of the model and a more extensive overview of the theory and application of the two wave generation methods. Next, the model setup and the data used for validation are introduced and explained. Results from the comparisons between the model results and experimental data are presented, along with a discussion of the role of relative water depth and beach slopes in wave generation. This is followed by concluding remarks.

2. Numerical model and wave generation methods

2.1. Model formulation

In this work, a two-dimensional (2D) numerical flume was used to investigate two wave generation procedures. The numerical flume, NEWRANS (Lin and Liu, 1998), was based on the Reynolds-averaged Navier-Stokes (RANS) equations and uses a volume-of-fluid capturing scheme to allow for accurate simulation of large deformations during wave breaking and overtopping. NEWRANS calculates the free surface and general turbulent flow by decomposing the flow in the model into the mean flow and turbulent fluctuations. As a result, a set of equations is determined for the mean flow containing contributions from the fluctuating turbulent flow. To describe the effects of these fluctuations on the mean flow, the model is coupled with a second-order k-ε turbulence closure model.

For turbulent flow, both the velocity field and pressure field are split into mean components ($\overline{u}_i$ and $\overline{p}$) and turbulent fluctuations (u_i' and p'). Thus, $u_i = \overline{u}_i + u_i'$ and $p = \overline{p} + p'$. Once substituted into the Navier-Stokes equations, the mean flow is governed by the RANS equations:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_i \frac{\partial \overline{u}_i}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + g_i + \frac{1}{\rho}\frac{\partial \overline{\tau}_{ij}}{\partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \tag{2}$$

where the subscripts i and j are equal to 1 or 2, representing the two directions in the Cartesian coordinate system; u_i is the ith component of the velocity vector; ρ is the density of the fluid; g_i is the ith component of the gravitational acceleration; t is the time; and $\overline{\tau}_{ij}$ is the viscous stress tensor of the mean flow. The Reynolds stress is modeled by an algebraic nonlinear Reynolds stress model (Shih et al., 1996):

$$\begin{aligned}\rho\overline{u_i' u_j'} = {} & \frac{2}{3}pk\delta_{ij} - C_{\mathrm{d}}\rho\frac{k^2}{\varepsilon}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \\ & \rho\frac{k^3}{\varepsilon^2}C_1\left(\frac{\partial \overline{u}_i}{\partial x_l}\frac{\partial \overline{u}_l}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_l}\frac{\partial \overline{u}_l}{\partial x_i} - \frac{2}{3}\frac{\partial \overline{u}_l}{\partial x_m}\frac{\partial \overline{u}_m}{\partial x_l}\delta_{ij}\right) + \\ & C_2\left(\frac{\partial \overline{u}_i}{\partial x_m}\frac{\partial \overline{u}_j}{\partial x_m} - \frac{1}{3}\frac{\partial \overline{u}_l}{\partial x_m}\frac{\partial \overline{u}_l}{\partial x_m}\delta_{ij}\right) + \\ & C_3\left(\frac{\partial \overline{u}_m}{\partial x_i}\frac{\partial \overline{u}_m}{\partial x_j} - \frac{1}{3}\frac{\partial \overline{u}_l}{\partial x_m}\frac{\partial \overline{u}_l}{\partial x_m}\delta_{ij}\right)\end{aligned} \tag{3}$$

where C_{d}, C_1, C_2, and C_3 are empirical coefficients; δ_{ij} is the Kronecker delta (equal to 1 if $i = j$, and 0 if $i \neq j$); k is the turbulent kinetic energy, where $k = u_i' u_i'/2$; ε is the dissipation rate of turbulent kinetic energy, and $\varepsilon = \nu\overline{(\partial u_i'/\partial x_j)^2}$, where ν is the molecular kinematic viscosity: $\nu = \mu/\rho$, where μ is the dynamic viscosity; and l and m follow the Einstein tensor notation for summation. Lin and Liu (1998) determined the coefficients in Eq. (3) as follows: