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Revisiting study on Boussinesq modeling of wave transformation over various reef profiles

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Abstract: To better understand the complex process of wave transformation and associated hydrodynamics over various fringing reef profiles, numerical experiments were conducted with a one-dimensional (1D) Boussinesq wave model. The model is based on higher-order Boussinesq equations and a higher-accuracy finite difference method. The dominant energy dissipation in the surf zone, wave breaking, and bottom friction were considered by use of the eddy viscosity concept and quadratic bottom friction law, respectively. Numerical simulation was conducted for a wide range of wave conditions and reef profiles. Good overall agreement between the computed results and the measurements shows that this model is capable of describing wave processes in the fringing reef environment. Numerical experiments were also conducted to track the source of underestimation of setup for highly nonlinear waves. Linear properties (including dispersion and shoaling) are found to contribute little to the underestimation; the low accuracy in nonlinearity and the ad hoc method for treating wave breaking may be the reason for the problem.

Key words: *wave-induced setup; wave-induced setdown; Boussinesq model; wave breaking; reef*

1 Introduction

Fringing reefs are commonly found in the tropics and subtropics. A typical fringing reef is characterized by a composite seaward sloping reef face with an abrupt transition to an inshore shallow reef platform extending towards the shoreline. This specific bathymetry significantly modifies the wave transformation process and makes the associated hydrodynamics far more complex than on normal coastal beaches in many respects (Demirbilek and Nwogu 2007; Nwogu and Demirbilek 2010; Monismith et al. 2010; Yao et al. 2012). Intense wave breaking typically occurs on the reef face, enhancing the oxygen content and circulation that support the coral ecosystem (Achituv and Dubinsky 1990). Also, by dissipating wave energy, fringing reefs provide protection for the shore and tropical shelter

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islands from the flood hazards induced by tsunamis, hurricanes, and high surf events (Roeber et al. 2000). However, wave-induced setup and low frequency waves emerging from the surf zone can induce extensive flooding with large and variable wave overwash, especially under high-energy wave conditions (Demirbilek and Nwogu 2007). Due to its profound geological, ecological, and environmental significance, there is an increasing amount of interest in investigating the hydrodynamic processes associated with waves occurring on fringing coral reefs (Demirbilek and Nwogu 2007; Massel and Gourlay 2000; Nwogu and Demirbilek 2010; Monismith et al. 2010; Yao et al. 2012).

Numerical simulations are widely used to predict the significant wave transformations over such bathymetry. However, numerical modeling of nearshore reef hydrodynamics is a challenging task owing to the steep reef face slopes, large and spatially-varied roughness of the reef bottom, and complicated reef profile configurations (Massel and Gourlay 2000; Yao et al. 2012). The most advanced Navier-Stokes models (Lara et al. 2008; Huang and Lin 2012; Hu et al. 2012) are well suited for the purpose because they have shown satisfactory accuracy in describing wave transformation before, during, and after wave breaking, even in a complicated nearshore environment. However, for the present, they remain an expensively computational approach, especially when the fine grid and long-term simulation are needed in a reef environment. Alternatively, numerical models built upon Boussinesq equations have the potential to handle these nearshore processes with the characteristics of nonlinearity and frequency dispersion, which play a key role in accurately describing wave motions in a reef environment (Yao et al. 2012; Shermert et al. 2011). The prevailing Boussinesq model is more computationally efficient for large spatial and temporal scales, in contrast to the expensive Navier-Stokes approaches. Detailed reviews of Boussinesq equations have been provided by Kirby (2002) and Madsen and Fuhrman (2010).

To the best of our knowledge, the published numerical results for waves and associated hydrodynamics from Boussinesq models are still limited. Skotner and Apelt (1999) developed a Boussinesq model based on the weakly nonlinear equations derived by Nwogu (1993) to compute the mean water level (MWL) of regular waves propagating onto a submerged coral reef, and the numerical results were compared against their measurements. With the model, they accurately computed the setdown and setup of regular waves of small incident wave heights, but there was a tendency to underestimate the wave setup as the incident wave height increased. Demirbilek and Nwogu (2007) and Nwogu and Demirbilek (2010) used variant forms of Nwogu’s (1993) Boussinesq equations to numerically investigate the infragravity motions in the wave runup process over fringing coral reefs. The computed wave height, MWL, time series of surface elevation, runup, and energy spectrum were compared against the experimental data. It was found that the developed model was able to describe complex changes of the wave spectrum over the reef flat due to nonlinear wave-wave interactions and wave breaking as well as wave runup at the shoreline. Yao et al. (2012) used the Boussinesq