Coastal Engineering 109 (2016) 9–19

Contents lists available at ScienceDirect

Coastal Engineering

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

Modeling wave processes over fringing reefs with an excavation pit

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 24 October 2015
Accepted 21 November 2015
Available online 23 December 2015

Keywords:
Wave transformation
Infragravity waves
Boussinesq equations
Fringing reef
Excavation pit

ABSTRACT

The excavation of reef-flat sand and aggregate for engineering projects is a common practice on atoll islands, with attendant coastal management and hazard mitigation issues. To assess the impact of reef-flat excavation pits on wave transformation, a numerical study is carried out based on one-dimensional weakly dispersive, highly non-linear Boussinesq equations. Model simulations are compared to field observations made at Majuro Atoll, Republic of the Marshall Islands (Ford et al., 2013a), at a 75-m-wide fringing reef flat with a 17-m-wide, 4-m-deep excavation pit and at an adjacent unmodified reef flat. With a calibrated empirical breaking model and uniform friction coefficient, the numerical model is shown to satisfactorily reproduce the observed sea and swell (SS) and infragravity (IG) frequency band wave heights for a moderate amplitude wave event. By removing the lateral morphological differences of the field experiment, the model shows that an excavation pit reduces/increases shoreline IG/SS wave heights compared to numerical tests without the pit, in qualitative agreement with Ford et al. (2013a). An EOF analysis demonstrates that the reduction in IG wave heights is associated with modifications of the ¼ and ¾ wavelength IG standing modes across the reef caused by the pit. Model tests are used to evaluate the effects of cross-reef pit location and width on wave transformation. Shoreline wave heights are least affected by a pit located near the reef crest, and both SS and IG wave heights increase as the pit location moves shoreward. Shoreline wave heights are an increasing function of pit width as the increase in SS wave height exceeds the decrease in IG wave height produced by the pit. The effects of incident wave height and spectral bandwidth are also examined for the reef with and without pit. It is found that both shoreline SS and IG wave heights increase with the increasing incident wave height for both profiles. The numerical model results also demonstrate that the shoreline response is sensitive to the bandwidth of the incident wave spectrum, and larger IG shoreline wave heights are excited for narrower spectral bandwidths until wave reflection limits the forcing.

1. Introduction

Dredging and excavating reef-flat sand and aggregate for engineering projects within atoll settings has the potential to impact a range of nearshore dynamics that include wave transformation and sediment transport. Densely populated atoll islands such as Majuro in the Republic of the Marshall Islands (RMI) are now faced with the challenge of finding sustainable sources of aggregate and armor stone to maintain and develop coastal protections along the heavily urbanized and highly engineered shorelines. The low-lying atolls are vulnerable to wave-driven inundation during extreme wave events (Hoeke et al., 2013; Merrifield et al., 2014; Terry and Chui, 2012; Yamano et al., 2007); hence, it is important to assess the effects of excavation on coastal management and hazard mitigation. It has been well observed (e.g., Brander et al., 2004; Hardy and Young, 1996; Lugo-Fernandez et al., 1998; Péquignet et al., 2009; Pomeroy et al., 2012) that a majority of energy within the Sea and Swell (SS) frequency band (defined here as between 0.04 and 0.4 Hz) is dissipated due to wave breaking near the reef crest or edge. Additional SS energy may be dissipated by bottom friction and/or turbulent bore dissipation during the wave transformation over the reef flat, and the shoreline run-up and overwash frequently are found to be dominated by wave energy within the infragravity (IG) frequency band (between 0.001 and 0.04 Hz). Previous studies (e.g., Péquignet et al., 2014; Pomeroy et al., 2012; Van Dongeren et al., 2013) have confirmed that the wave group effect resulting in the time variation of the break point is the dominant mechanism for the generation of IG waves over steep fringing reefs. Both field observations (e.g., Péquignet et al., 2009) and laboratory experiments (e.g., Nwogu and Demirbilek, 2010) also have reported that under certain wave conditions, especially for large wave events, the IG energy level could be further amplified due to the excitation of reef-flat normal modes. Reef-flat excavation causes significant and often permanent change to reef-flat morphology. The implications of such reef-flat modification on SS and IG waves at the

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http://dx.doi.org/10.1016/j.coastaleng.2015.11.009
0378-3839/

shoreline, and potential impacts on wave-driven coastal inundation are poorly understood.

A variety of studies (Benedet and List, 2008; Benedet et al., 2013; Lopes et al., 2009; Work et al., 2004 and many others) have examined the impacts of dredging on nearshore wave processes and the subsequent shoreline response for sandy beaches. While sandy beaches may morphodynamically adjust to the dredging over time, the excavation pit on the reef flat is, however, a more permanent and static feature. Few studies have examined the impacts of such anthropogenic modifications to the reef flat on the nearshore hydrodynamics. Ford et al. (2013a) (hereinafter referred to as FBM13) examined field observations of wave transformation across a reef-flat excavation pit and the potential impacts for coastal management at Majuro Atoll. Experiments were conducted on two neighboring cross-shore transects of a reef flat (with comparable width, topography, and incident wave energy), one modified by the excavation of a 17-m-wide, 4-m-deep pit, and the other unmodified. They observed that the shoreline with the excavation pit received slightly smaller wave heights (~8% smaller) than those recorded at the nearby unmodified transect. They concluded that the net decrease in wave height at the shoreline was due to a slight increase in wave height from the sea and swell (SS) frequency band, and a larger decrease in wave height from the infragravity (IG) band. Payo and Muñoz-Pérez (2013) raised a number of concerns about the hydrodynamic interpretations and management implications presented in FBM13 that were addressed in Ford et al. (2013b). Payo and Muñoz-Pérez (2013) suggested that nonlinear energy transfer between SS and IG waves offered an alternative explanation for wave energy changes across the reef flat described by FBM13. They further noted that alongshore variations in incident SS wave energy between the excavated and unmodified reef flat and lateral variations in the profiles required further investigation. While our one-dimensional modeling study does not address alongshore dynamics, we address the effects of lateral variations in profiles and incident wave heights in the field data by considering artificially mined and filled in profiles subject to the same incident conditions. In view of the complex physical forcing and reef morphology at natural reef sites, it is difficult to resolve these issues with observations alone; thus, we carry out a numerical modeling study to investigate wave transformation over fringing reefs under a variety of controlled conditions representative of the field observations of FBM13.

Over decades, wave transformation over coral reefs has been described by analytical models using one-dimensional horizontal (1DH) idealized reef profiles (a typical idealized reef profile has a plane sloping reef face and a horizontal platform reef flat). Conventionally, following studies of wave-driven alongshore flows and wave-induced setup/setdown on beaches, analytical solutions based on the radiation stress concept introduced by Longuet-Higgins and Stewart (1964) have been used to study 1DH reef hydrodynamics (e.g., Becker et al., 2014; Gourlay, 1996; Tait, 1972; Vetter et al., 2010). In recent years, the effects of complex bathymetry and different forcing mechanisms have been modeled by using two-dimensional horizontal (2DH) and three-dimensional (3D) models to study both the waves and the mean flows, where typically the radiation stress concept is used to couple the waves and the mean flows (e.g., Douillet et al., 2001; Kraines et al., 1998, 1999; Lowe et al., 2009; Pomeroy et al., 2012; Van Dongeren et al., 2013). Among those models, we apply a computationally efficient and phased-resolving model based on the Boussinesq-type equations. This depth-integrated modeling approach employs a polynomial approximation to the vertical profile of velocity field, thereby reducing the dimensions of a three-dimensional problem by one. It has been shown to account for both nonlinear and dispersive effects for intermediate water levels. One of the pioneering studies of extending the Boussinesq-type model to coral reef studies was conducted by Skotner and Apelt (1999), who studied wave setup induced by monochromatic waves propagating onto a submerged near-horizontal fringing coral reef with a relatively steep reef face. They found that the Boussinesq-type model could simulate satisfactorily the patterns of mean water level for 1DH reef profiles subjected to small waves. Nwogu and Demirbilek (2010) used a different set of Boussinesq equations to study spectral waves transforming over a reef profile that is similar to the one used by Skotner and Apelt (1999) and confirmed the ability of their Boussinesq model to describe the variation of significant wave height, the mean water level across the reef profile, the evolution of the wave spectrum, the generation of infragravity oscillations, and shoreline run-up. Recently, Roeber et al. (2010) and Roeber and Cheung (2012) employed a shock-capturing Boussinesq-type model to simulate wave transformation over fringing reefs. They showed good model comparison to laboratory data of solitary wave transformation on a 1DH reef. Their model was applied to a field site in Hawaii, and the transformation of irregular incident waves, wave-induced setup, and development of sub and super-harmonics were reproduced. More recently, Shimozono et al. (2015) implemented a Boussinesq model to simulate wave transformation over shallow reefs and used the model to assess the dominant dynamical contributions to field measurements of extreme run-up at Eastern Samar from super typhoon Haiyan.

FBM13 conclude that a quantitative assessment of the impact of pit width, depth, and position on reef flats of varying widths and in different physical settings may be required to better understand impacts of reef-flat excavation on hydrodynamic processes. This study implements and validates a weakly dispersive and fully nonlinear depth-integrated Boussinesq-type model (Lynett and Liu, 2008) to help interpret some findings from the field experiment of FBM13 and assess the effects of pit geometry on shoreline wave height. The present model has proven to be capable of simulating a wide range of long and short wave problems (Hsiao et al., 2005; Lynett, 2006; Lynett et al., 2002), and it also has been applied successfully by Yao et al. (2012) for wave transformation over a 1DH idealized laboratory reef under various incident wave conditions. After validating the model using a moderate wave event from FBM13 for both the excavated reef flat and the unmodified reef flat, the model is used to address the following: (1) To what degree does the morphological difference between the two neighboring cross-reef transects affect the conclusions of FBM13? (2) How does the shoreline energy within the SS and IG frequency bands respond to variations in the pit position, pit size, incident wave height, and incident spectral bandwidth?

This paper is organized as follows. In Section 2, the mathematical formulation, numerical scheme, boundary conditions, and energy dissipation sub-models are described. In Section 3, numerical simulations are calibrated using a representative field scenario to show the robustness of the model. In Section 4, the validated model is applied to investigate both SS and IG wave transformations over the reef flat under a series of pit/reef configurations and incident wave conditions. Discussions on the findings in this study and main conclusions are given in Section 5.

2. The numerical model

2.1. Governing equations and numerical scheme

Let the x-coordinate point in the direction of wave propagation with its origin at the toe of the reef face and the z-coordinate point upward with its origin at the still water level. The 1DH equations in conservative form are expressed as

$$\frac{\partial H}{\partial t} + \frac{\partial H u_\alpha}{\partial x} + D^c = 0 \tag{1}$$

$$\frac{\partial H u_\alpha}{\partial t} + \frac{\partial H u_\alpha^2}{\partial x} + gH\frac{\partial \eta}{\partial x} + gHD^x + u_\alpha D^c + R_f - R_b = 0 \tag{2}$$

where $H = h + \eta$ is the total water depth, η is the water surface elevation, h is the still water depth, g is the gravitational acceleration, and $u_\alpha(x, z_\alpha(x, t))$ is a reference horizontal velocity in the x-direction at a