Modeling Wave Processes over Fringing Reefs with an Excavation Pit

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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 nonlinear 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 $\frac{1}{4}$ and $\frac{3}{4}$ 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.

KEYWORDS

Wave transformation, infragravity waves, Boussinesq equations, fringing reef, excavation pit.

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 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., Gourlay 1996; Tait, 1972; Vetter et al., 2010; Becker et al., 2014). 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 runup. Recently, Roeber et al. (2010), 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 concludes 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 et al., 2002; Lynett, 2006), 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? and (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

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

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

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 specified depth of $z_\alpha(x, t) = -0.53lh$ (Nwogu, 1993). In (1) and (2), D^c and D^x are the second-order terms describing nonlinear dispersion. The complete derivation and the expressions for D^c and D^x can be found in Kim et al. (2009). R_f and R_b are ad-hoc dissipative terms accounting for bottom friction and wave breaking, respectively. Sub-models for R_b and R_f will be discussed in Section 2.2 below.

The numerical solver for the above equations has been described in detail in Kim et al. (2009). A third-order Adams–Bashforth predictor and a fourth-order Adams–Moulton corrector scheme are used for time marching. For the spatial discretization, a shock-capturing FV-based approach is used. The leading order terms are solved with the fourth-order MUSCL-TVD (monotone upstream-centered scheme for conservation laws–total variation diminishing) scheme, while a cell-averaged finite volume method is implemented for the second-order terms. Compared to traditional Finite Difference (FD)-based methods, FV formulations in conservative form are generally very stable and accurate, and thus are appropriate for the present problem, which may have complex flow conditions and rapid bottom variations. The numerical scheme is accurate to $O(\Delta t^4)$ in time and $O(\Delta x^4)$ or $O(\Delta x^2 \mu^2)$ in space, where μ is the wavelength scaling parameter defined by $\mu = h/L$, where L is the incident wave length.

2.2 Sub-models of Wave Breaking and Bottom Friction

It is well known that the depth-integrated Boussinesq-type models cannot describe the overturning of a free surface and the detailed breaking process. Hence several empirical models have been proposed for wave breaking in surf and swash zones. The most common approach is to add an ad-hoc dissipation sub-model to the momentum equation. This approach requires an energy dissipation mechanism and a trigger mechanism for the initiation of wave breaking. In this study, the eddy viscosity-type formulation proposed in Kennedy et al. (2000) is used to model the wave energy dissipation caused by wave breaking. It has been proven that the adopted wave-breaking model can adequately predict the energy dissipation for both spilling and

plunging breakers (Kennedy et al., 2000; Lynett, 2006; Roeber et al., 2010; Yao et al., 2012). For completeness, the breaking model is described in Appendix A. The parameter δ in Eq. (A.2) is essential for energy dissipation, and values of δ ranging from 1.4 to 10 have been used in the published literature for beaches (Kennedy et al., 2000; Lynett, 2006; Lynett and Liu, 2008). It is necessary to recalibrate δ for the reef profiles in this study (see Section 3.2). For the trigger-related parameters in Eq. (A.4), the following values suggested by Lynett and Liu (2008) are used in the model

$$\eta_t^{(I)} = \alpha_1 \sqrt{gH}; \quad \eta_t^{(F)} = \alpha_2 \sqrt{gH}; \quad T^* = \alpha_3 \sqrt{H/g} \quad (3)$$

where $\alpha_1 = 0.65$, $\alpha_2 = 0.08$, $\alpha_3 = 8$.

The bottom friction term R_f is calculated by the quadratic friction law

$$R_f = f u_b |u_b| \quad (4)$$

where u_b is the bottom velocity that is evaluated from u_α , and f is an empirical friction coefficient. Here, u_b does not include contributions due to undertow. The present numerical model uses the Manning formula to parameterize the friction coefficient according to

$$f = \frac{gn^2}{H^{1/3}} \quad (5)$$

Values of the Manning roughness coefficient, n , ranging from 0.01 to 0.1 may be found in the published literature (e.g., Akan, 2006) for commonly used surface materials.

2.3 Boundary and Initial Conditions

Two types of numerical boundary conditions may be applied at the ends of the computational domain: the reflective (or no-flux) boundary condition and the radiation (or open) boundary condition. For the latter, sponge layers are frequently used to effectively damp the energy of outgoing waves. The sponge layer typically is applied in a manner similar to that recommended by Kirby et al. (1998). The moving boundary at the shoreline may be simulated using an extrapolating boundary algorithm (Lynett et al., 2002). Internal source methods are frequently employed as efficient and accurate methods for numerical wave generation. The method using a distributed source function in the continuity equation as proposed by Wei et al. (1999) is adopted in this study. The initial condition assumes no wave or current motion in the computational domain.

3 MODEL VALIDATION

3.1 Description of Field Measurements

The area studied by FBM13 (see Fig. 1) is located at Majuro Atoll, RMI. The mixed tidal regime at Majuro has a typical spring tide range of 1.6 m. The most highly urbanized areas are located within 3 m of mean sea level, and large wave events have contributed to coastal inundation (Hoeke et al., 2013; Merrifield et al., 2014). Field observations were made at an existing excavation site on the south facing shoreline of Majuro Atoll. The shoreline is characterized by a mix of revetment and unarmoured section of reclamation. The revetment and beach sit atop a raised conglomerate platform and the transition from the platform to the reef flat is sharp. The reef flat is approximately 70

to 80 m wide and is largely exposed at low tide. There are sporadic fragments of branching corals on the reef flat. The reef crest is relatively flat without the presence of a raised algal rim, and the seaward reef face slope is estimated to be 1:5 with a series of spur and grooves. The inner and central reef flats are largely devoid of living coral. The reef flat within the study site contains a number of excavation pits ranging in cross-shore width from 15 to 35 m. The pits are of variable depth but typically between 4 and 5 m deep. The walls of the pits are nearly vertical, and both the walls and the bottom of the pits have been colonized by corals.

Two deployments took place during June and July 2011 as shown in Fig. 1. The first experiment took place during 4-16 June 2011 and involved the deployment of four pressure sensors along a cross-shore transect with a 17-m wide, 4-m deep pit near the mid-reef (Line A). The four instrument positions were near the shoreline (S1), on the reef flat landward of the pit (S2), on the pit bed (S3), and near the reef crest (S4). A second deployment took place between 16 June and 16 July 2011. Instruments were recovered from S2 and S4 for the reef with excavation pit, and redeployed at S5 (shoreline) and S6 (mid-reef flat) along an unmodified reef nearby (Line B). For comparison purposes, S5/S6 of Line B were designed to be equal in distance from the reef edge with S1/S3 of Line A. These two neighboring cross-shore transects were also considered to be comparable in view of reef-flat morphology, and incident wave energy, although the shoreline behind the platform for the reef with pit is steeper than that of the unmodified reef (see also Fig. 2). The pressure sensor at each instrument position sampled at 2 Hz for 21580 seconds every 6 hours. Offshore wave conditions were measured throughout the deployments by a directional CDIP wave buoy located

approximately 5 km E-NE from the deployment site. For more details of the field observations, see FBM13.

3.2 Numerical Settings

Referring to the 1DH computational domain (Fig. 2), the location of the instruments and morphology of the reefs were designed to reproduce the field observations. The reef profiles (Line A: pit transect, and Line B: unmodified transect) follow those in FBM13 (see their Figure 2). Since we lack wave and bathymetry measurements between the offshore wave buoy and the reef in this study, we extend the reef-face slope seaward by 700 m and the slope is truncated and replaced with a flat bottom.

We remark that this numerical model also has been used to simulate field observations across two reefs in the Republic of the Marshall Islands. That modeling effort for a reef fronting the College of the Marshall Islands (CMI) on Majuro, and a reef on the northern tip of Kwajalein atoll (Roi-Namur) was calibrated with sensor arrays that had greater spatial resolution on the reef flat and a sensor on the reef face providing incident wave conditions (Yao et al., 2014) and reproduced the observed shoreline SS and IG waves satisfactorily. Experience gained from Yao et al. (2014) informed the calibration performed here where the observations are sparse (see Section 3.3). In addition, model tests that varied the offshore truncation depth between 5 and 15 meters did not give notable differences in the results; hence an offshore water depth of 10 m (where the incident waves are imposed in the model) was used.

By assuming normal incidence (which is a reasonable assumption for the steep reef

studied here), the incident wave field is assumed to be generated approximately 250 m from the reef-face slope using the aforementioned internal source method (Wei et al. (1999)). In the absence of reef face data, the standard TM spectrum, which is derived from the JONSWAP spectrum with a shallow water correction, is used in this study to generate the incident wave spectra. The incident time series of the free surface elevation was obtained assuming random phases among the spectral components. Dissipative sponge layers, typically of a width of 1.25 times the incident (peak) wavelength (L), are placed at the seaward boundary to ensure that the outgoing waves are absorbed satisfactorily. The adopted model combined with current damping layer setting ($W=1.25L$) has been proven to work reasonably well in both reproducing the laboratory reef of Yao et al. (2012) and natural reefs of Yao et al. (2014). The numerical results did not vary significantly for further tests with $W>1.25L$. For the shoreward boundary, the extrapolating moving boundary algorithm proposed by Lynett et al. (2002) is used to describe wave runup and rundown processes near the coastline, and a 'solid wall' is placed behind the platform to confine the possible overtopping in the domain.

Numerical wave gauges are placed at the same positions as their counterparts in the field observations (see Table 1 for the detailed positions). The initial condition assumes no wave or current motion in the computational domain, thus the initial 100 wave cycles for spectral waves are not used in the data analysis to reduce the transient effect. A grid size approximating 1.0 m with a Courant number of 0.35 as suggested by Lynett and Liu (2008) is found to be sufficient to discretize the computational domain and maintain the numerical stability in this study. Finally, a 4-point filter is used to reduce the curvature of the rapidly varying bathymetry, especially around the

walls of the pit, since the derivatives of the bathymetry are included in the higher-order terms of the Boussinesq equations.

Yao et al. (2012) found that δ in the breaking model is a key parameter for modeling wave-induced setup on an idealized laboratory fringing reef flat. However, for wave transformation on natural reef sites, Yao et al. (2014) found that numerical tests were less sensitive to δ than the bottom friction, thus a reasonable value of $\delta=6$ following Yao et al. (2012) was used in the subsequent simulations. Previous numerical work (e.g., Van Dongeren et al., 2013) using other models suggested that frictional dissipation on the reef flat was significant for both shortwave transformations and low-frequency wave motions. The friction coefficient was also found to be a sensitive parameter in the present model. By calibrating the same model against the wave measurements at a separate site at the College of the Marshall Islands (CMI) on Majuro for which reef face measurements were available, Yao et al. (2014) has found that a uniform Manning coefficient is sufficient to represent the reef surface roughness. Since we lack the reef face wave measurements for the studied reef, the friction coefficient $n = 0.015$ calibrated based on the CMI profile in Yao et al. (2014) is used here due to the proximity of the two sites and the similar reef surface features. This roughness value is equivalent to that of open channels constructed from some commonly used surface materials such as cement, wood, concrete, etc. (Akan, 2006).

3.3 Comparison of Numerical Results and Field Observations

To calibrate the present numerical model, we select a 6-hour pressure record from a moderate wave event during the second deployment. While the first deployment had

additional sensors on the reef flat, no significant shoreline energy was observed during the first deployment. During the second deployment, enhanced shoreline energy was observed during two wave events, and we use data from the second wave event of the second deployment to calibrate the model. This record from 14 July 2011 had a significant wave height of $H_s = 1.42\text{ m}$ and peak wave period of $T_p = 13.8\text{ sec}$ measured at the offshore buoy. The estimated tidal level on the reef flat was approximately $h_r = 0.40\text{ m}$ based on the mid-reef sensor measurements. As reef face observations were not available, the model was calibrated by varying the incident significant wave height in the TMA spectrum and seeking a global best agreement between the observed and predicted SS and IG wave heights at the mid-reef (S3/S6) and shoreline locations (S1/S5) for both the reef with a pit (Line A) and the unmodified reef (Line B). Using the Manning friction coefficient obtained from the CMI calibration ($n = 0.015$) of Yao et al. (2014), a calibrated $H_s = 0.89\text{ m}$ is obtained at the wave generation location in the TMA input spectrum. The numerical model then was run for 6 hours using the numerical setting described in Section 3.2.

Comparisons of the measured and simulated wave spectra (obtained by fast Fourier transform of a 2500 second record smoothed over 11 adjacent frequency bands) are presented for the unmodified reef (Fig. 3) and for the reef with a pit (Fig. 4). The total, SS and IG wave height are estimated as four times the standard deviation of the free surface elevation within total (0.001-0.4 Hz), SS (0.04-0.4 Hz) and IG (0.001-0.04 Hz) bands, respectively. Overall the numerical model satisfactorily reproduces the cross-shore changes in SS and IG wave heights. Some differences, however, in IG wave height (Fig. 3) or SS wave height (Fig. 4) still exist between the model and the observed spectra closest to the shoreline. The mismatch between the model and the observations

is partly due to the model calibrations (we seek a global best agreement between predictions and observations for both Lines A and B thus the agreement may not be best for an individual profile) and partly due to the model inputs (e.g., we lack detailed observations of the reef face forcing and bathymetry). When examining the cross-reef transformation of the incident waves, we found in the model that most of the surf zone dissipation occurs near the reef crest. At the mid-reef flat sensors (S3 for Line A and S6 for Line B), a considerable amount of SS energy around the peak frequency (around 0.07 Hz) still exists as shown in both Figs. 3 and 4. As the SS waves propagate further shoreward, they are dissipated by friction on the reef flat, and the remaining SS energy around the peak frequency is small at the shoreline locations (S1 for Line A and S5 for Line B). In contrast, for both Lines A and B, the IG energy increases shoreward from the mid-reef to the shoreline, and provides a significant contribution to the shoreline energy, consistent with previous studies (e.g., Nwogu and Demirbilek, 2010; Pequignet et al., 2009; Pequignet et al., 2014; Pomeroy et al., 2012; Torres-Freyermuth et al., 2012).

We remark that in this study the model simulations will be used to determine the effects of pit location and size, and incident wave conditions on shoreline wave heights for a moderate wave event. While the above calibrated model results are qualitatively consistent with the observations of FBM13 (see also Section 4.1 below), they are not accurate enough to assess the small (8%) differences in total wave heights between Lines A and B as observed by FBM13. Additionally, the present simulations are unable to reproduce the shoreline observations during an overwash event during the first wave event of the second deployment (29 June 2011, see Section 4.3 below), which is attributed to uncertainties in the bathymetry and incident wave conditions.

4 MODEL APPLICATIONS

In this section, we apply the numerical model to examine a series of factors (reef morphology, pit location and size, incident wave height, and incident TMA spectral band width) that may affect the wave transformation across the reef based on the calibrated wave event (i.e., $H_s = 0.89\text{ m}$, $T_p = 13.8\text{ sec}$, $h_r = 0.40\text{ m}$).

4.1 Morphological Effects

Payo and Muñoz-Pérez (2013) suggested that the lateral variations in incident wave height as well as the reflection due to the difference in shoreline slope between the two transects might explain the difference in IG energy at the shoreline observed by FBM13. To address the potential effects of shoreline geometry on both SS and IG wave transformation over the pit, the numerical model was re-run for the field profile (Line A) by artificially filling in the pit on the excavated transect (Line A_{np}) while the incident waves and model settings were kept unaltered. In this way, the effects of possible variations in shoreline profiles as well as potentially differing roughness between the two field profiles are removed, and the effect of the pit on the wave transformation process is isolated. In addition, we consider the transformation of waves over the unmodified profile (Line B), and a new profile created by artificially excavating a pit on the unmodified profile (Line B_p) for the same incident waves and model settings.

The cross-reef transformation of the SS and IG wave heights are presented in Fig. 5 for the four profiles described above, and the respective shoreline wave heights (the shoreline is defined as $x=0$) in Table 2. In all cases, the SS band wave height, H_s^{SS} and the total wave height H_s^a (not shown) on the reef face through the break zone ($75 \text{ m} < x < 100 \text{ m}$) are nearly identical. On the reef flat ($0 \text{ m} < x < 75 \text{ m}$), the wave heights in the SS band, H_s^{SS} , decay shoreward for the profiles without pits (Figs. 5a and 5c, Lines A_{np} and B , respectively). For the profiles with pits (Figs. 5a and 5c, Lines A and B_p , respectively), an analysis of the incoming and outgoing linear fluxes (Sheremet et al., 2002) shows that some reflection from the seaward edge of the pit occurs ($38 \text{ m} < x < 60 \text{ m}$) for the SS band and smaller H_s^{SS} are observed over the pit ($21 \text{ m} < x < 38 \text{ m}$), than over the corresponding profiles without pits (Lines A_{np} and B) due to deshoaling. SS wave heights then decrease to the shoreline due to wave breaking near the shoreline and bottom friction ($0 \text{ m} < x < 21 \text{ m}$).

The IG wave heights H_s^{IG} are small offshore and shoaling in the IG band is observed on the reef face ($75 \text{ m} < x < 100 \text{ m}$, Figs. 5b,d). While the incident waves are generated from the TMA spectrum that does not include IG energy, we find that the numerical solution has adjusted to the dynamics by $x \approx 200 \text{ m}$ such that the envelope of the free surface elevation in the SS band is negatively correlated with the IG band free surface elevation consistent with a forced difference interaction (bound wave). In all cases, the IG wave heights increase across the reef flat and are comparable to the SS wave heights at the shoreline ($x=0 \text{ m}$). A cross-covariance analysis between the envelope of the SS free surface elevation computed as the magnitude of the analytic signal obtained using a Hilbert transform, and the IG band elevation across the reef (not

shown) is consistent (positively correlated) with the nonlinear transfer of energy from the SS band to the IG band through break point forcing (e.g., Janssen et al., 2003, Pomeroy et al., 2012). Inshore of $x=0$ m, the effects of the differing profiles are evident on the IG wave heights with some shoaling and subsequent dissipation observed for Lines B and B_p (Fig. 5d)and with some shoaling, dissipation and reflection observed for Lines A and A_{np} (Fig. 5b).

Removing the morphological differences of the profiles in the numerical simulations by filling in the pit (Line A_{np} , Figs. 5a,b) or by artificially mining a pit (Line B_p , Figs.5c,d) demonstrates that the effect of the pit is to increase the shoreline SS waveheights and to decrease the shoreline IG waveheights (see Table 2), consistent with the findings of FBM13. As mentioned above, the numerical simulations are not accurate enough to simulate the small differences in total wave height between Line A and Line B as observed in FBM13. Accounting for the lateral differences in bathymetry, the total shoreline wave heights H_s^a predicted from the model are similar for the profiles with and without pits (i.e., 0.50/0.51 m for Line B/ B_p and 0.46/0.48 m for Line A_{np} /A, see also Table 2).

The decrease in shoreline IG wave energy in the numerical simulations for the profiles with the pit appears to support the argument of FBM13 that the existence of the pit disrupts a standing wave pattern on the reef flat. To test this argument with the present high spatial resolution numerical simulations, an empirical orthogonal function (EOF) analysis of the simulated IG free surface elevations was carried out for the model run for the reef with a pit (Line A), and for the same bathymetric profile with the pit removed (Line A_{np}). In Fig. 6, the spatial structure (Fig. 6a) and spectra of the

associated time amplitudes (Fig. 6b) are presented for the first two EOF modes for $0 < x < 75$ m. The most energetic mode that accounts for 53% and 54% of the IG surface elevation variance for Lines A_{np} and A, respectively, has a spatial and temporal structure that is consistent with the excitation of a $\frac{1}{4}$ wavelength mode on the reef flat. For an idealized step reef, the spatial structure of the gravest mode is $\cos(\pi x / 2L)$, and the gravest normal mode period is $T_0 = 4L_r / \sqrt{gh}$ where L_r is the reef length, and h is the total water level on the reef flat. To compare with the EOF analysis here, we take $L_r \approx 75$ m and $h \approx 0.5$ m (tide + setup) yielding $T_0 \approx 140$ sec for the idealized step profile, which is consistent with spectral peak in the EOF mode 0 time amplitude near $T \approx 170$ sec ($f \approx 0.006$ Hz in Fig. 6b) for the model bathymetry. The inclusion of a pit in the profile slightly distorts the spatial structure of the $\frac{1}{4}$ wavelength mode (Fig. 6a), and reduces the spectral peak near $f \approx 0.006$ Hz in shoreline IG energy (Fig. 6b), confirming that the pit disrupts the $\frac{1}{4}$ wavelength normal mode on the reef flat. The mode 1 EOFs account for 24% and 18% of the IG surface elevation variance for Lines A_{np} and A, respectively and is consistent with a $\frac{3}{4}$ wavelength normal mode on the reef flat (Fig. 6a). Again, the addition of the pit to the profile distorts the spatial structure of the mode, and reduces the spectral peak near $T_0 \approx 56$ sec (Fig. 6b). As a result, weaker IG amplitudes are observed at the shoreline of Line A than at the shoreline of Line A_{np}. The EOF analysis also supports the cross-covariance analysis indicating that nonlinear transfer from the SS band to the IG band occurs through breakpoint forcing on the reef face which has been observed in field studies (e.g., Pequignet et al., 2014; Pomeroy et al., 2012) and in numerical simulations (e.g., Ma et al., 2014; Su et al., 2015).

4.2 Pit Location and Width

In this section, we investigate the role of pit location and width in the wave transformation process by carrying out numerical simulations for transects with the pit and with artificially mined pits. Typical pit depths have a relatively narrow range (between 4 and 5 m deep) thus the pit depth was not varied. Simulations were conducted for the original pit with its center located 10 m (near the shoreline), and 50 m (near the reef crest) from the shoreline, and results are compared in Fig. 7 (left panels) with the original pit with its center located 29.8 m from the shoreline (the mid-reef flat). We also varied the width of the original 17-m wide pit, and investigated three additional cross-shore pit widths (7 m, 27 m, 37 m) as shown in Fig. 7 (right panels). The model predicts that incipient wave breaking occurs within a cross-reef region between 63 m and 85 m from the shoreline. In our tests, even the pit location near the reef crest or the pit with the largest width simulated is shoreward of this region, thus our simulations indicate that the initiation of wave breaking is not altered by the present variations of pit location and width.

Fig. 7 presents wave heights across the reef in the total, SS, and IG frequency bands for the pit location runs (Figs. 7a-c) and pit width runs (Figs. 7d-f). For the pit location runs, the total shoreline wave heights (Fig. 7a, Table 3) are smallest for the pit located near the reef crest. This near reef crest pit location results in both the smallest shoreline SS and IG wave heights for the three configurations considered (Figs. 7b, c, Table 3). The shoreline SS wave heights are reduced by reflection at the seaward edge of the pit (similar to Figs. 5a,c), and by dissipation due to breaking and bottom friction. An EOF analysis of the simulated IG free surface elevations for the three pit

locations (not shown) reveals that the near reef crest pit disrupts most effectively the gravest (and most energetic) normal mode resulting in the smallest shoreline IG wave heights.

The numerical simulations of wave propagation over a centered pit of varying width show that shoreline IG wave heights increase, but shoreline SS wave heights decrease with decreasing pit size (Figs. 7f,e, Table 4). The smallest shoreline total wave heights that are simulated for the narrowest pit are the result of a larger decrease in shoreline SS wave heights due to frictional dissipation compared to the IG wave height increase (Fig. 7d, Table 4). The narrowest pit has the least effect on the IG band gravest normal mode, consistent with the predictions in Section 4.1 that a reef with a narrow pit approximates an unmodified reef.

4.3 Incident Wave Conditions

We next isolate the effect of the pit by carrying out numerical simulations for Lines A and A_{np} for a range of forcing conditions. The site studied has a spring tidal range of 1.60 m, and wave heights on the reef flats are tidally modulated. During deployment 1, the offshore waves observed at the CDIP buoy had significant wave heights ranging from 1 to 2 m and peak periods ranging from 5 to 13 sec. During the second deployment, the peak wave period at the CDIP buoy increased to 18 sec during a storm event, with offshore wave heights up to 2 m. Based on these ranges, we examined the effect of variations in significant wave height and peak wave period of the TMA spectrum on the shoreline IG energy for both Lines A and A_{np} . The effect of varying the peak period of the TMA spectrum while holding the total incident

energy fixed results in numerical experiments that demonstrate the effect of incident spectral bandwidth on the shoreline response. We only vary one wave parameter from the standard calibrated case ($H_s = 0.89\text{ m}$, $T_p = 13.8\text{ sec}$, $h_r = 0.40\text{ m}$) while keeping the other two fixed. The shoreline SS and IG wave heights are compared in Figs. 8a and 8b for a series of incident wave heights (H_s) as well as in Figs. 8c and 8d for a series of peak wave periods (T_p , i.e., spectral bandwidths), respectively.

As the incident wave height increases, the SS wave heights on the reef flat increase (Fig. 8a). This is due to the fact that larger waves are associated with larger radiation stress gradients at breaking near the reef crest and subsequently generate more wave setup. The resulting increase in mean water level on the reef flat allows more SS elevation on the reef flat due to depth-limited breaking (e.g., Becker et al., 2014). In addition, the increased breaking associated with the larger incident wave height also generates more IG energy on the reef flat. Consequently, a corresponding increase in IG wave heights is observed at the shoreline as the incident wave height is increased (Fig. 8b). In all cases, we observe that the shoreline SS wave heights are smaller for Line A_{np} than for Line A (Fig. 8a) whereas the IG wave heights are larger (Fig. 8b).

For this suite of numerical experiments of increasing incident wave heights, the total shoreline wave heights are comparable for the two profiles as the increase in SS wave heights offsets the decrease in IG wave heights caused by the introduction of the pit (Table 5). For the smallest incident wave height, larger total shoreline wave heights are observed for Line A over Line A_{np} due to limited break point forcing of the IG waves.

We next consider the effect of varying the peak period of the incident TMA spectrum on wave transformation over Lines A and A_{np}. Figs. 8c and 8d present the SS and IG wave heights at the shoreline for Lines A and A_{np} as the peak period is increased. For both profiles, the shoreline IG wave heights increase with increasing peak period until reflection at the reef face ($T_p \approx 18$ sec, Table 6) limits the energy transfer onto the reef flat. The frequency averaged reef face reflection coefficients $R = \sqrt{E_R / E_I}$ as defined by Goda (2000) are used here where E_I and E_R are the energy over the total frequency range contained in the incident and reflective spectra, respectively, and they are obtained by two-point wave separation method (see also Goda, 2000).

It was observed that varying the peak period, T_p , while holding H_s and h_r fixed, changes the bandwidth of the incident TMA spectrum. Moreover, for breakpoint forcing of IG motions over steep reef faces, the envelope of the incident waves is coherent with the IG response on the reef flat (e.g. Janssen et al., 2003; Pomeroy et al. 2012). The spectral content of the incident envelope is related to the bandwidth of the spectrum and for the incident TMA spectrum used here, the bandwidth decreases with increasing T_p . To estimate the effect of peak period on the spectrum of the incident envelope, we first compute the elevation time series associated with the incident TMA spectrum by assuming random phases among the spectral components, and the envelope of this elevation time series as the magnitude of the analytic signal using a Hilbert transform. A spectral analysis of the envelope time series (not shown) confirms that the incident TMA spectra with narrower bandwidths (larger T_p) have more low frequency energy in their envelopes than those with wider bandwidths (smaller T_p). As the frequency of the gravest ($1/4$ wavelength) normal mode is approximately

0.006Hz for the simulations here (Fig. 6b), we find that the shoreline IG wave heights increase with decreasing spectral bandwidth (increasing T_p) as the low frequency spectral content of the envelope matching the normal mode frequency increases until reflection at the reef face limits the effectiveness of the breakpoint forcing (i.e., $T_p \approx 18$ sec, Table 6).

Table 7 presents the total shoreline wave heights for Lines A and A_{np} for the suite of simulations obtained by increasing the peak period in the incident TMA spectrum. Similar to the smallest wave height case of Table 5 ($H_s = 0.4$ m), for the smallest peak period ($T = 6$ sec) TMA spectrum corresponding to local seas, larger total shoreline wave heights are observed for Line A over Line A_{np} (Figs. 8c,d, Table 7) due to smaller IG wave heights generated from reduced breakpoint forcing (Table 7). For larger peak periods, the total shoreline wave heights are similar for both profiles.

The current Boussinesq model configuration was unable to simulate accurately the reef flat observations of FBM13 for the small overwash event of 29 June 2011 that resulted in wave heights near the shoreline of $H_s^{IG} = 0.8$ m and $H_s^{SS} = 0.4$ m and breaking wave setup of 0.2m occurring during a moderate tide (0.7m). This disagreement between simulation and observation was attributed in part to the lack of the observed reef face elevation time series to drive the model. The shoreline response is sensitive to the envelope of the incident elevation, which in this study we are only able to approximate from the incident TMA spectrum and the assumption of random phase amongst energetic frequency components. Field observations such as those presented in Yao et al. (2014) for which the incident elevation time series are available demonstrate that the spectral content of the envelope depends on the phasing

of the energetic frequency components. While the model simulations presented here are representative of the transformation of moderate wave events over excavated and unmodified reef platforms, care should be taken in extending the present results to extreme wave events.

5 DISCUSSION AND CONCLUSIONS

Numerical experiments based on weakly dispersive, fully nonlinear Boussinesq-type equations with a FV-based solver have been performed to study the wave transformation over a fringing reef with an excavation pit. The model simulations provide the opportunity to assess effects of reef flat excavation pits on wave transformation over a fringing reef in Majuro, RMI. Observations from the field experiment of FBM13 were used to calibrate the numerical model, and a suite of simulations was carried out for the field profile with the pit (Line A), and the same profile with the pit artificially filled in (Line A_{np}) to remove the effect of differing cross-reef profiles. The effect of a pit is to increase the SS energy and to decrease the IG energy that reaches the shoreline over that for an unmodified reef, qualitatively consistent with the findings of FBM13. An EOF analysis of the model free surface elevation in the IG band confirms that $\frac{1}{4}$ (gravest) and $\frac{3}{4}$ wavelength normal modes were excited on the reef flat. The addition of the pit disrupts these normal modes resulting in smaller shoreline IG wave heights for the transects with pits.

The calibrated model then is used to investigate the effects of cross-reef pit location and width on wave transformation over the reef. Total shoreline wave heights are least affected by a pit located near the reef crest, and both shoreline SS and IG wave

heights increase as the pit location moves from the reef crest to the shoreline. Shoreline wave heights increase with increasing pit width as the increase in SS wave heights exceeds the decrease in IG wave heights caused by the pit. An EOF analysis for the IG bands suggests that the most energetic $\frac{1}{4}$ wavelength mode is affected more by a pit located near the reef crest than located mid-reef or near the shore, and by wider pits.

Increasing the incident wave height of the TMA spectrum resulted in larger shoreline wave heights for both profiles. Increases in shoreline SS wave heights compensate for decreases in IG wave heights when the pit is introduced in the profile (Figs. 8a,b, Table 5). Varying the peak period of the TMA spectrum has the effect of varying the spectral bandwidth, and larger IG wave heights are observed for narrower spectral bandwidths (by increasing T_p) until reflection at the reef face limits the breakpoint forcing of the IG waves (here for $T_p \approx 18$ sec). Again, increases in shoreline SS wave heights are compensated by the decrease in shoreline IG wave heights when the pit is introduced in the profile (Figs. 8c,d, Table 7).

The numerical simulations provide insight into the nature of the IG energy on the reef flat. An EOF analysis of the numerical experiments reveals a dominant peak in the low frequency energy on the reef flat near 0.006 Hz, consistent with a $\frac{1}{4}$ wavelength normal mode response. In addition, the numerical experiments for variable wave height (Figs. 8a,b) and spectral bandwidth (Figs. 8c,d) show the effect of the incident waves on the IG reef flat response. The localized breaking that occurs on the steep reef face forces IG reef flat motions at frequencies where the envelope of the incident waves is energetic. As the wave height increases, the energy in the TMA input spectra

increases, but its bandwidth remains constant (not shown). As a result, the envelope spectrum is more energetic, and its relative frequency content remains fixed as wave height is increased. This leads to an increase in the gravest mode IG shoreline response as the incident wave height increases (Fig. 8b). In contrast, for the variable bandwidth experiments, the energy in the TMA spectrum remains fixed, but its spectral bandwidth decreases with increasing peak period, resulting in an envelope that is more energetic at low frequencies for increasing period. As a result, the gravest normal mode is forced by the energetic part of the envelope spectrum as the incident period increases resulting in a larger shoreline IG response for larger periods until reflection at the reef face limits the forcing (Fig. 8d). Finally, to accurately simulate the range of observations in FBM13, direct measurements of the incident time series that provide the phase relationship amongst the energetic frequency components are necessary rather than simply the bulk parameters used in the incident TMA spectrum. The inability of the present model to reproduce the conditions of 29 June 2011 that resulted in the small overwash event is attributed in part to the lack of direct measurements of the incident time series.

We emphasize that the numerical results are limited by our lack of detailed reef-face wave and bathymetry measurements and the errors associated with these uncertainties may account for some of the differences between the present numerical results and the observations. In addition, wave transformation over natural reefs includes a number of complex processes that have been neglected in the simulations presented. For example, cross-shore or alongshore currents, inhomogeneity of the reef surface roughness, laterally continuous pits in the reef flat, etc. may potentially affect both SS and IG wave transformation over reefs in ways that may not be captured by a 1DH

model. The present IDH numerical results, however, provide a starting point for describing observations of wave transformation over a steep reef face and give insights into the effects of reef flat excavation for a variety of pit configurations and incident wave conditions. Future studies using 2DH models are needed to assess how the alongshore dimensions of excavation pits affect wave transformations and shoreline water levels.

We conclude with a few remarks regarding excavation pits for reef-fringed atolls. While the study of FBM13 showed that 8% smaller total wave heights were observed at the shoreline of a reef with an excavated pit compared to an adjacent unmodified profile, the present numerical results indicate that the robust result of FBM13 is that an excavation pit on a steep, short reef disrupts the modal IG energy excited by breakpoint forcing, while transmitting compensating SS energy. The present numerical results consider only moderate incident wave conditions over a shallow reef flat, and caution should be exercised when extending the present results to higher wave conditions and deeper reefs. And while these results for a specific physical setting and wave regime indicate small changes in shoreline total wave heights due to the presence of an excavation pit, we emphasize that further research is needed to understand the broad implications that mining reefs has on the coastal environment.

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TABLES

Table 1 Instrument positions. Instruments S2 and S4 were redeployed as S5 and S6 for deployment 2.

Instrument No.	S1	S2	S3	S4	S5	S6
Distance from shoreline (m)	0	21.31	35	57.36	0	37.84
Reef morphology	Line A	Line A	Line A	Line A	Line B	Line B

Table 2 Shoreline wave heights in the total, SS and IG frequency bands for the simulations of varying reef profiles in Fig. 5.

Reef profile	H_s^a	H_s^{SS}	H_s^{IG}
Line A	0.48	0.37	0.30
Line B	0.50	0.28	0.39
Line A _{np}	0.46	0.32	0.34
Line B _p	0.51	0.35	0.37

Table 3 Shoreline wave heights in the total, SS and IG frequency bands for the simulations of varying pit locations in Fig. 7.

Pit Location	H_s^a	H_s^{SS}	H_s^{IG}
shoreline	0.52	0.41	0.32
reef flat	0.48	0.38	0.30
reef crest	0.46	0.36	0.28

Table 4 Shoreline wave heights in the total, SS and IG frequency bands for the simulations of varying pit widths for Line A in Fig. 7.

Pit Width (m)	H_s^a	H_s^{SS}	H_s^{IG}
7	0.48	0.34	0.34
17	0.48	0.38	0.30
27	0.54	0.46	0.28
37	0.62	0.55	0.27

Table 5 Shoreline wave heights in the total, SS and IG frequency bands for the simulations of varying incident wave heights in Fig. 8.

Incident Wave height (m)	Line A _{np}			Line A		
	H_s^a	H_s^{SS}	H_s^{IG}	H_s^a	H_s^{SS}	H_s^{IG}
0.4	0.25	0.19	0.16	0.30	0.28	0.08
0.8	0.44	0.23	0.37	0.44	0.36	0.26
1.2	0.63	0.28	0.56	0.63	0.44	0.45
1.6	0.81	0.36	0.73	0.82	0.52	0.64

Table 6 The reflection coefficient (R) of the reef face as a function of incident peak wave period (T_p).

T_p (sec)	R : Line A _{np}	R : Line A
6	0.06	0.08
10	0.12	0.15
14	0.15	0.18
18	0.20	0.24

Table 7 Shoreline wave heights in the total, SS and IG frequency bands for the simulations of varying incident peak wave periods in Fig. 8.

Incident peak	Line A _{np}			Line A		
wave period (sec)	H_s^a	H_s^{SS}	H_s^{IG}	H_s^a	H_s^{SS}	H_s^{IG}
6	0.31	0.22	0.21	0.37	0.34	0.15
10	0.41	0.22	0.35	0.43	0.35	0.25
14	0.49	0.25	0.42	0.49	0.38	0.31
18	0.50	0.28	0.42	0.49	0.38	0.31

FIGURE CAPTIONS

Fig. 1. Left: Location of the study site; Right: Satellite image of the study site with transects and instrument locations indicated (adapted from Google map).

Fig. 2. Reef profiles and numerical settings (elevation related to the mean sea level, seaward side of the reef is not to scale).

Fig. 3. Calibration run 1, wave spectra for Line B: (a) at the mid-reef flat (S6); (b) at the shoreline (S5). Dashed lines: field observations from FBM13; solid lines: numerical simulations. Here, and in subsequent figures, the wave spectra are computed from 2500 second records averaged over 11 adjacent frequency bands. At the mid-reef flat, the observed and predicted wave heights are 0.41m and 0.49m (SS) and 0.25 m and 0.26 m (IG), respectively. At the shoreline, the observed and predicted wave heights are 0.28m and 0.28m (SS) and 0.31 m and 0.39 m (IG), respectively.

Fig. 4. Calibration run 2, wave spectra for Line A: (a) at the mid-reef flat (S3); (b) at the shoreline (S1). Dashed lines: field observations from FBM13; solid lines: numerical simulations. At the mid-reef flat, the observed and predicted wave heights are 0.28 m and 0.38 m (SS) and 0.24 m and 0.24 m (IG), respectively. At the shoreline, the observed and predicted wave heights are 0.30m and 0.37m (SS) and 0.30m and 0.30m (IG), respectively.

Fig. 5. Transformation of wave heights across the four profiles ($x=0$ is shoreline) for the incident TMA spectrum with $H_s = 0.89\text{ m}$, $T_p = 13.8\text{ sec}$ and $h_r = 0.40\text{ m}$. The top panels show transformation in the SS band, and the middle panels in the IG band for Lines A and A_{np} (a,b) and for Lines B and B_p (c,d).

Fig. 6. The spatial structure (a), and spectra of the temporal amplitudes (b) of the mode 0 and mode 1 EOFs for the Line A and Line A_{np} under the incident wave conditions of Fig. 5.

Fig. 7. The effects of varying pit locations (left panels) and pit widths (right panels) on wave transformation across the reef (Line A) for the incident wave conditions of Fig. 5.

Fig 8. The effects of varying incident wave heights (a,b) and peak periods (c,d) in the incident TMA spectrum with $h_r = 0.40\text{ m}$ on shoreline SS (a,c) and IG (b,d) wave heights normalized with the offshore wave height (H_s^a at $x=250\text{m}$) over Line A_{np} (solid symbols) and Line A (open symbols).

APPENDIX A

The 1DH form expression for R_b is given by

$$R_b = [\nu(Hu_\alpha)_x]_x \quad (\text{A.1})$$

where ν is an empirical eddy viscosity and given by the following zero-equation turbulence model

$$\nu = B\delta H\eta_t \quad (\text{A.2})$$

where δ is an empirical coefficient to correct both the mixing-length and friction-velocity scales. The parameter B accounts for the trigger mechanism to ensure a smooth transition between breaking and non-breaking states. The expression for B is given by

$$B = \begin{cases} 1 & \eta_t \geq 2\eta_t^* \\ \eta_t/\eta_t^* - 1 & \eta_t^* < \eta_t \leq 2\eta_t^* \\ 0 & \eta_t \leq \eta_t^* \end{cases} \quad (\text{A.3})$$

where η_t^* determines the onset and stoppage of the breaking process and is evaluated by

$$\eta_t^* = \begin{cases} \eta_t^{(F)} & t - t_0 \geq T^* \\ \eta_t^{(I)} + \frac{t - t_0}{T^*}(\eta_t^{(F)} - \eta_t^{(I)}) & 0 \leq t - t_0 < T^* \end{cases} \quad (\text{A.4})$$

where $\eta_t^{(I)}$ is a threshold value at the breaking inception, $\eta_t^{(F)}$ is a saturated value for the breaking cessation, t_0 is the time at which the breaking event starts, $t - t_0$ is the age of breaking event, T^* is the duration of the breaking event.

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

Figure7

Figure8