Coastal Engineering 137 (2018) 11–27

Contents lists available at ScienceDirect

Coastal Engineering

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

Nonhydrostatic and surfbeat model predictions of extreme wave run-up in fringing reef environments

Christopher H. Lashley [a,*], Dano Roelvink [a,b], Ap van Dongeren [b], Mark L. Buckley [c], Ryan J. Lowe [d]

[a] *Coastal Systems, Engineering & Port Development Chair Group, IHE-Delft Institute for Water Education, Delft, The Netherlands*
[b] *Department of Applied Morphodynamics, Unit of Marine and Coastal Systems, Deltares, Delft, The Netherlands*
[c] *Pacific Coastal and Marine Science Center, U. S. Geological Survey, Santa Cruz, CA, USA*
[d] *School of Earth Sciences, The Oceans Institute, and ARC Centre of Excellence for Coral Reef Studies, University of Western Australia, Crawley, Western Australia, Australia*

ARTICLE INFO

Keywords:
Wave run-up
Coral reefs
XBeach
Infragravity waves
Numerical modelling
Coastal flooding

ABSTRACT

The accurate prediction of extreme wave run-up is important for effective coastal engineering design and coastal hazard management. While run-up processes on open sandy coasts have been reasonably well-studied, very few studies have focused on understanding and predicting wave run-up at coral reef-fronted coastlines. This paper applies the short-wave resolving, Nonhydrostatic (XB-NH) and short-wave averaged, Surfbeat (XB-SB) modes of the XBeach numerical model to validate run-up using data from two 1D (alongshore uniform) fringing-reef profiles without roughness elements, with two objectives: i) to provide insight into the physical processes governing run-up in such environments; and ii) to evaluate the performance of both modes in accurately predicting run-up over a wide range of conditions. XBeach was calibrated by optimizing the maximum wave steepness parameter *(maxbrsteep)* in XB-NH and the dissipation coefficient (*alpha*) in XB-SB) using the first dataset; and then applied to the second dataset for validation. XB-NH and XB-SB predictions of extreme wave run-up ($R_{\max}$ and $R_{2\%}$) and its components, infragravity- and sea-swell band swash (S_{IG} and S_{SS}) and shoreline setup ($\langle\eta\rangle$), were compared to observations. XB-NH more accurately simulated wave transformation but under-predicted shoreline setup due to its exclusion of parameterized wave-roller dynamics. XB-SB under-predicted sea-swell band swash but over-estimated shoreline setup due to an over-prediction of wave heights on the reef flat. Run-up (swash) spectra were dominated by infragravity motions, allowing the short-wave (but not wave group) averaged model (XB-SB) to perform comparably well to its more complete, short-wave resolving (XB-NH) counterpart. Despite their respective limitations, both modes were able to accurately predict $R_{\max}$ and $R_{2\%}$.

1. Introduction

Wave run-up is defined as the uprush of water above the still water level (SWL) on a beach or structure. Run-up is the result of two nearshore processes: i) the time-averaged surface elevation at the shoreline (i.e. wave setup); and ii) the time-varying fluctuations about that mean (i.e. swash) (Holman and Sallenger, 1985; Stockdon et al., 2006). Its accurate prediction is essential for the effective design of coastal structures, beach nourishment planning and for predicting the extent of damage associated with storms (Didier et al., 2016; Gallien, 2016).

Accurately predicting run-up is especially important for tropical and sub-tropical regions fronted by reef structures. These regions, which often have low-lying coastal areas, are often threatened by severe tropical storms with impacts ranging from severe beach and dune erosion to the complete inundation of the adjacent coastal communities (Massel and Gourlay, 2000; Sallenger, 2000; Cheriton et al., 2016). Coastal inundation is often a result of several interacting meteorological and coastal processes; however, on steeper coasts without continental shelves, the contribution of wave processes such as run-up becomes more dominant than that due to storm surge (Wang et al., 2005; Wolf, 2009).

Coastal engineers and managers typically parameterise run-up using Iribarren-based empirical models (Equations (1) and (2)) developed for

---

* Corresponding author. Present address: Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands.

E-mail address: C.H.Lashley@tudelft.nl (C.H. Lashley).

https://doi.org/10.1016/j.coastaleng.2018.03.007
Received 29 October 2017; Received in revised form 1 February 2018; Accepted 18 March 2018

open, sandy coasts which use offshore wave height (H_{m0}), period (T_p) and a constant beach slope (β) as input values to predict the magnitude of run-up (Holman, 1986; Nielsen and Hanslow, 1991; Hedges and Mase, 2004; Stockdon et al., 2006). These relationships typically quantify extreme wave run-up as either of two characteristic values: i) $R_{\max}$, the maximum run-up at any specific time; and ii) $R_{2\%}$, the value exceeded by only 2% of the run-up maxima in the distribution.

$$\frac{R_{max}}{H_{m0}} \quad \text{or} \quad \frac{R_{2\%}}{H_{m0}} = f(\xi_0) \tag{1}$$

$$\xi_0 = \frac{tan\beta}{\sqrt{\frac{2\pi H_{m0}}{gT_p^2}}} \tag{2}$$

where, g is the gravitational acceleration and ξ_0 is the Iribarren number.

However, these formulations are not readily applicable to the fringing reef environments commonly found in tropical and subtropical regions, as run-up depends not only on the beach slope at the shoreline but also on the reef morphology itself. The presence of these reef structures results in significantly more complex nearshore hydrodynamic processes than on typical sandy profiles (Munk and Sargent, 1948; Gerritsen, 1980; Massel and Gourlay, 2000; Cheriton et al., 2016). Fringing reefs are characterized by a seaward sloping reef face leading up to a shallow reef flat platform that extends towards the beach. Wave transformation in these environments is subject to several simultaneous and interacting processes (Kench and Brander, 2006), which include: shoaling; dissipation by wave breaking (Lowe et al., 2009); wave-induced setup (Massel and Gourlay, 2000; Buckley et al., 2015); nonlinear energy transfer to higher and/or lower (infragravity) frequencies (Pomeroy et al., 2012; Péquignet et al., 2014; van Dongeren et al., 2016); dissipation by bottom friction (Lowe et al., 2005); low-frequency wave reflection; and resonance (Nwogu and Demirbilek, 2010), where a significant amount of wave energy is distributed about the natural frequency of the reef. This reef flat resonance may in turn result in an amplification of run-up at the shoreline, further adding to the complexity of making accurate predictions in such environments (Nakaza and Hino, 1991; Demirbilek et al., 2007; Péquignet et al., 2009; Shimozono et al., 2015).

Although not originally developed for and tested using reef-type environments, numerical models are now widely applied to reef systems given their ability to accurately represent complex nearshore processes (Sheremet et al., 2011; Filipot and Cheung, 2012; McCabe et al., 2013; Van Dongeren et al., 2013; Fang et al., 2014; Ma et al., 2014; Shimozono et al., 2015). These numerical models generally fall into two categories groups: i) phase-resolving models and ii) phase-averaged models. Phase-resolving models utilize a grid resolution high enough to completely describe the sea-surface and resolve individual waves. These models are then able to capture the higher frequency wave motions (short-waves); however, this comes at greater computational expense. In contrast, phase-averaged models describe wave processes in a stochastic manner, typically based on linear wave theory and empirical formulations. As such, phase-averaged models require a lower grid resolution and are considerably less computationally demanding (Buckley et al., 2014). Nearshore wave models have been primarily developed for mild-sloping, sandy coastal environments. Thus, when they are applied to steep reef environments it is expected that some of their inherent parameterizations (e.g. for simulating wave breaking and frictional dissipation) would require some adjustment (Buckley et al., 2014). However, wave transformation models derived using the mild-slope approximation have been shown to perform reasonably accurately with minimal parameter tuning, even on slopes up to 1:3, which is steeper than typical coral reef slopes (e.g. Berkhoff, 1973; Booij, 1983; Kirby and Dalrymple, 1983).

Therefore, the choice of numerical model should be carefully considered based on the relative importance of the wave processes and the manner in which they are simulated in each model. Given that low-frequency motions often dominate near the shoreline of fringing reef environments, it is imperative that the numerical model applied be able to correctly describe the non-linear transfer of wave energy to the infragravity (low-frequency) band (Filipot and Cheung, 2012; Buckley et al., 2014; van Dongeren et al., 2016). For this study, we consider the XBeach numerical model that combines both phase-resolving and phase-averaged approaches. The XBeach nonhydrostatic mode (XB-NH) resolves all wave motions including short-waves; while the surfbeat mode (XB-SB) resolves long-wave motions but is short-wave averaged. The overall ability of XBeach to accurately simulate infragravity motions in a wide range of coastal environments has been demonstrated in many studies (Roelvink et al., 2009; Harley et al., 2011; Cox et al., 2013; Masselink et al., 2014; McCall et al., 2015).

With respect to its application to fringing reef systems, Van Dongeren et al. (2013) applied XB-SB to study low-frequency wave dynamics over a fringing reef at field scales. The study showed the increasing dominance of infragravity (low-frequency) waves shoreward of the reef crest. In their comparison of nearshore models for wave transformation across reef environments, Buckley et al. (2014) concluded that XB-SB was indeed capable of handling the transformation of wave energy from the sea-swell (high-frequency) band to the infragravity band. More recently, Quataert et al. (2015) applied XB-SB to investigate the influence of the reef characteristics on the nearshore hydrodynamics and the potential for wave-driven flooding in light of climate-driven sea level rise. This study found that run-up increased with narrower, smoother reef flats and steeper, rougher reef slopes. While highly informative, the main limitation of their study was the fact that their model was not quantitatively validated for wave run-up. While each of the above-mentioned studies applied XB-SB, Storlazzi et al. (2017) recently used the short-wave resolving mode XB-NH to successfully simulate sea-swell band wave run-up and flooding on an atoll island. However, like that of Quataert et al. (2015), the modelled run-up and associated inundation extent were only qualitatively compared to observations. Likewise, Pearson et al. (2017) concluded that XB-NH was able to simulate reef hydrodynamics with reasonable accuracy and recommended its use as an early warning tool to predict flooding on reef-lined coasts.

Despite the promising results displayed by XBeach to-date, the performance of either mode to predict wave run-up at reef coasts has not been rigorously validated using experimental data. Thus, it is primary aim of the present paper to evaluate the model in simulating extreme wave run-up in such systems. In particular, attention is given to the physical processes that need to be captured for accurate run-up predictions. This is done by comparing both the short-wave resolving and short-wave averaged modes of the model to two laboratory (physical model) experiments carried out in large-scale wave flumes by: i) Demirbilek et al. (2007); and ii) Buckley et al. (2015).

In Section 2, the experiments used for model-data comparison are described, followed by a brief overview of the XBeach numerical model and the equations pertinent to this study. In addition, the metrics and objective functions used to quantify model accuracy are presented. Section 3 presents the results of the model calibration through its application to the Demirbilek et al. (2007) dataset; while Section 4 presents the results of the model validation and application to the Buckley et al. (2015) dataset. Section 5 provides an in-depth discussion on the performance of the short-wave resolving and short-wave averaged modes; and examines the contribution of various physical processes to model results. Section 6 concludes the paper by addressing the overarching research objective and making recommendations for future studies.

2. Methods

2.1. Description of the experiments

2.1.1. Demirbilek et al. (2007) experiment

The experiment was conducted in a 35-m long, 0.7-m wide and 1.6-m high wave flume at the University of Michigan. The reef platform was