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Study on wave-induced setup over fringing reefs in the presence of a reef crest

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ABSTRACT

It has been well observed that a reef crest (ridge) may be present at the reef edge, but so far very few published studies focusing on the effects of such reef-crest on the wave dynamics over fringing reefs. To understand the role of a reef-crest configuration in determining breaking-wave induced setup over the reef flat, a series of experiments were carried out in a wave flume using an idealized fringing reef model with a reef crest. Experimental results were reported for a trapezoidal reef crest with five reef-crest widths under a series of monochromatic waves. Also examined was the reef without a reef crest. Data analysis shows that larger energy dissipation associated with smaller surfzone width around the reef edge occurred with a wider reef crest. The maximum wave-induced setup on the reef flat in the presence of the reef crest was significantly larger than that without, and it also increased with increasing reef-crest width. The reef-crest submergence was found to be a primary parameter controlling the magnitude of wave setup on the reef flat provided that the reef crest was sufficient wide. An alternative semi-analytical 1DH model based on the balance of cross-shore momentum was proposed. The model was validated by present laboratory data as well as three existing 1DH laboratory studies. Comparing with other two representative semi-analytical models in the literature showed that the proposed model was capable of better reproducing the maximum wave-induced setup on the reef flat for a variety of reef profiles with/without a reef crest, different reef-crest water levels, as well as both monochromatic and spectral waves. The model parameter was physically related to the two characteristic lengths in the surf zone and its value was dependent on the fore-reef slope as well as the presence of a reef crest. The 1DH model was also satisfactorily applied to a fringing reef in field conditions where the effects of fore-reef friction and back-reef lagoon were not important.

1. Introduction

Wave interaction with fringing coral reefs has been a primary focus of nearshore hydrodynamics over decades. A typical fringing reef is characterized by a seaward sloping fore-reef and an inshore shallow reef flat extending towards the coastline [1]. Corals commonly grow to mean low-tide levels and may impose a shallow water control on the waves reaching reef flats [2]. Similar to the wave transformation over a shallow shelf, ocean waves first shoal on the sloping fore-reef and then break near the reef edge, dissipating their energy and generating a rise of mean sea level known as “wave setup”, a phenomenon first described by Munk and Sargent [3]. The surfzone always extends over a certain distance on the reef flat, starting from the incipient breaking point to the location where wave breaking ceases. After wave breaking, shorter waves may reform on the reef flat and propagate towards the shoreline. The maximum setup usually occurs at or near the reef edge, because over the reef flat, where the depth is almost constant, wave breaking ceases and there is no cross-shore gradient in the radiation stress as introduced by Longuet-Higgins and Stewart [4] to generate the wave setup. Study of wave-induced setup over coral reefs has profound geological, ecological, engineering and environmental implications. For example, wave setup on the reef flat can drive flow across a shallow reef flat, through a deeper lagoon, and finally exits to the open sea through a channel, thus building up a 2DH regional circulation in the reef area [5]. The 2DH reef-lagoon-channel system are crucial to the transport of organisms, nutrient and sediments [6]. Wave-induced setup is an important compo-

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nent of wave runup along reef shorelines [7], which may result in shoreline inundation during hurricanes, or high surf events at the low-lying atolls surrounded by fringing reefs.

Although reef-flat bathymetry varies with the site, a reef crest in the form of an algal ridge or similar configuration is frequently observed at the edges of many coral reefs [6,8–11 and many others]. Ridges, consisting of coral colonies, rubble algal, etc., might be formed due to long-term exposure of high energy dissipation areas at the reef edges where metabolic rates (nutrient uptake, photosynthesis, production etc.) and biomechanical tolerances of benthic organisms are significantly enhanced by the hydrodynamic gradient [12]. Most previous laboratory investigations of wave setup over reefs [e.g.,1,13–15] have generally ignored these reef-crest structures, and focused mainly on simple reef morphologies with constant fore-reef slopes and horizontal reef flats. Yao et al. [16] were the pioneers to systematically study the effects of a rectangle reef-crest structure locating at the seaward edge of a horizontal reef flat, showing that the reef crest could increase wave-induced setup on the reef flat under monochromatic waves. Subsequently, their experiments were extended to spectral waves by Yao [17] and were reproduced by a Boussinesq-typed numerical model by Yao et al. [18]. The reef-crest submergence was found to be a primary parameter controlling the magnitude of wave setup on the reef flat in these studies, but they only tested one idealized rectangle reef-crest configuration. The reef crest controlling the reef-top hydrodynamics resembles a submerged breakwater as demonstrated by Gourlay [1], asides from its reef-crest submergence (in analogy to “freeboard” of the breakwater), we suppose that its crest width may also alter wave breaking and associated wave setup over the reefs by the fact that an increasing width leads to a longer distance of wave breaking over reef crest with shallower depth and higher dissipation rate.

Conventionally, in analogy to wave-induced setup/setdown and wave-driven flows on beaches, The one-dimensional horizontal (1DH) analytical solutions, obtained using the well-known radiation stress concept of Longuet-Higgins and Stewart [4], were frequently used in the past to study reef hydrodynamics associated with ocean waves [e.g.,19–22]. Although several 1DH theories proposed to predict the wave setup over reefs differ in many respects, they all rely on fundamental conservation laws. Traditionally, two main types of 1DH semi-analytical models have been commonly used in the literature to predict the maximum wave-induced setup on a reef flat. One approach is to derive an expression for the wave setup by integrating the momentum equation in the surf zone, with energy balance being supplemented to estimate some boundary values. Tait [19] (hereafter T72) was the first one to use this approach to obtain the following expression

$$\bar{\eta}_r = \frac{1}{1+8/3\gamma^2}(h_b - h_r) \quad (1)$$

where $\bar{\eta}_r$ is the maximum wave setup on the reef flat, γ is the breaker depth index, h_b is the breaker depth for monochromatic waves and h_r is the still water depth on the reef flat (reef-flat submergence). Eq. (1) is the original form used in T72, where the wave-induced setdown at breaking point was not considered. Meanwhile, T72 did not give any analytical expression for h_b. In fact h_b can be estimated by using a simple 1D energy balance (see Appendix A) so that Eq. (1) can be rewritten as

$$\frac{\bar{\eta}_r}{H_0} = \frac{1}{1+8/3\gamma^2}\left[\frac{(1-K_r^2)^{0.4}}{(4\pi\gamma^2)^{0.4}S^{0.2}} - \frac{h_r}{H_0}\right] \quad (2)$$

where K_r is the reflection coefficient, H_0 is the deep water wave height, S is the offshore wave steepness which is defined by $S = H_0/gT^2$, g is the gravity acceleration and T is the wave period. Similar approaches have also been used by [20–23].

Alternatively, by using conservation of energy, Gourlay and Colleter [24] (hereafter GC05) improved the model of Gourlay [25], and showed that the wave-induced setup in the water above a reef flat could be calculated by

$$\frac{\bar{\eta}_r}{T\sqrt{gH_0}} = \frac{3}{64\pi}K_p\left[1 - K_r^2 - 4\pi\gamma^2\left(\frac{\bar{\eta}_r + h_r}{H_0}\right)^2 \frac{1}{T}\sqrt{\frac{\bar{\eta}_r + h_r}{g}}\right]\left(\frac{H_0}{\bar{\eta}_r + h_r}\right)^{3/2} \quad (3)$$

where K_p is a free parameter describing effects of reef profile. The breaker depth index, γ, is the value for waves breaking on or near the reef flat and believed to be smaller than that used in Eq. (2) for waves breaking on the fore-reef. It is important to note that GC05 also used the radiation stress concept in the surf zone. Instead of carrying out an exact integration of the momentum equation across the surf zone, they assumed that the change of radiation stress should take place at an effective depth, $h_p = (1/K_p)(\bar{\eta}_r + h_r)$. In essence, by assuming a constant γ on the reef flat, they were able to use K_p to parameterize the surfzone process.

Both above models were originally developed for an idealized reef geometry (a plane fore-reef slope followed by a horizontal reef flat) and validated only by their own dataset. How their model performances for a series of existing laboratory data, particularly for reefs in presence of a reef crest were not examined in the literature. When there is a reef crest, it was suggested that the reef-crest submergence (h_c) rather than the reef-flat submergence (h_r) should be used instead in the models [25]. T72 model did not explicitly consider the presence of reef crest although replacing h_r by h_c may be part of the solution. CC05 introduced a shape factor K_p to describe the effect of surfzone seabed profile but it was a fitting parameter whose physical interpretation was still unknown. We will address such deficiencies of the two models by introducing a new model in the present study.

Therefore, aiming to improve the laboratory settings as reported by Yao et al. [16], and pursuing the hypothesis that the reef-crest width may play a role in determining the wave setup on the reef flat, new laboratory experiments for a fringing reef model with a series of reef-crest widths were conducted. An alternative 1DH analytical model that can account for the reef-crest configuration was also proposed, which was compared to the above semi-analytical approaches (i.e., T72 and CC05). The rest of the paper is arranged as follows: the laboratory settings is introduced in Section 2. Detailed analysis of present experimental data is conducted in Section 3. The 1DH analytical model is formulated and validated by a series of published laboratory datasets and some field observations in Section 4. Discussion about the model is given in Section 5, and major conclusions are drawn in Section 6.

2. Experimental settings

The experimental settings were designed to reproduce main aspects of the settings from [16] in view of the flume dimensions as well as the location and size of the idealized reef model, except for slight modification of the reef-crest configuration. Laboratory experiments were conducted in a wave flume 40 m long, 0.50 m wide and 0.8 m high at Hydraulics Modeling Laboratory, Changsha University of Science and Technology, P.R. China. A servo-controlled piston type wavemaker was placed at one end of the flume to generate the designed waves. At the other end, a beach with slope of 1:8 started at approximately 34 m from the wave maker and was covered with porous material of 3 cm thick to reduce wave reflection. To study wave-induced setup over a reef profile with different reef-crest widths, we rebuilt an idealized fringing reef model by using PVC plates consisting of a relatively steep fore-reef slope (1:6), a