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NUMERICAL EXPERIMENTS ON RESONANT WAVE AMPLIFICATION OVER A FRINGING REEF

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INTRODUCTION

Waves are important drivers for reef hydrodynamics, and therefore strongly contribute to flooding over reef-lined coasts. While high-frequency waves are largely dissipated when they propagate over the reef flat due to breaking and friction, low-frequency (LF) waves are generally able to reach the back-reef beach. There, they can reflect and form (quasi-)standing wave patterns, which under resonant conditions can lead to disproportionally high run-up on the beach (e.g., Péquignet et al., 2009; Gawehn et al., 2016). The probability of this phenomenon is expected to increase due to sea-level rise (e.g., Péquignet et al., 2009). In this study, we numerically investigate long wave resonance and the processes enhancing or limiting the resonant amplification of long waves over the reef flat. Besides the role of frictional dissipation (e.g., Pomeroy et al. 2012), we investigate how the nonlinear transformation of long waves influences the amplification rate. We indeed hypothesize that LF wave growth due to resonance may lead to an increase in wave steepness and possibly to long wave breaking, which could counterbalance the amplification due to resonance. In addition, the amplification of LF wave heights could influence the propagation speed (via amplitude dispersion) and therefore modify the resonant frequency modes, decreasing the efficiency of the incoming, previously resonant, forcing.

METHODS

To investigate the processes determining the maximum long wave amplification over the reef, we perform a series of numerical experiments using the wave-resolving model SWASH (Zijlema et al., 2011). We consider the propagation of long regular waves of varying amplitudes and periods over the schematized fringing reef shown in Figure 1, and examine the conditions leading to maximum wave amplification and run-up. The bathymetry chosen for these numerical experiments is a 1D schematized version of the fringing reef analyzed by Gawehn et al. (2016), over which resonance was observed. A small amount of friction was accounted for in these simulations using Manning's formulation with $n = 0.01\, s/m^{1/3}$. For the simulations presented below, the water depth above the reef flat was $d_{reef} = 0.8\, m$.

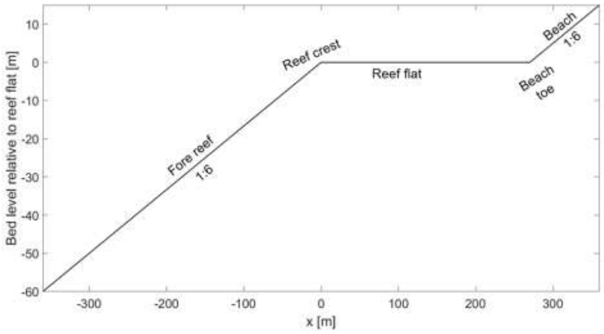

Figure 1 – Bathymetry used for numerical experiments. Note that the forereef slope extends offshore up to an elevation of -440 m.

If the reef is seen as an open-ended basin of width W_{reef} (reef flat width) and waves are assumed to propagate at the linear shallow water wave speed, resonant amplification should occur when the incoming long wave period coincides with one of the natural frequencies of the reef T_n:

$$T_n = \frac{4W_{reef}}{(2n+1)\sqrt{gd_{reef}}}, \qquad (1)$$

where n is mode number (n≥0), and g is the gravitational acceleration. To identify the periods leading to the maximum amplification for our reef, simulations were first performed for a fixed offshore wave height and a range of periods varying around the theoretical periods for the fundamental and first modes (see Eq. (1) for n=0 and n=1, respectively). The modeled resonant modes were then defined as the conditions leading to the largest wave height/run-up at the beach once stationary conditions were reached.

After finding the first two resonant modes, we investigated the influence of offshore wave height on resonant amplification by varying the offshore wave height (H_{off}) of each resonant mode. We additionally quantified the time needed for the wave height to build-up and reach maximum amplification for a given resonant wave forcing.

A first evaluation of the influence of friction on resonant amplification was finally performed by comparing the above-mentioned simulations (including a small, but non-zero, amount of friction) to frictionless simulations. This analysis was done for different offshore wave heights and periods.

FIRST RESULTS

Resonance was found to occur in a bandwidth of periods generating two resonant peaks, one for each resonant mode (Figure 2). Figure 2 shows that the maximum resonance (red dots) in our experiments is obtained at longer periods than the theoretical resonant periods of our schematized reef (yellow dots), which is consistent with previous studies (e.g., Pearson et al. 2017). Moreover, the run-up and wave height resonant amplification were more significant for the fundamental mode than for the first mode.

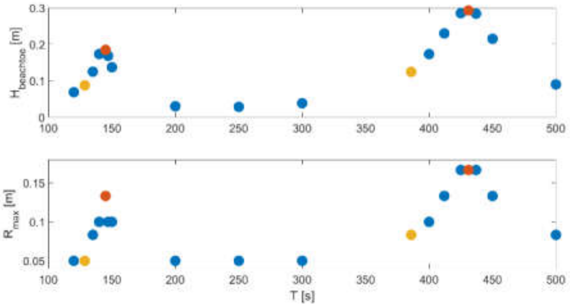

Figure 2 – Wave height at the beach and maximum run-up on the beach for regular waves of height H_{off} = 1 cm in 440 m depth (calculated once stationary conditions have been reached).

The time needed for resonance to build-up and thus for the maximum wave height and run-up to be reached was also examined. For the reef setup, range of wave heights and resonant modes considered in this study, between 10 and 20 wave periods were needed to reach the maximum resonant amplification. In practice, this corresponds to a build-up duration between 1h12 and 2h23 for the fundamental mode, but only 30 and 46 min for the first resonant mode.

Interestingly, the build-up time seems to depend on the incoming wave height, where for a given resonant mode (T_0 or T_1), cases with a larger H_{off} reach maximum amplification faster than cases with smaller H_{off}.

Comparisons with frictionless simulations showed that the relatively small friction imposed in our reference simulations already significantly affected the resonant amplification. Moreover, it reduces the resonant amplification much more efficiently for the fundamental mode (26%) than for the first resonant mode (>5%) (not shown).

The influence of friction on resonant amplification was also studied for the fundamental mode with varying wave heights (Figure 3). This amplification was measured as A_{Shoal}, which represents the ratio between the modeled incoming wave height and the expected wave height due to linear wave shoaling. The incoming wave height at the beach toe can reach up to 4.3 times the shoaled wave height. As expected, the amplification decreases due to friction, and this frictional energy dissipation increases with increasing wave height.

Figure 3 also shows that, for the fundamental mode ($T = T_0$), the smallest offshore waves amplify relatively more on the reef than the largest waves. This process is clearer when friction is accounted for (blue dots), but still visible for the frictionless case above a given threshold (here H_{off}>0.75 cm). The processes driving this behavior in the frictionless case need to be further investigated. Still, it could be (partly) explained by nonlinear energy transfers to higher harmonics, leading to bore formation on the reef flat and harmonic release at the reef edge.

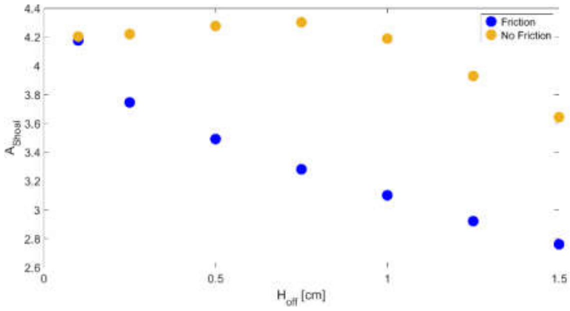

Figure 3 – Resonant amplification (defined as the ratio of the observed incoming wave height over expected wave height due to shoaling only) for different offshore wave heights with and without friction for the fundamental mode.

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