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Laboratory study of solitary-wave transformation over bed-form roughness on fringing reefs

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ABSTRACT

This paper presents the formulation and implementation of a series of two-dimensional flume experiments to investigate effects of bed-form roughness on coastal wave processes. The experiments were carried out on a fringing reef model in a 104-m long and 4.6-m high flume at Oregon State University. The reef model has a 1:12 face slope and a long flat section for examination of wave shoaling and breaking as well as bore formation and propagation. The model is 2.36 m tall and the water depth ranges from 2.36 to 2.66 m to produce dry and wet reef conditions. The bed-form roughness is modeled by timber beams placed across the flume in four configurations by varying the height from 0.038 to 0.076 m and the spacing from 0.388 to 0.768 m to provide a range of pitch ratios from 5 to 20. The incident solitary wave height varies from 10 to 50% of the water depth to cover a range of breaking and non-breaking conditions. A series of wire and sonic gauges measured the wave transformation along the flume and a digital camera recorded images of the breaking waves on a background grid painted on a flume wall. The bed forms decrease the effective depth for wave propagation and modify the structure of the free surface flow. In comparison to a control experiment with plain concrete surface, the solitary wave breaks earlier and dissipates more energy on the reef slope. The subsequent bore slows down with undulation over the shallow reef flat, but speeds up for more energetic flows in deeper water.

1. Introduction

Many tropical and sub-tropical islands in the Pacific are susceptible to flood hazards due to tsunamis, hurricanes, and high-surf events. Accurate prediction of the near-shore wave conditions is important in coastal structure design, land-use planning, and hazard assessment. The presence of fringing reefs along these coastlines results in more complex near-shore processes than those on gentle slopes and sandy beaches in non-tropical environments (Gerritsen, 1981). Fig. 1 shows a cross section of the reef at Mokuleia on the north shore of Oahu, Hawaii. The profile, which references to the mean sea level (MSL), includes a fore reef and a shallow reef flat typical of Pacific island environments. The abrupt slope transition at the reef edge introduces energetic breaking waves that result in bore formation and propagation over the shallow reef flat (Roeber et al., 2010). The energy dissipation processes are augmented by the irregular reef surface with an abundance of coral heads and colonies of reef organisms (Hardy and Young, 1996; Lowe et al., 2005; Nelson, 1996).

Wave breaking and dissipation in fringing reef environments have recently received attention in the research community. Nwogu and Demirbilek (2010) reported a wave flume experiment on irregular wave transformation over a scaled model of a fringing reef on Guam. Roeber (2010) described two series of large-scale flume experiments with 10 two-dimensional reefs modeled after cross-shore profiles in Hawaii, Guam, and American Samoa. Swigler (2009) conducted basin experiments for solitary wave transformation over a three-dimensional reef design. These studies provided data for validation and calibration of numerical models and understanding of wave processes over reef geometries (e.g., Bai and Cheung, 2012, 2013; Filipot and Cheung, 2012; Kazolea and Delis, 2013; Roeber and Cheung, 2012; Sheremet et al., 2011; Shi et al., 2012; Tonelli and Petti, 2013). These experiments, however, were performed on plexiglass or finished concrete surface without the bed-form roughness commonly found in reef environments. Lowe et al. (2005) concluded from a field experiment at Kaneohe Bay on the east shore of Oahu, Hawaii that bottom friction may dominate the energy dissipation over the reef flat.

The dissipation mechanism due to free surface flows over rough beds has been a subject of intense investigation. Sleath (1987), Chen et al. (2007), Dixen et al. (2008), and Lowe et al. (2008) conducted flume experiments to investigate dissipation over gravel, stone, and coral beds. Parameterized roughness geometries consisted of regularly placed pipes and triangles provide a systematic approach to examine energy dissipation in unidirectional and oscillatory flows

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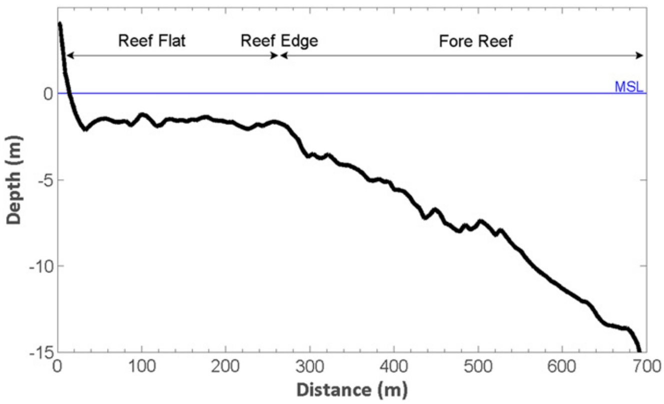

Fig. 1. Fringing reef profile at Mokuleia, Hawaii.

(e.g., Mirfenderesk and Young, 2003; Ojha and Mazumder, 2010; Suntoyo et al., 2008). Their results advance the understanding of laminar and turbulent boundary layers over rough beds and provide a good resource for validation of computational fluid dynamic, wave propagation, and circulation models (e.g., Fuhrman et al., 2009; Lowe et al., 2010; Suntoyo and Tanaka, 2009). These flume experiments use a small roughness height compared to the water depth allowing formation of laminar and turbulent layers well below the free surface for parameterization of the dissipation processes with a wave friction factor.

Coral reef organisms form some of the most jagged surfaces in coastal waters. The roughness height, for example, is typically 0.5–1.0 m on Oahu, Hawaii (Nunes and Pawlak, 2008). The reef flat is quite shallow, usually less than a couple of meters deep. The dissipation might depend on the water depth in addition to the roughness height and spacing suggested by Raudkivi (1988). For reef environments with sparse coral communities, the flow from surface waves detaches behind a roughness element and re-attaches in front of the next. A recirculation region is formed adjacent to the roughness element with an internal boundary layer. This process plays an important role on the macro-turbulence structure and dissipation rate from bed-form roughness (Leonardi et al., 2003). For shallow flows, the wakes behind the roughness elements may extend to the water surface. The coupling between free surface and bed-form induced flows is sporadic and not well understood with little information in the technical literature.

Prior experiments on wave breaking over fringing reefs have been performed over smooth or finished surfaces, while dissipation due to bed-form roughness has been investigated with water depth much greater than the roughness height. Due to coupling between bottom friction and wave breaking over shallow reefs, it is necessary to combine the two dissipation mechanisms in a single laboratory experiment to characterize the physical processes. Since scaling is an issue for these processes, physical experiments in a large flume are preferred. Quiroga (2012) extended the large-scale experiments of Roeber (2010) by including bed-form roughness on a fringing reef model. The laboratory study provided measurements of solitary wave transformation over roughness elements constructed of timber beams with the height and spacing varied under a range of flow conditions. The controlled laboratory environment enables a systematic investigation of the bed-form effects on wave shoaling, breaking, and bore propagation. This paper provides a summary of the experiments and results from Quiroga (2012) as well as further analysis and interpretation of the data.

2. Laboratory experiments

A series of flume experiments were carried out at the O.H. Hinsdale Wave Research Laboratory, Oregon State University in 2009. The test facility is a National Science Foundation designated site for tsunami research within the Network for Earthquake Engineering Simulation. Fig. 2 shows a schematic of the experiments and the pertinent physical variables. The wave flume measures 104 m long, 3.66 m wide, and 4.6 m high. Prefabricated concrete slabs of 0.2 m thickness, 3.66 m width, and 4.57 m length were mounted at bolt holes in the flume walls to construct a fore reef with a 1:12 slope and a reef flat 2.36 m above the bottom. A wedge in front of the fore reef provides a smooth transition between the 0.2-m slab and the floor of the flume. A piston-type wavemaker with a programmable hydraulic actuator generates the incident solitary wave, which has been commonly used in laboratory studies of wave transformation and runup (e.g., Briggs et al., 1995; Grilli et al., 1994; Hsiao et al., 2008; Li and Raichlen, 2002; Roeber, 2010; Swigler, 2009; Synolakis, 1987). The use of solitary waves allows precise measurements of wave transformation and energy dissipation without interference from return flows, wave setup, and end-wall reflection. The laboratory experiments represent a simplification of wind generated waves, which resembles a series of solitary waves in shallow reef environments.

Coral reef roughness is inhomogeneous with varying length scales and a broad spectral distribution (Nunes and Pawlak, 2008). For generalization and ease of installation, a geometrical representation of the bed-form roughness was made using assemblies of 2 × 4 timber beams at regular intervals across the reef model. This allows parameterization of the roughness in terms of the height k and spacing λ. The pitch ratio λ/k defines the wake behind a roughness element and the overall dissipation mechanism (Raudkivi, 1988). We focus on the k-type roughness with $\lambda/k \geq 5$ that exposes the recirculation vortices to the free surface flow. Fig. 3 illustrates the four bed-form configurations in the experiments. BF1 and BF3 have the same pitch ratio of 10, but roughness heights of 3.8 and 7.6 cm. BF2 and BF3 have the same roughness

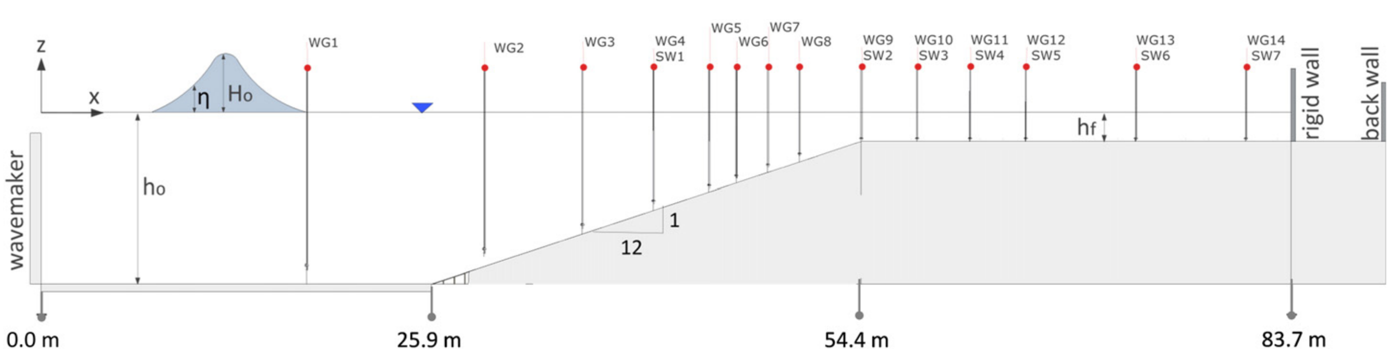

Fig. 2. Schematic of wave flume experiments.