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A study of tsunami-like solitary wave transformation and run-up over fringing reefs

Yu Yao [a,c], Fang He [b,*], Zhengjiang Tang [a,d], Zengsheng Liu [a,d]

[a] School of Hydraulic Engineering, Changsha University of Science and Technology, Changsha, Hunan 410114, China
[b] Ocean College, Zhejiang University, Zhoushan, Zhejiang 316021, China
[c] Key Laboratory of Coastal Disasters and Defence of Ministry of Education, Nanjing, Jiangsu 210098, China
[d] Key Laboratory of Water-Sediment Sciences and Water Disaster Prevention of Hunan Province, Changsha 410004, China

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ABSTRACT

After the 2004 Indian Ocean tsunami, the effectiveness of fringing reefs in protecting coastlines from tsunami-induced inundation has aroused great attention in the post-tsunami surveys. To better understand the role of fringing reefs in the mitigation of a tsunami hazard, laboratory experiments were conducted in a wave flume to study the transformation and run-up of tsunami-like solitary waves over various fringing reef profiles. The effects of incident wave height, reef-flat submergence, lagoon width and reef surface roughness were examined. Cylinder arrays were employed to create artificial roughness elements on the reef surface. Empirical formulas based on the experimental data were also proposed for the wave run-up. The ratio of the reef flat submergence to the incident wave height was always found to be the dominant parameter to characterize the wave run-ups over various tested reef profiles. Subsequently, a numerical model based on the improved Boussinesq equations including the drag effect of roughness elements was validated by the experimental data. The validated model was then applied to investigate the impacts of variations of reef morphologies (fore-reef slope, back-reef slope, reef-flat width, reef-crest width) on the solitary wave run-up.

1. Introduction

Tsunami is an extremely destructive natural disaster, which can be generated by earthquakes, landslides, volcanic eruptions, and meteorite impacts. Tsunami damage occurs mostly in the coastal areas where tsunami waves run up or run down the beach, overtop or ruin the coastal structures, and inundate the coastal towns and villages (Yao et al., 2015). Such destructive hazard is devastating, as witnessed in both the 2004 Indian Ocean tsunami and the 2011 East Japan tsunami (Mori et al., 2012; Titov et al., 2005). In addition to establishing global tsunami early warning systems, there is also increasing interests in understanding the possible functions of coastal vegetation (such as mangrove forest, coral reef, etc.) in effective coastal management and hazard mitigation for the countries around the Pacific and Indian Oceans. Coral reefs are abundant in the tropic and sub-tropic regions, especially around the low-lying atolls. Among various coral reefs, fringing reefs are the most common type. As introduced by Gourlay (1996), a typical cross-shore reef profile can be characterized by a steep offshore fore-reef slope and an inshore shallow reef flat. There is also possibly a reef crest lying at the reef edge (e.g., Yao et al., 2017) and/or a narrow shallow lagoon existing behind the reef flat (e.g., Lowe et al., 2009). Fringing reefs have been reported as efficient buffers to the wind-driven wave energy over decades (e.g. Lowe et al., 2005a, b; Lugo-Fernandez et al., 1998; Péquignet et al., 2011; Young, 1989). However, after the 2004 Indian Ocean Tsunami, the protective role of reefs in mitigating tsunami waves has begun to arise the attentions of the scholars who conducted the post-disaster surveys on tsunami hazards (Chatenoux and Peduzzi, 2007; Ford et al., 2014; Mcadoo et al., 2011; and many others). For example, Ford et al. (2014) observed the tsunami dynamic characteristics within the lagoons and on the surrounding fringing reefs of two mid-ocean atolls in the Marshall Islands after the 2011 Tohoku Tsunami. Particularly, Mcadoo et al. (2011) showed an example of the damaged coastal reefs at the Upolu Island, Samoa, after the 2009 South Pacific tsunami caused by an 8.0-magnitude submarine earthquake (see their Fig. 4).

Most of the existing studies about the impact of coral reefs on the tsunamis were based on the field observations. However, field observations are not sufficient to quantitatively determine the importance of different reef parameters in blocking tsunami energy (Kunkel et al., 2006).

* Corresponding author.
E-mail address: hefang@zju.edu.cn (F. He).

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Therefore, some scholars alternatively resort to the well-controlled laboratory experiments. Comparing to the field observations, the laboratory investigations on the interaction between waves and fringing reefs are relatively few, and most of them focused only on the transformation of regular waves (e.g. Gourlay, 1994; Yao et al., 2013, 2017) or irregular waves (e.g. Buckley et al., 2015, 2016; Demirbilek et al., 2007; Nwogu and Demirbilek, 2010; Seelig, 1983). Among these studies, only Nwogu and Demirbilek (2010) had ever investigated the wave run-up over a back reef beach. Different from using regular and irregular waves to model wind waves, a solitary wave has been employed in many related studies to model the leading wave of tsunami because the former can represent many important properties of the latter (Lin, 2004). However, laboratory studies on the interaction between tsunami-like solitary waves and coral reefs are even fewer. We are aware in the literature that only Quiroga and Cheung (2013) attempted to study the effects of reef roughness on the solitary wave transformation over a laboratory reef profile but the solitary wave run-up on the back-reef beach was not yet considered.

Conventionally, following the 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 widely used to study the wave transformation over one-dimensional horizontal (1DH) reef profiles (e.g., Becker et al., 2014; Gourlay, 1996; Tait, 1972; Vetter et al., 2010; Yao et al., 2017). In recent years, the effects of complex bathymetry and different forcing mechanisms have also been modeled by using the two-dimensional horizontal (2DH) and three-dimensional (3D) models to study both the waves and the mean flows, which are typically coupled by the radiation stress concept (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, a type of computationally efficient and phased-resolving model based on the Boussinesq-type equations is the most pervasive. This depth-integrated modeling approach employs a polynomial approximation to the vertical profile of velocity field, thereby reducing one dimension of the three-dimensional problem. It has been proved to be able to consider both the nonlinear and dispersive effects at different degrees of accuracy. It is found that the improved Boussinesq model combined with some semi-empirical breaking-wave and bottom friction models can well simulate the motions of regular wave (Skotner and Apelt, 1999; Yao et al., 2012), irregular wave (Nwogu and Demirbilek, 2010; Yao et al., 2016), solitary wave (Roeber et al., 2010; Roeber and Cheung, 2012) and infragravity wave (Su et al., 2015) over fringing reefs.

So far, to the best of our knowledge, we are only aware of that Kunkel et al., 2006 implemented a nonlinear shallow water model to study the effects of wave forcing and reef morphology factors (i.e. wave height, reef-flat submergence, lagoon width and reef surface roughness) on the wave run-up. However, their numerical model was not verified by any field observations or laboratory data. Moreover, comparing to the nonlinear shallow water equations adopted in their study, the Boussinesq equations are reported better in simulating the process of wave transformation under deeper water in front of the fore-reef slope because of the retention of dispersion terms (Yao et al., 2012). Although Roeber and Cheung (2012) have simulated the solitary wave transformation over a laboratory fringing reef with a Boussinesq-typed model, they did not investigate the wave run-up, letting alone the effects of lagoon width and reef surface roughness.

Therefore, to remedy the numerical study of Kunkel et al. (2006), we firstly carried out a series of laboratory experiments in a wave flume to investigate the solitary wave transformation and run-up over a fringing reef profile, by which four aforementioned factors (wave height, reef-flat submergence, lagoon width and surface roughness) that possibly affect the behaviors of solitary wave transformation and run-up are examined in the well-controlled laboratory environments. We then implemented and validated sophisticated Boussinesq-type model (Lynett and Liu, 2002) to reproduce our laboratory data. We finally applied the validated numerical model to further investigate the impacts of reef morphology variations on the solitary wave run-up over a back-reef beach.

The remaining of this paper is organized as follows. In Section 2, the experimental setup is described. In Section 3, the experimental results including the reflective wave height in front of the fore-reef slope, the transmitted wave height on the reef flat and the wave run-up on the back-reef beach are analyzed and discussed. In Section 4, the governing equations, numerical scheme, boundary conditions, and energy dissipation sub-models of the adopted numerical model are described. The model validation with our laboratory data are presented in Section 5. In Section 6, the validated model is applied to investigate the effects of reef morphology variations on the wave run-up. Main conclusions of this study are drawn in Section 7.

2. Experimental setup

The schematic layout of the experimental arrangement is shown in Fig. 1. Laboratory experiments were conducted in a wave flume of 40 m in length, 0.50 m in width and 0.8 m in height at the Hydraulics Modeling Laboratory, Changsha University of Science and Technology, P. R. China. A servo-controlled wave maker was installed at one end of the flume to generate the target waves. To establish an idealized reef model that replicates the fringing reef, a plane slope of approximate 1:6 was built with the PVC plates at 27.3 m from the wave maker and was truncated to a platform when it reached 0.35 m above the flume bottom. A horizontal reef flat of 9.6 m in length follows immediately after the fore-reef slope and extends all the way to a back-reef beach of 1:6 slope. The reef-flat width matches the flume width. The entire model was firmly held by some stainless steel rods attached to the two walls of the flume. To prevent water escaping or coming out from the gaps between the model and the flume walls, glass glue was used to fill the gaps. Meanwhile, the connection slots between two adjacent plates or between the slope and the flume bottom were sealed by adhesive tapes.

As indicated in Fig. 1, we examined three scenarios based on various laboratory reef profiles and denoted them as Scenario 1, Scenario 2 and Scenario 3 for the convenience of description. Scenario 1 was for the variations of wave height and reef-flat water level. As also shown in Fig. 1, the solitary wave height, H, at any location is defined as the vertical distance between the maximum surface elevation and the initial still water level at that location. Based on above idealized reef model, a series of solitary wave conditions with a combination of five incident wave heights ($H_0 = 0.04$ m, 0.06 m, 0.08 m, 0.10 m, and 0.12 m) and five

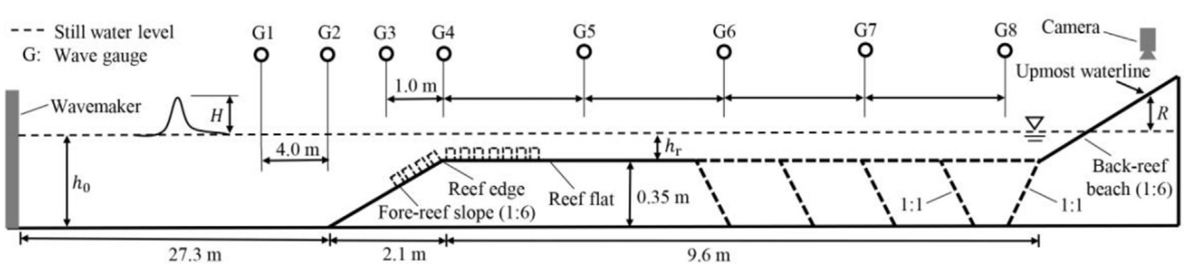

Fig. 1. A sketch of the experimental setup (not to scale).