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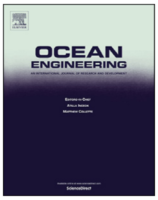

Influence of offshore fringing reefs on infragravity period oscillations within a harbor

Junliang Gao[a,b,*], Xiaojun Zhou[a], Jun Zang[b], Qiang Chen[b], Li Zhou[a,**]

[a] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212003, China
[b] Research Unit for Water, Environment and Infrastructure Resilience (WEIR), Department of Architecture and Civil Engineering, University of Bath, BA2 7AY, UK

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ABSTRACT

The main objective of this paper is to systematically study the influence of offshore fringing reef topography on the infragravity-period harbor oscillations under the condition of wave breaking occurring over the reef. The infragravity (IG) period oscillations inside an elongated harbor excited by bichromatic wave groups are simulated using a fully nonlinear Boussinesq model. Based on a wave analysis technique, influences of plane reef-face slope, reef-face profile shape and reef ridge on the maximum IG period component amplitude, the bound and the free IG waves and their relative components inside the harbor are comprehensively investigated. Results show that under the condition of wave breaking occurring over the reef, all the four above-mentioned variables increase gradually with the reef-face slope, and tend to increase first, then decrease, and then increase again with the mean water depth over the reef face. For the reef-face profile shapes with relatively large mean water depth (equal to or larger than 3.0 m), the existence of the reef ridge always significantly enhances the bound IG waves inside the harbor, while its influences on the maximum IG period component amplitude and the free IG waves both depend on the incident primary wave amplitudes.

1. Introduction

Infragravity (IG) period waves are surface gravity waves with periods between 30 s and 5 min and wave lengths between 100 m and 10 km (Rabinovich, 2009). Via nonlinear wave-wave interactions, the IG period waves can be generated and propagate beneath the primary (short) wave groups (Longuet-Higgins and Stewart, 1962). When the IG period waves with frequencies close to those of resonating harbor modes come into a harbor entrance, they can be highly amplified into inner basins and cause large oscillations of the water surface (Bowers, 1977). Although other external forces can also excite significant oscillations within a harbor, which include atmospheric pressure fluctuations (De Jong and Battjes, 2004), shear flows (Fabrikant, 1995), tsunamis (Gao et al., 2017a, 2018) and impact waves induced by landslides or the failure of structures near the harbor (Dong et al., 2010), for most harbors around the world (where the surface water area is about 1–10 km^2 and the depth is about 5–10 m), the most common external force may be the IG period waves mainly generated through nonlinear interaction of primary wave groups. By creating unacceptable vessel movements, harbor oscillations may interrupt cargo handling, disturb operational efficiency and generate excessive mooring forcing that may break mooring lines (Kumar et al., 2016).

González-Marco et al. (2008) studied the influences of the IG period waves on harbor operations in Gijón Port (Spain) and found that if the IG period waves are present in the wave trains, the port's inactivity time is significantly increased, although very good protection against short wind waves is provided by the harbor. Similar situations were also observed in many other ports and harbors, such as Pohang New Harbor in South Korea (Kumar et al., 2014), Marina di Carrara harbor in Italy (Guerrini et al., 2014), Two Rocks Marina in Australia (Thotagamuwage and Pattiaratchi, 2014), Port of Ferrol in Spain (López and Iglesias, 2013) and Paradip Port in India (Kumar and Gulshan, 2017). Therefore, to relieve the disturbance to harbor operation and minimize possible destructive effects, further research efforts are essential to enhance our present knowledge for the IG period oscillations and thus improve our forecasting ability for the potential adverse effects.

Dong et al. (2013) proposed an IG wave analysis technique to decompose the IG period components inside the harbor into bound and free IG waves, and by using a Boussinesq model, further investigated the influences of the short wavelength on the bound and the free IG

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[*] Corresponding author. School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang, 212003, China.
[**] Corresponding author.
E-mail addresses: gaojunliang880917@163.com (J. Gao), zhouli209@hotmail.com (L. Zhou).

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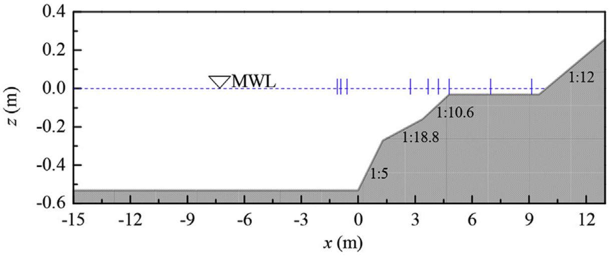

Fig. 1. The computational domain and reef topography for the flume experiment of Nwogu and Demirbilek (2010). The solid blue lines demonstrate the locations of nine wave gauges (gauge 1 to gauge 9 from left to right). The water depth at the reef flat is $h_I = 3.1$ cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

waves and their relative components inside the harbor when the lowest resonant mode, which was induced by bichromatic wave groups, occurred. Subsequently, Gao et al. (2016a) extended the study of Dong et al. (2013) to the lowest four modes, and the effects of not only the short wavelength but also the incident short wave amplitude on IG period waves inside the harbor were systematically investigated. For these two papers, the water depths inside and outside the harbor were set to a constant, and the influence of the offshore topography on harbor oscillations was not considered. Recently, given that the offshore fringing reefs can raise the IG wave energy towards the nearshore and remarkably strengthen the IG period oscillations inside the harbor (Thotagamuwage and Pattiaratchi, 2014), Gao et al. (2017b) further systematically studied the influences of the fringing reefs on the bound and the free IG waves and their relative components inside the harbor when the lowest mode was induced by bichromatic wave groups. Subsequently, Gao et al. (2017c) expanded the investigations of Gao et al. (2017b) to the second to the fifth modes. Although the research findings in Gao et al. (2017b) and Gao et al. (2017c) improved the knowledge on the influence of offshore fringing reefs on the IG period oscillations inside the harbor to some degree, both of them adopted relatively small incident wave amplitudes and wave breaking did not occur over the offshore fringing reefs. In fact, because the water depth over offshore fringing reefs is often very shallow, the phenomenon of wave breaking can be frequently observed (Dong et al., 2014; Nwogu and Demirbilek, 2010; Thotagamuwage and Pattiaratchi, 2014; Yao et al., 2016, 2018). Hence, the studies of Gao et al. (2017b) and Gao et al. (2017c) need to be further expanded to consider wave breaking over the fringing reef.

To enhance the understanding of the IG period waves inside the harbor that is involved in IG period oscillations and offshore reef topographies, this article further studies how the maximum IG period component amplitude, the bound and the free IG waves and their relative components vary with respect to the topographic variation over the offshore fringing reef. Identical to Gao et al. (2017b), investigations in current paper are only confined to the lowest resonant mode induced by bichromatic primary wave groups with two slightly different frequencies. However, different from Gao et al. (2017b), the amplitudes of the incident bichromatic primary waves adopted in this paper are much larger, which leads to the occurrence of wave breaking over the offshore fringing reef. The similarities and differences of wave hydrodynamics inside the harbor under the two conditions of with and without considerations of wave breaking are comprehensively compared and discussed in this paper. All simulations in this article are implemented by using a fully nonlinear Boussinesq model. For simplification, the harbor is assumed to be long and narrow, and then the free surface movement inside the harbor essentially becomes one dimensional.

The remainder of the paper is organized as follows: Section 2 briefly introduces the numerical model and the analysis technique. The applicability of the numerical model for wave motions over the fringing reef under the condition of wave breaking will be verified by experimental data. Section 3 presents the numerical experiment setup and the experimental wave parameters. Section 4 illustrates the simulation results, which are explained in detail. Concluding remarks based on the results are shown in Section 5.

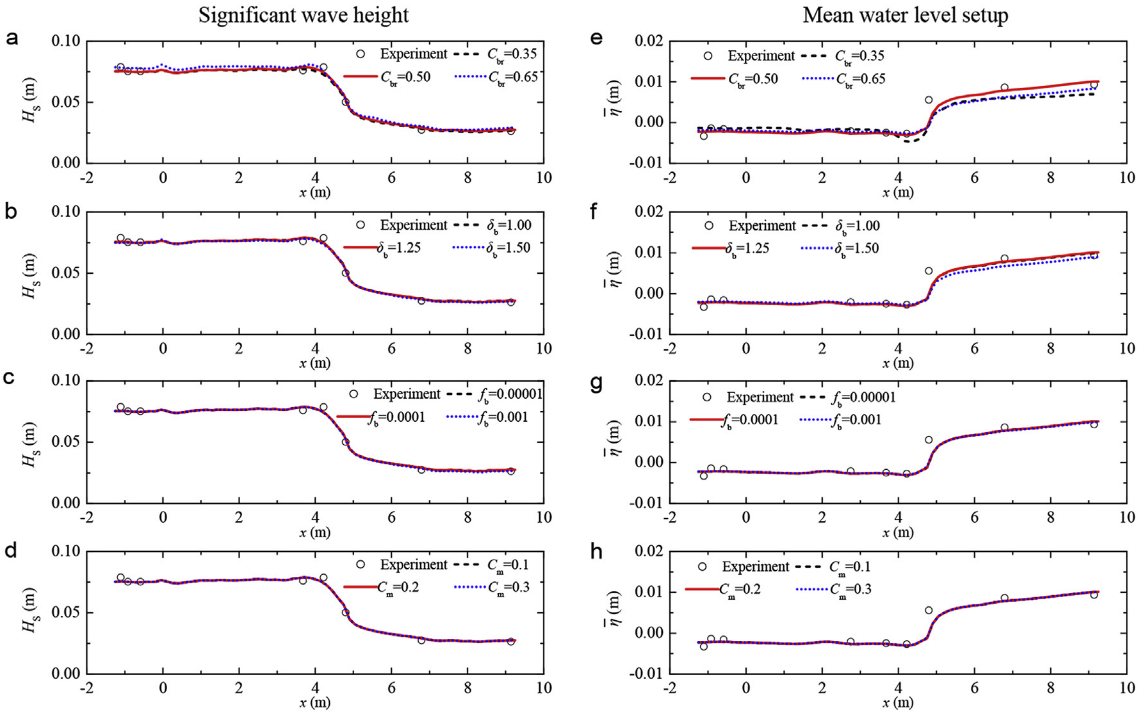

Fig. 2. Sensitivity analyses of the parameters, C_{br}, δ_b, f_b and C_m, for (a–d) significant wave height variation and (e–h) mean water level setup for the experiment of Nwogu and Demirbilek (2010) (incident wave conditions: $H_S = 0.075$ m, $T_p = 1.5$ s, $h_I = 3.1$ cm).