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Influence of offshore topography on the amplification of infragravity oscillations within a harbor

Junliang Gao[a,b,c,*], Chunyan Ji[a], Yingyi Liu[d], Xiaojian Ma[a], Oleg Gaidai[a]

[a] School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China
[b] Jiangsu Key Laboratory of Coast Ocean Resources Development and Environment Security, Hohai University, Nanjing 210098, China
[c] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[d] Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan

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ABSTRACT

The main purpose of this article is to systematically investigate the influence of offshore fringing reef topography on the infragravity-period harbor oscillations. The infragravity (IG) period oscillations inside an elongated harbor induced by normally-incident bichromatic wave groups are simulated using a fully nonlinear Boussinesq model, FUNWAVE 2.0. Based on an IG wave decomposition method, effects of plane reef-face slopes, reef-face profile shapes and the existence of reef ridge on bound and free IG waves and their relative components inside the harbor are comprehensively studied. For the given harbor and reef ridge, the range of the reef-face slopes and the various profile shapes studied in this paper, results show that the amplitude of the free IG waves inside the harbor increases with the increasing of the reef-face slope; while the bound IG waves inside the harbor seem insensitive to it. The effects of the profile shapes on the IG period waves inside the harbor are closely related to the width of the reef face. The existence of the reef ridge can relieve the bound IG waves to some extent when the incident short wave amplitudes are relatively large, while its effects on the free IG waves are negligible.

1. Introduction

In the real ocean, wind waves and swell waves always propagate in the form of wave groups. Via nonlinear wave–wave interactions, long waves with periods of 30–300 s, also defined as infragravity (IG) waves, can be generated and propagate beneath the primary (short) wave groups. When the IG 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 [1–3]. By creating unacceptable vessel movements, harbor oscillations may interrupt the operation of docks and generate excessive mooring forces that may break mooring lines [4]. Besides the IG waves through nonlinear interactions of the primary waves, other external forces can also induce significant oscillations within a harbor, which include atmospheric pressure fluctuations [5], shear flows [6], tsunamis and impact waves induced by landslides or the failure of structures near the harbor [7,8].

Although research efforts on harbor resonance began in the early 1950s [9], the majority of past studies have assumed that the water depth inside and outside the harbor is constant (e.g., [1–3,10–13]), and the topographic influence on harbor oscillations has not been considered in these papers. In fact, the investigation of the influence of topography on harbor resonance started relatively late and few researchers focused on this problem. Using the method of matched asymptotic expansion, Liu [14] analytically examined the effects of water depth discontinuity near the harbor entrance on harbor oscillations. Panchang et al. [15] proposed an elliptic harbor wave model combining with a one-dimensional representation of the exterior bathymetry to consider exterior bathymetric effects on the wave field inside the harbor. Recently, based on analytical or numerical methods, the effects of various topographies inside the harbor on harbor oscillations were investigated by several researchers (e.g., [16–18]). Although different methods and bottom profiles inside the harbor were adopted in these works, consistent evidence of the influence of topographic variation on the wave conditions inside the harbor was found.

The vast majority of the world's coastlines, perhaps reaching up to 80%, contain a broad class of submerged reef structures, which include tropical coral reefs, relic temperate limestone platforms and rocky coastal features [19]. Therefore, in the last few decades,

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

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wave interactions with fringing coral reefs have been one of the primary focuses of the offshore and nearshore hydrodynamics [19,20]. However, the existing literature on wave hydrodynamics over fringing reefs mainly focused on the problems such as wave setup/setdown, wave-generated flow, wave dissipation and energy evolution. Investigations on influences of fringing reefs on the wave fields inside the harbor are rare. In addition, based on field measurements in Two Rocks Marina in south-west Australia and numerical simulations of a Boussinesq model, Thotagamuwage and Pattiaratchi [21] found that during stormy sea conditions, offshore reefs can increase the IG wave energy over the offshore reefs by a factor of 8–10 compared to the IG wave energy at offshore, and the increased IG wave energy over the offshore reefs elevated the IG wave energy toward the nearshore and significantly enhanced the IG period oscillations inside the harbor. Therefore, considering remarkable impacts of fringing reefs on harbor oscillations and relatively few studies so far, more investigation efforts should be made to improve the knowledge on wave hydrodynamics related to fringing reefs.

The geometrical characteristics of fringing reefs are different from those of normal coastal beaches in many aspects. A typical fringing reef is characterized by a seaward sloping reef face and an inshore shallow reef flat extending toward the coastline, and reef ridges or similar configurations ("reef crest" or "reef rim" in some literature) have been frequently observed at the edges of coral reefs although the reef profile may vary from site to site [22]. To enhance the understanding of influences of fringing reefs on the IG period harbor oscillations, this paper systematically investigates how reef-face slopes, profile shapes and the existence of reef ridge affect the bound and free IG waves and their relative components inside the harbor. In this article, all simulations are based on the fully nonlinear Boussinesq model, FUNWAVE 2.0, which was proposed by Kirby et al. [23]. For simplification, the harbor is assumed to be long and narrow such that the free surface movement inside the harbor becomes one dimensional. The water depth inside the harbor is constant, and the incident waves are bichromatic with two slightly different frequencies. The analysis technique proposed by Dong et al. [11] is adopted to decompose the IG period components inside the harbor into bound and free IG waves.

It should be noted here that although considerable free IG waves can be generated by wave breaking over fringing reefs [21], which would dramatically change the IG wave fields and the relative components of bound and free IG waves inside the harbor, due to the following two reasons, wave breaking is not considered in the current study. Firstly, the wave breaking phenomenon when the incident waves from the open ocean propagate across fringing reefs does not always occur. Hardy and Young [24] conducted field experiments which obtained measurements of the attenuation and transformation of short gravity waves as they propagated across the windward edge of John Brewer Reef, located 70 km northeast of Townsville, Queensland, Australia. Water-level data were collected for over 3000 individual time series during a wide range of environmental conditions. They found that the wave energy on the reef flat was controlled by both incident wave energy and the water depth. At higher tide levels, wave breaking is nonexistent when the incident wave energy is relatively small; on the contrary, wave breaking mainly occurs at lower tide levels. Similar evidence for the existence of the nonbreaking wave condition over fringing reefs can also be found in Gourlay [25]. Therefore, the present study also has practical engineering and scientific significance although wave breaking over fringing reefs is not considered. Secondly, the current study can lay a good foundation for the further research in which wave breaking is considered. Specifically speaking, the investigation findings in this paper can be utilized to investigate similarities and differences with related phenomena when wave breaking is considered, which will help people to understand the IG wave hydrodynamics inside the harbor located near fringing reefs more comprehensively. Thus, the present study also has certain reference value for the further study in which wave breaking is considered.

The remainder of the paper is organized as follows: Section 2 describes the numerical model and the analysis technique. The applicability of the former over rapidly varying bathymetry will be verified by a set of numerical experiments. Section 3 presents the numerical experiment setup and the experimental wave parameters. Section 4 demonstrates the simulation results, which are explained in detail. Concluding remarks based on the results are given in Section 5.

2. Numerical model and analysis technique

2.1. Numerical model

2.1.1. Model description

All numerical experiments in this paper are performed using the well-known and widely implemented FUNWAVE 2.0 model [23], which uses the fully nonlinear Boussinesq wave model on curvilinear coordinates. The one-way wave maker theory proposed by Chawla and Kirby [26] is used to generate monochromatic or random waves. Sponge layers are placed at the boundaries of the domain to effectively absorb the energy of outgoing waves with various frequencies and directions. The capability of the model to predict wave propagation and transformation from deep to shallow water has been well validated by laboratory experiments [23,27].

To verify the applicability of the FUNWAVE 2.0 model to simulate harbor oscillations with strong wave nonlinearity inside the harbor, Gao et al. [28] used the model to reproduce the physical experiments conducted by Rogers and Mei [29]. Gao et al. [28] compared the numerical results of the first three super harmonics with the experimental data of Rogers and Mei [29] for two elongated rectangular bays of different lengths. Overall agreement was observed between the measured data and the numerical results for all the three super harmonics. It was shown that the numerical model can also simulate strong nonlinear harbor oscillations accurately.

2.1.2. Model validation for rapidly varying bathymetry

Unlike coastal beaches, which normally have mild slopes, a typical fringing reef often includes a steep transition from the relatively deep to shallow waters. One of the major concerns with applying Boussinesq equation models to fringing reefs is the relatively steep reef-face slopes; this is because certain higher-order derivative terms of the water depth are discarded in the derivation process of Boussinesq equations.

To verify the ability of the FUNWAVE 2.0 model to deal with rapidly varying bathymetry, a train of monochromatic waves propagating over plane reef faces with different slopes are considered here. Booij [30] first investigated this problem to examine the accuracy of a mild-slope equation by comparing the predicted reflection coefficients with finite element method (FEM) solutions. Booij's FEM solution, however, covers the slope range steeper than about 1:3 and no data is provided for the milder slopes. Subsequently, Suh et al. [31] extended Booij's FEM solution to the milder slopes. Then, Madsen et al. [32] and Yao et al. [22] reproduced this problem to validate the capacity of their respective Boussinesq equation models. Fig. 1 shows the bottom profile for this problem, which consists of a plane slope connecting two constant-depth regions. The offshore water depth, h_0, is 0.6 m; while the reef-flat water depth, h_l, is set to 0.2 m. A train of monochromatic waves with a period of $T = 2.0$ s are simulated. The width of the reef face, b, varies from 0.2 m to 10 m, corresponding to the slope of $S = (h_0 - h_l)/b = 2.0–0.04$. Iden-