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Numerical study of infragravity waves amplification during harbor resonance

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ABSTRACT

The infragravity (IG) period oscillations inside an elongated rectangular harbor excited by bichromatic wave groups are simulated using a fully nonlinear Boussinesq model. Based on an IG wave analysis technique, this study presents a comprehensive investigation on how bound and free IG waves and their relative components change with respect to the amplitudes and wavelengths of incident primary (short) waves under the condition of the lowest four resonant modes. For the given harbor and ranges of wavelength and amplitude of the primary waves studied in this paper, it is shown that the amplitudes of both the bound and free IG waves become more evident when the short wavelengths increase, and the latter are always larger than the former due to resonant amplification. The amplitudes of both the bound and free IG waves change quadratically with the amplitudes of the incident short waves.

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). Theoretical knowledge of the generation, propagation, dissipation and interaction of IG waves with coastlines and port structures has been highly developed since the early 1950 s. Munk (1949) and Tucker (1950) carried out the first observation of the IG waves, associated with wave groups. Longuet-Higgins and Stewart (1962, 1964) determined analytical relations to explain the propagation of IG waves at wave group celerity, the genesis of bound IG wave energy and its relationship with nonlinear, spatial and temporal changes of the momentum flux of the wave trains traveling towards the shore.

When the long period waves with frequencies close to those of resonating harbor modes come into a harbor opening, they can be highly amplified into inner basins resulting in large oscillations of the water surface (Miles and Munk, 1961; Vanoni and Carr, 1950). A variety of dynamic forcings can induce significant oscillations within a harbor. These external forcings include tsunamis originating from distance earthquake, longshore-propagating edge waves, wind and pressure fluctuations, and impact waves induced by landslides or the failure of structures near the harbor (Bellotti et al., 2012; Chen et al., 2004; De Jong and Battjes, 2004; Dong et al., 2010a). For the very long-period incident waves such as tsunamis and waves originating from wind and pressure fluctuations, they can affect only very large harbors because their natural oscillation periods are generally longer than 10 min, which matches the very long-period wave band. 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 forcing may be IG waves, mainly generated through nonlinear interaction of short wave groups. González-Marco et al. (2008) analyzed the effect of IG waves on port operations in Gijón harbor (Spain) and found that the port's inefficiency is significantly increased if IG waves are present in the wave trains, although the harbor offers very good protection against wind short waves. Similar situations can be found in various other ports and harbors around the world, such as Hua-Lien harbor in Taiwan (Chen et al., 2004), Hosojima harbor in Japan (Yoshida et al., 2000), Port of Long Beach in California (Kofoed-Hansen et al., 2005), and Pohang New Harbor in South Korea (Kumar et al., 2014). Hence, in order to identify layouts and technical solutions that minimize the downtime of the facility, it is crucial to further improve the knowledge of the IG waves inside the harbor.

The importance of incident short wave groups on IG period harbor oscillations was initially proved by Bowers (1977), both theoretically and experimentally. He studied mean free-surface oscillations in a narrow rectangular channel of constant depth and

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discontinuous width. A train of sinusoidally modulated wave groups incident from infinity generates not only bound IG waves, but also additional free IG waves. Bowers (1977) demonstrated that the free IG waves are generated in the diffraction process with the same frequency as the bound IG waves because of an imbalance between the long-period fluctuations in the water pressure inside and outside the harbor entrance. This imbalance arises because the primary wave heights inside the harbor are different from the wave heights outside, giving rise to different bound IG waves inside and outside the harbor. Thus, it becomes necessary to introduce additional free IG waves for purposes of the total second-order water pressure continuity at the harbor entrance; the free IG waves will then be amplified when the group period is close to a natural period of the harbor. In the last few decades, extensive field observations and numerical simulations on IG waves inside harbors, such as Esperance harbor and Two Rocks Marina in Australia (Morison and Imberger, 1992; Thotagamuwage and Pattiaratchi, 2014a, 2014b), Marina di Carrara harbor in Italy (Bellotti and Franco, 2011; Guerrini et al., 2014), Port of Ferrol in Spain (López and Iglesias, 2013; López et al., 2012), and Barbers Point harbor in Hawaii (Okihiro et al., 1993), have subsequently confirmed those findings by showing strong correlation between IG waves inside the harbor and short wave groups outside the harbor.

Dong et al. (2010b) implemented numerical experiments based on the Boussinesq model and employed a wavelet-based bispectrum to analyze temporary features of wave–wave interactions at various phases of IG period oscillations excited by short wave groups. The influence of short wave frequencies on IG period oscillations was also investigated in that paper. Dong et al. (2010b) found that short waves with low frequencies can excite more obvious long-period fluctuations than those with higher frequencies. The subharmonics not only get energy through difference interactions, but also export energy through sum interactions in the response and quasi-steady phases. In the damp phase, wave energy is concentrated at the lowest resonance mode, and there is a reversal energy transfer from the subharmonics to other components. Subsequently, Dong et al. (2013) proposed a wave separation procedure to decompose the IG period components inside the harbor into bound and free IG waves, and further investigated the influence of the short wavelengths on the bound and free IG waves and their relative components inside the harbor when the lowest resonant mode, which are excited by regular wave groups, occurs. For comparison, the non-resonant wave condition was also considered. Dong et al. (2013) demonstrated that the amplitudes of bound and free IG waves and their ratio are closely related to the short wavelengths, regardless of whether the harbor is resonant or not.

To improve the understanding of the IG waves inside harbors involved in IG period oscillations, this paper further investigates how the bound and free IG waves and their relative components change with respect to the incident short waves. Compared to Dong et al. (2013), there are mainly two research developments in this paper. Firstly, in Dong et al. (2013), only the lowest resonant mode was investigated; while in this paper, we extended the resonant mode to the lowest four modes to explore the similarities and differences between different modes. Secondly, this paper systematically investigated the influence of not only the short wavelengths but also the amplitudes of the incident short waves on the bound and free IG waves and their relative components inside the harbor. In this paper, all simulations are based on the fully nonlinear Boussinesq model proposed by Wei et al. (1995). For simplification, the harbor is assumed to be long and narrow; the free surface movement inside the harbor then essentially becomes one dimensional. The water depth inside and outside the harbor is constant, and the incident waves are bichromatic with two slightly different frequencies.

The remainder of this paper is organized as follows. Section 2 describes the numerical model and the analysis technique, which will be verified using physical experimental data and known analytical signals, respectively. Section 3 presents the numerical experimental 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

Numerical experiments are performed using the well-known and widespread Funwave2.0 model (Kirby et al., 2003), referring to the fully nonlinear Boussinesq wave model on curvilinear coordinates. The Funwave2.0 model retains information to $O[(kh)^2]$ for frequency dispersion and to all orders for nonlinearity a/h (where k denotes the wavenumber scale, h denotes the water depth and a denotes the wave amplitude). The one-way wave maker theory proposed by Chawla and Kirby (2000) 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 Funwave2.0 model to predict wave propagation and transformation from deep to shallow water has been well validated by laboratory experiments (Bruno et al., 2009; Kirby et al., 2003).

To verify the applicability of the Funwave2.0 model to the simulation of nonlinear harbor resonance, Dong et al. (2010b) used the model to reproduce the physical experiments conducted by Rogers and Mei (1978). Dong et al. (2010b) compared the numerical results of the first three super-harmonics with the experimental data of Rogers and Mei (1978) for three long and narrow bays of different lengths. Overall agreement was observed between the measured data and the numerical results. It was demonstrated that the numerical model can also simulate nonlinear harbor resonance accurately.

2.2. Analysis technique

This paper employs the wave separation procedure originally proposed by Dong et al. (2013) to decompose the IG period components inside the harbor into bound and free IG waves. To facilitate the reader's understanding of this paper, the wave separation procedure is illustrated briefly in this section.

Fig. 1 shows the setup of the numerical experiment studied in this paper. The length of the harbor is $L = 100.0$ m, and the width of the opening is $W = 5.0$ m. Twenty-one wave gauges are equidistantly deployed along the central line inside the harbor; the

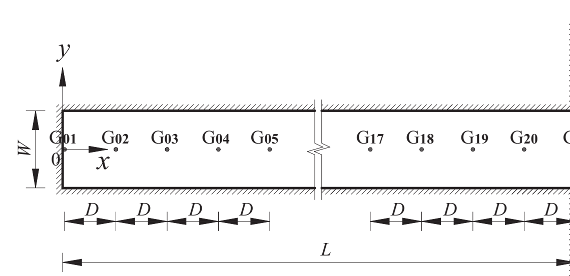

Fig. 1. Definition sketch of the harbor, the arrangement of the wave gauges and the coordinate system.