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Numerical study on transient harbor oscillations induced by solitary waves

Junliang Gao[a,b,c,*], Chunyan Ji[a], Yingyi Liu[d], Oleg Gaidai[a], Xiaojian Ma[a], Zhen Liu[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 the variation of the incident wave height and the bottom profile inside an elongated rectangular harbor on relevant physical phenomena involved in transient harbor oscillations induced by normal-incident solitary waves. These phenomena include wave height evolution, oscillation amplification, total wave energy and relative wave energy distribution inside the harbor. A series of numerical experiments are carried out using the FUNWAVE 2.0 model. Results show that the height evolution of the incident wave during the shoaling process inside the harbor coincides well with Green's law. When the wave nonlinearity is relatively weak, the maximum oscillation inside the harbor can be regarded as increasing linearly with the incident solitary wave height; while as the wave nonlinearity becomes strong, the amplification factor of the incident solitary wave increases gradually with the wave nonlinearity. The total wave energy trapped in the harbor depends on both the mean water depth and the bottom profile. The relative wave energy distribution inside the harbor is greatly affected by the incident solitary wave height; however, the variation of the bottom profile inside the harbor has a negligible effect on it.

1. Introduction

Harbor resonance is the phenomenon of trapping and amplifying of wave energy inside a semi-enclosed water body, such as a bay or harbor. It may be induced by infragravity waves, wave groups, tsunamis, atmospheric fluctuations and shear flow traveling into bays or harbors (Bellotti et al., 2012; Bowers, 1977; De Jong and Battjes, 2004; Dong et al., 2013, 2010a,b; Fabrikant, 1995; Okihiro and Guza, 1996). By creating unacceptable vessel movements, harbor resonance may interrupt the operation of docks and generate excessive mooring forces that may break mooring lines (López and Iglesias, 2014; Uzaki et al., 2010). Rabinovich (2009) reviewed recent advances in understanding and modeling of harbor oscillations.

Among different generation mechanisms, harbor oscillations induced by tsunamis usually have destructive impact. Tsunamis are triggered by submarine earthquakes, offshore landslides, undersea volcanic eruptions, or other kinds of disturbances, such as onshore landslides falling into water, or meteors falling into the open ocean, etc. As tsunamis approach the coastal area, the wave height increases significantly due to the continuous decrease of the water depth and the focus of the wave energy (Zhao et al., 2012). For example, the Indian Ocean tsunami, which was induced by the Sumatra earthquake on December 26, 2004, propagated for about 2 h to Colombo harbor (Sri Lanka), triggering extreme oscillations with a maximum wave height of 3.87 m and a resonant period of about 75 min. It then propagated for about 14 h to Bunbury harbor (Western Australia), triggering oscillations with a maximum wave height of 1.75 m (Pattiaratchi and Wijeratne, 2009). In order to reduce the disturbance to normal harbor operation and minimize the possible destructive effect, a further research effort is necessary to improve our current knowledge for this type of wave amplification and thus enhance our predictive capability.

Although research efforts on harbor oscillations began in the early 1950s (Vanoni and Carr, 1950), the majority of past studies have been restricted to stationary oscillations induced by the steady wave climate (Bowers, 1977; Dong et al., 2013; Gao et al., 2016a; Ippen and Goda, 1963; Lee, 1971; Mei and Agnon, 1989; Miles and Munk, 1961; Olsen and Hwang, 1971; Raichlen and Naheer, 1976; Vanoni and Carr, 1950; Wang et al., 2011a, 2015, 2014; Wu and Liu, 1990). The study on transient harbor oscillations induced by transient long waves started relatively late and few researchers focused on this problem. Using theoretical and experimental methods, Lepelletier (1980); Lepelletier and Raichlen (1987) studied transient nonlinear oscillations inside the harbor induced by transient long waves, such as tsunamis. Based on a mild-slope equation model, Bellotti (2007) quantified the time-response of harbor basins to long waves under resonance conditions. Using laboratory experiments combined with a Boussinesq model

* 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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(FUNWAVE 2.0), Dong et al. (2010a) explored the response of a rectangular harbor with constant depth to subaerial landslide-generated impact waves. They found that landslide-generated impact waves usually include components with solitary wave characteristics and also components with dispersive wave characteristics. Moreover, the components with solitary characteristics play an important role in the resonance of the harbor. Wang et al. (2011b) developed a second-order dispersive Boussinesq model, which can describe the generation and propagation of earthquake- and landslide-induced tsunamis. Then transient oscillations induced by seafloor movements inside a harbor of constant slope were studied systematically. More recently, using the FUNWAVE 2.0 model, Gao et al. (2016b) carried out a series of numerical experiments on transient harbor oscillations triggered by solitary waves, and further analyzed the relative wave energy distribution systematically inside the harbor by employing the normal mode decomposition method (Gao et al., 2015; Sobey, 2006).

As some characteristics observed in the tsunami events can be well modeled by solitary waves, for instance, the stable form of hump-like waves after a long period of propagation, solitary waves have been employed in tsunami research for decades (e.g., Goring, 1978; Synolakis, 1987; Liu et al., 1995; Li, 2000). Studies on solitary waves provide a great deal of information in the investigation of tsunamis, including the runup of solitary waves on a uniform sloping beach (Synolakis, 1987), the interaction of solitary waves with a harbor (Dong et al., 2010a; Gao et al., 2016b), etc. In order to further improve the knowledge of tsunami-induced oscillations, this paper uses solitary waves to explore the related resonant phenomena. The focus of this paper is to comprehensively investigate the wave height evolution, the oscillation amplification, the total wave energy and the relative wave energy distribution during transient harbor oscillations induced by normal-incident solitary waves with different heights. Effects of different bottom profiles inside the harbor on these phenomena are also studied systematically. Compared to Dong et al. (2010a) and Gao et al. (2016b) that have studied transient harbor oscillations excited by solitary waves, there are mainly three research developments in this paper. Firstly, in the above two papers, the incident solitary wave height was relatively small and the wave climate inside the harbor was restricted to weakly nonlinear wave conditions; while in this paper, the wave condition inside the harbor is extended to strong wave nonlinearity close to wave breaking. Secondly, investigations on the wave height evolution and the total wave energy inside the harbor are considered for the first time in the present study. Thirdly, in the above two papers, only simple bathymetries inside the harbor, that is, flat bottom and constant slope bottom, were used; whereas in this study, more complex bathymetries inside the harbor are considered. In this paper, identical to Dong et al. (2010a) and Gao et al. (2016b), all numerical experiments are performed using the FUNWAVE 2.0 model as well. For simplification, the harbor is assumed to be long and narrow; the free surface movement inside the harbor then essentially becomes one-dimensional.

The remainder of the paper is organized as follows: Section 2 describes the numerical model, which will be verified using physical experimental data and an analytical solution. 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

2.1. Model description

All numerical experiments in this paper are performed using the well-known and widely implemented FUNWAVE 2.0 model. It was proposed and developed at the University of Delaware (Kirby et al., 2003). The one-way wavemaker theory proposed by Chawla and Kirby (2000) is used to generate monochromatic or random waves, while solitary waves are generated by a two-way wavemaker method. 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 FUNWAVE 2.0 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).

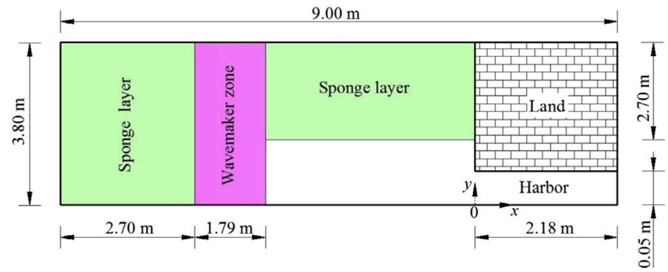

Fig. 1. Schematic plan view of the numerical wave flume used to simulate the experiment of Rogers and Mei (1978) for Bay 3. Since the geometry is symmetric with respect to the *x*-axis, only a half-domain is used for computations. The half-harbor domain is located in the region $0 \le x \le 2.18$ m and $0 \le y \le 0.05$ m.

2.2. Model verification

To verify the applicability of the FUNWAVE 2.0 model to simulate harbor resonance with strong wave nonlinearity inside the harbor, the model is used to simulate nonlinear harbor resonance experiments of Rogers and Mei (1978). Meanwhile, because the runup of solitary waves on a vertical wall is involved in accurate prediction of solitary wave amplification inside the harbor, the capacity of the model to predict the maximum runup of solitary waves on the vertical wall is also examined here. Numerical results are compared with existing experimental data and a second-order analytical solution.

2.2.1. Nonlinear harbor resonance

When the incident wave amplitude is small compared to the water depth, oscillations inside the bay can be predicted by linear theory; whereas when the incident amplitude is large, higher harmonic wave components can be expected due to the nonlinear effect. Rogers and Mei (1978) (hereinafter referred to as RM), performed laboratory experiments in a 7.6 m wide and 13.7 m long wave tank to study nonlinear oscillations for three bays with lengths of 0.37 m, 1.27 m, and 2.18 m (hereinafter referred to as Bay 1, Bay 2, and Bay 3) and the uniform width of 0.10 m. The wavemaker generated regular waves with a wave period of 1.545 s, and a constant water depth of 0.15 m was used. In Rogers and Mei (1978), due to nonlinearity, the lengths of the three bays were experimentally determined in accordance with the lowest three resonant modes. According to the linear dispersion relationship

$$\frac{2\pi}{T^2} = \frac{g}{L}\tanh\left(\frac{2\pi}{L}h\right), \tag{1}$$

the wavelength of the regular waves is equal to 1.79 m. The symbols h, T, L and g denote the water depth, the wave period, the wavelength and the gravitational acceleration, respectively.

In this paper, the nonlinear harbor oscillations inside Bays 2 and 3 are simulated. Fig. 1 shows the computational domain of the numerical wave flume used for Bay 3 in the simulation. Because the geometry is symmetric with respect to the central line of the bay, only half of the domain is used for simulation.The numerical wave flume has a length of 9.00 m and a width of 3.80 m. All boundaries are set to be fully reflective. At the left and upper boundaries of the numerical wave flume, sponge layers are installed to absorb the energy of reflected and radiated waves, and the width of the sponge layers is set to be slightly larger than 1.5 times the wavelength of incident regular waves. The