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Numerical investigation of oscillations induced by submerged sliding masses within a harbor of constant slope

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ABSTRACT

Oscillations within a rectangular harbor of constant slope induced by submerged sliding masses are investigated numerically based on Boussinesq-type equations and results are used to reveal the characteristics of the generated oscillations. The numerical result of each transverse eigenfrequency is very close to the theoretical prediction and the spatial structure of each mode of the oscillations may also be well captured by the existing analytical solutions based on shallow water equations. The investigation shows that relatively small-scale sliding masses whose width is small compared with the harbor width may induce obvious transverse oscillations. The predominant transverse components are those with small mode numbers when the solid slides start moving from the backwall. In comparing the oscillations induced by the slides of constant velocity and those accelerated by gravity force with bottom friction, it is observed that the movements accelerated by gravity force may facilitate the development of very low transverse oscillation modes while those with constant velocity may also be in favor of the higher ones. The augmentation of the sliding velocity along the constant slope may shift the amplitudes of the oscillation components to smaller values, which corresponds to the physical understandings of the waves generated by underwater sliding masses or landslides. While the sliding masses may not act on an isolated point of the bottom but follow a certain trajectory along the harbor, the transverse oscillations induced by them are sensitive to their position of departure in both the cross-harbor direction and the offshore direction. Longitudinal oscillations may be induced by relatively large sliding masses of harbor width on a constant slope within the harbor. Although the longitudinal oscillations may not reach a steady state without forcing terms at the entrance of the harbor, some patterns of several low-mode ones occur and wavelet spectra are used to analyze their evolutions and comparisons are made with theoretical predictions. It is revealed that the longitudinal oscillations are also sensitive to the moving velocity and initial location of the sliding masses.

1. Introduction

Oscillations and trapped modes in harbors and bays may cause many problems such as preventing of cargo operations, breaking of mooring ropes, damaging of infrastructures or moored vessels and can be triggered by the match of the eigenvalues of the free oscillations of a harbor and the external forces coming from wave groups, atmospheric pressure disturbances, seafloor motions, landslides or shear flows etc. Investigations of harbor oscillations are in the first place carried out with theoretical analysis, which presents a useful method for capturing the characteristics of the resonant mechanism influenced particularly by the factors such as the geometry features, topography effects, etc. Miles and Munk [1] firstly considered the resonance in a harbor with narrow entrance. The wave motions within the harbor were described by matching conditions at the opening. Fourier transformation methods were applied by Ippen and Goda [2] to obtain the solution in a rectangular harbor. By employing the Weber solution of the Helmholtz equation, Lee [3] presented an analytical solution for wave-induced oscillations in a harbor of arbitrary geometry. For a harbor of two coupled basins with periodic incident waves, Mei and Ünlüata [4] derived the solution by applying the method of matched asymptotic expansions. Wu and Liu [5] examined the second-order low-frequency oscillations excited by incident wave groups in a rectangular harbor. Wang et al. [6] reported their formulations in harbors of a constant slope and of a hyperbolic-cosine squared bottom for both longitu-

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dinal and transverse oscillations. Although with relatively simple geometries and topographies, these analytical investigations have been informative and improve the physical understandings of the mechanism of harbor oscillations.

In parallel to the analytical investigations of the harbor oscillations, some numerical models have been developed, including linear ones based essentially on mild-slope equations [7–9] and nonlinear ones based on Boussinesq-type models [10–14]. For reproducing short wave disturbances in harbors, the linear models are convenient with their computational efficiency and can be applied to relatively large domains. For relatively long-period oscillations induced by incident short waves and higher harmonics, the Boussinesq-type nonlinear ones may be suitable and can predict the behaviors of long waves generated in relatively shallow water, including their propagation, diffraction and resonant amplification.

As to the sliding masses or landslides, the wave phenomenon generated by them have been intensively studied especially in the last decade. Both physical and numerical experiments have been conducted. The physical experiments are carried out in wave tanks or wave basins of different dimensions with two or three dimensional solid landslides [15–18] while the numerical models include the large-eddy-simulation approach with the volume of fluid method to track the free surface [19] and the depth integrated Boussinesq-type equations [20]. Based on experimental studies, the overall pictures of waves induced by a solid slide are summarized by Seo and Liu [21]. In particular, the numerical results obtained by Lynett and Liu [20] using a Boussinesq-type model show that in the nearshore waves generated by sliding masses or landslides, the edge waves are dominant patterns which propagate along the coastline and decay rapidly in the offshore direction. As the transverse oscillations within harbors are typically standing edge waves, the Boussinesq-type numerical model may present an efficient tool to investigate the harbor oscillations due to the movements of underwater sliding masses.

A brief introduction of the Boussinesq type model established for the simulations of the waves on a time-dependent bottom following the derivations of Nwogu [22] and Wang et al. [23] is presented in Section 2. The validation of the numerical model with the results of a typical physical experiment is shown in Section 3, accompanied by a comparison of the numerical results of the oscillations generated by a submerged sliding wedge within a harbor of two different constant slopes with the analytical solutions of Wang et al. [23] In Section 4, more detailed numerical investigations are presented on the oscillations induced by the underwater sliding masses moving on the surface of the constant slope within the harbor. Oscillations generated by a sliding mass of constant velocity and by a free falling one accelerated by gravity force with bottom friction along the constant slope are compared firstly. Effects of the changing velocity of the sliding masses traveling relatively fast along the surface of the seafloor are studied afterwards. The effects of different shapes of the sliding masses are preliminarily tested with the two-dimensional Boussinesq type model. Influences of the initial location of the sliding masses are examined in both the cross-harbor direction and the offshore direction. Conclusions are drawn in the last section.

2. Numerical model

Following the derivations of Nwogu [22] and Wang et al. [23], a three dimensional wave field with surface elevation $\eta(x,y,t)$ propagating over a time depending water depth $h(x,y,t)$ is considered with a Cartesian coordinate system (x,y,z) while z measured positive upwards from the still water level. Dimensionless variables (marked with apostrophe) are defined by introducing the characteristic water depth h_c as the vertical length scale, the typical wave length l_c as the horizontal length scale and the characteristic wave amplitude a_c as the scale of the wave motion:

$$\left(x',y'\right)=\frac{(x,y)}{l_c},\ z'=\frac{z}{h_c},\ t'=\frac{t\sqrt{gh_c}}{l_c},\ h'=\frac{h}{h_c},\ p'=\frac{p}{\rho g a_c},\ \left(u',v'\right)=\frac{(u,v)}{\varepsilon\sqrt{gh_c}},\ w'=\frac{w}{\frac{\varepsilon}{\mu}\sqrt{gh_c}},\ \eta'=\frac{\eta}{a_c} \tag{2.1}$$

where g is the gravitational acceleration, (u,v,w) is the water particle velocity vector, p is the pressure and ρ is the fluid density. There are two small parameters induced, $\varepsilon=\frac{a_c}{h_c}$, $\mu=\frac{h_c}{l_c}$, which signify nonlinearity and frequency dispersion respectively. Assuming that the fluid is inviscid and incompressible, the wave motion can be described by Euler's equations in the dimensionless form (for simplicity, as all the variables in the following derivations are dimensionless ones, the apostrophes are eliminated in the equations):

$$\mu^2\nabla\boldsymbol{u}+w_z=0,\quad -\mathrm{h}\le \mathrm{z}\le\varepsilon\eta \tag{2.2}$$

$$\boldsymbol{u}_t+\varepsilon\boldsymbol{u}\nabla\boldsymbol{u}+\frac{\varepsilon}{\mu^2}\mathrm{w}\boldsymbol{u}_z=-\nabla\mathrm{p},\quad -\mathrm{h}\le \mathrm{z}\le\varepsilon\eta \tag{2.3}$$

$$\varepsilon w_t+\varepsilon^2\boldsymbol{u}\nabla\mathrm{w}+\frac{\varepsilon^2}{\mu^2}\mathrm{w}w_z=-\varepsilon p_z-1,\quad -\mathrm{h}\le \mathrm{z}\le\varepsilon\eta \tag{2.4}$$

with $\mathbf{u}=(u,v)$ the dimensionless horizontal velocity vector, $\nabla=\left(\frac{\partial}{\partial x},\frac{\partial}{\partial y}\right)$ the dimensionless horizontal gradient vector and the subscripts denoting partial derivatives.

On the free surface of the water $z=\varepsilon\eta$, the kinematic and dynamic boundary conditions can be expressed as

$$w=\mu^2\left(\eta_t+\varepsilon\mathbf{u}\nabla\eta\right) \tag{2.5}$$

$$p=0 \tag{2.6}$$

The kinematic boundary condition at the seafloor $z=-h$ is given by

$$w=-\mu^2\left(\mathbf{u}\nabla\right)h-\frac{\mu^2}{\varepsilon}h_t \tag{2.7}$$

The irrotationality of the flow is assumed furthermore with the condition

$$u_y-v_x=0,\quad \nabla\mathrm{w}-\boldsymbol{u}_z=0 \tag{2.8}$$

According to the formulations of Wang et al. [23] with the derivation procedure of Nwogu [22] retaining terms to order $O(\varepsilon)$ and $O\left(\mu^2\right)$, a set of Boussinesq type equations facilitating the landslides are obtained:

$$\eta_t+\frac{1}{\varepsilon}h_t+\nabla\left((h+\varepsilon\eta)\mathbf{u}_\alpha\right)+\mu^2\nabla\left(\left(\frac{z_\alpha^2}{2}-\frac{h^2}{6}\right)h\nabla\left(\nabla\mathbf{u}_\alpha\right)+\left(z_\alpha+\frac{h}{2}\right)h\nabla\left(\nabla\left(h\mathbf{u}_\alpha\right)+\frac{h_t}{\varepsilon}\right)\right)=0 \tag{2.9}$$

$$\mathbf{u}_{\alpha t}+\nabla\eta+\varepsilon\left(\mathbf{u}_\alpha\nabla\right)\mathbf{u}_\alpha+\mu^2\frac{\partial}{\partial t}\left(\frac{z_\alpha^2}{2}\nabla\left(\nabla\mathbf{u}_{\alpha t}\right)+z_\alpha\nabla\left(\nabla\left(h\mathbf{u}_\alpha\right)+\frac{h_t}{\varepsilon}\right)\right)=0 \tag{2.10}$$

where $\mathbf{u}_\alpha$ is dimensionless horizontal velocity vector at an arbitrary elevation $z=z_\alpha(x,y,t)$ with α denoting the arbitrary elevation and may not be confused with subscripts signifying differentiation. As a major limitation of the Boussinesq type equations is that they are only applicable to relatively shallow water depth while they reduce the three dimensional problem to a two dimensional one, the elevation of the velocity variable z_α is a free parameter which can be chosen to extend the applicability to relatively deep water. The Boussinesq Eqs. (2.9) and (2.10) are solved on staggered grids to eliminate the abrupt changes introduced by impulsive landslides imposed. As the dispersive terms embedded in the Boussinesq