Ocean Engineering 145 (2017) 290–303

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Hydrodynamic characteristics of internal waves induced by a heaving body in a two-layer fluid

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ARTICLE INFO

Keywords:
Two-layer fluid
Numerical wave tank
Barotropic mode
Baroclinic mode
Time domain
Oscillating body

ABSTRACT

The stratification of fluid caused by the change of water densities can generate two water waves on each fluid boundary. One is the surface wave on the free surface, and the other is the internal wave on the interface between the fluid layers. Two wave modes exist in the two-layer fluid: barotropic mode and baroclinic mode. This study develops a numerical model to simulate the surface and internal waves in the time domain. The time histories of the water waves on both surface boundaries are simulated using the numerical wave tank (NWT) technique by an oscillating circular body located on the free surface or underwater in the lower fluid domain. The NWT technique is based on the boundary element method with properly defined boundary conditions, including interface boundaries. The leapfrog method is used for the time integration of the water surface boundary conditions. The time-varying generated waves are disassembled through the Fast Fourier Transform (FFT). Each wave component is compared with analytic solutions. The relative magnitudes of the generated waves on both fluid layers are examined according to each wave mode. The dominant wave mode varies according to the oscillating body frequencies. The amplitude ratios of the two waves are compared for various density ratios and fluid depths.

1. Introduction

The stratified fluid may be a critical issue from time to time, especially when the hydrodynamic behaviors of a floating body in waves are investigated. Unlike most of the conventional hydrodynamic studies, the real ocean is not a fluid with uniform density. It is composed of stratified fluids with different water densities caused by the variation in water temperature and salinity. The water waves in a two-layer fluid exist on both the free surface and the interface between the two fluids called internal waves.

Internal waves have often been observed in real ocean environments. Internal waves with wavelengths of several kilometers were observed in the Strait of Gibraltar (Alpers and La Violette, 1993). The internal waves have also often been observed and reported in the South China Sea. The waves appear to be very brisk internal solitons, and are frequently observed from spring to early summer (Wendong et al., 2005). They have also been reported on the east shelf of the Hainan Island in the South China Sea, observed by ERS-1 SAR (Synthetic Aperture Radar) on June and April 1993 (Liu et al., 1998). These waves have very long wavelengths and high amplitudes because of the strong Kuroshio Current in the South China Sea (Hsu et al., 2000).

The internal waves, which frequently occur in the South China Sea, can affect the development of deep-sea oil and gas fields, such as responses of deep-draft offshore structures and the structural safety of risers and mooring lines, and their characteristics and impacts have yet to be fully elucidated. Therefore, in this study, we try to understand the characteristics of the internal waves according to each mode by numerically generating the waves in the same way as the experimental wave tank in the time domain analysis.

According to wave height and phase between two generated waves, two types of wave modes generally exist in the two-layer fluid, namely, the barotropic and baroclinic wave modes. The barotropic wave mode means that the surface wave height is greater than the internal wave, and two waves have the same phase angles. The baroclinic wave mode indicates that the internal wave is greater than the surface wave with 180° out of phase. Accordingly, two different wave numbers are generated with one wave frequency for the respective wave modes (Yeung and Nguyen, 1999).

Several numerical studies have been conducted using the boundary integral equation method to simulate the internal wave phenomenon in stratified fluids. Yeung and Nguyen (1999) described Green function for the boundary integral equation of the two-layer fluid in a 3D frequency domain. Ten and Kashiwagi (2004) and Kashiwagi et al. (2006) studied a 2D body in the two-layer fluid. Kim and Koo (2010) also analyzed the

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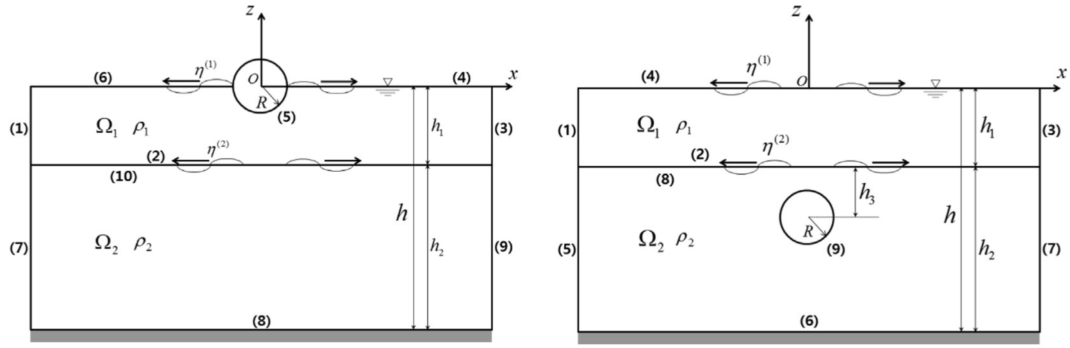
http://dx.doi.org/10.1016/j.oceaneng.2017.09.017
Received 18 April 2016; Received in revised form 17 December 2016; Accepted 11 September 2017



(a) Case 1: floating oscillating body case

(b) Case 2: submerged oscillating body case

Fig. 1. Overview of the computational domain of the two-layer density fluids.

Table 1
List of the computational boundaries for each case.

No.	Case 1	Case 2
(1)	Left side boundary of the upper domain	Left side boundary of the upper domain
(2)	Interface boundary of the upper domain	Interface boundary of the upper domain
(3)	Right side boundary of the upper domain	Right side boundary of the upper domain
(4)	Right free surface boundary	Free surface boundary
(5)	Body boundary	Left side boundary of the lower domain
(6)	Left free surface boundary	Bottom boundary
(7)	Left side boundary of the lower domain	Right side boundary of the lower domain
(8)	Bottom boundary	Interface boundary of the lower domain
(9)	Right side boundary of the lower domain	Body boundary
(10)	Interface boundary of the lower domain	–

interaction of a floating body with internal waves in the frequency domain.

With regard to the wave radiation phenomenon in an enclosed space, Zhang and Bandyk (2013) studied the resonance of radiated waves by heaving twin bodies in the moon pool. They developed the Eigenfunction matching method for the boundary value problem to solve the linearized system. In addition, there are more studies on waves which are interacted with the body in two-layer fluid. Sherief et al. (2004) considered the forced axisymmetric motion generated by a cylindrical porous wave maker immersed vertically in two-layer fluid. Alam et al. (2009) studied the linear problem of wave generation by an oscillatory source with the steady translational speed in two-layer fluid. Manam and Sahoo (2005) and Kumar et al. (2007) studied the radiation and scattering of oblique water waves past porous structures in two-layer fluid. Behera et al. (2013) studied oblique wave trapping by the partial porous flexible barriers near the rigid wall in two-layer fluid. They also analyzed the oblique wave scattering by thick partial porous structure and trapping by the partial porous structure near the wall (Behera et al., 2015).

However, many studies on internal waves have been mostly conducted using an analytic solution or frequency domain analysis. As for time domain analysis in two-layer fluid, Gou et al. (2012) computed time histories of linear wave diffraction forces from a 3-D body located in the upper fluid in two-layer fluid. In real oceans, internal waves observed are generally known to be highly non-linear. Therefore, the shape of the internal wave is much different from that of the water surface waves. Accordingly, the non-linear behavior of the internal waves can only be fully captured through the time domain analysis. Therefore, the present study is carried out by necessity of time-domain numerical modeling for two-layer fluid, and the numerical model of internal wave simulation induced by a heaving body is developed. This study also aims to investigate the hydrodynamic characteristics of the simulated waves for various conditions. The numerical model of a heaving circular cylinder in the two-layer fluid is developed in the time domain using a 2D numerical wave tank (NWT) technique. The developed model can examine the characteristics of the barotropic and baroclinic wave modes. The two-layer fluid domain comprises two different density fluids, which are incompressible, inviscid, and irrotational. The computational domain is modeled with discretized boundary elements. The sea bottom is assumed to be a flat rigid boundary. The proper boundary conditions are defined according to each boundary's property. The transient wave profiles in the time domain are simulated through a leapfrog time marching scheme used for the time integration of both water surface boundary conditions.

Two progressive waves are generated on both the free surface and the interface between the fluid layers by a heaving circular cylinder in the

Table 2
The optimum number of surface nodes per wavelength in the barotropic mode [λ_T] for the respective oscillating frequencies.

Oscillating frequency	0.5–2.5 rad/s	2.6–2.9 rad/s	3.0–4.0 rad/s
Case 1	60	40	30
Case 2	60	40	30

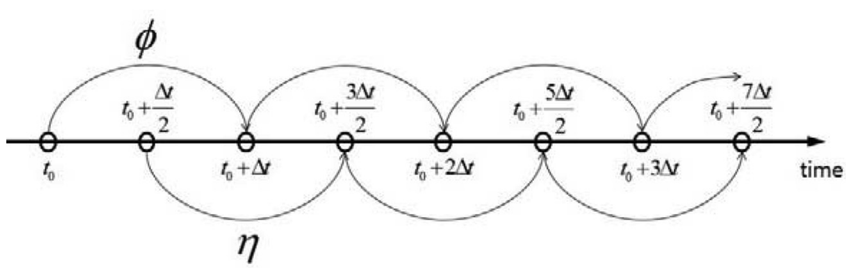


Fig. 2. Leapfrog method for the time integration scheme on the boundary surface.