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Research paper

Dynamic response of density-stratified fluid in a submarine rectangular trench

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Abstract

Interfacial waves under various wave conditions are numerically and experimentally investigated within a submarine rectangular trench. The three-dimensional numerical model Truchas is employed to trace the free surface and the interfacial motion using the volume of fluid method. The free surface and interfacial motion are measured using a CCD camera to validate the model. Both the numerical and experimental results show two types of interfacial motion, namely, partial standing wave patterns and traveling wave patterns. The numerical model is then employed to study the mechanisms of the different modes of interfacial motions (partial standing/traveling waves) and their corresponding amplification factors (external/internal modes). It is shown that the partial standing wave patterns are easily generated when the motion of the surface waves is 180° out of phase at the two sides of the trench. However, the existence of partial standing wave patterns does not mean partial standing internal waves occur. The partial standing internal waves are triggered as internal wave wavelengths reach resonant condition. Furthermore, the ratio of the interface wave height to the surface wave height decreases with wave nonlinearity, suggesting that the nonlinear effect may significantly change the interfacial wave motion. Finally, it is found that the excited pairs of counter-rotating vortices around the interfacial wave can induce a large velocity in the lower layer for the internal mode, indicating that bottom erosion can be enhanced in this manner.

Keywords: Density-stratified fluid; Trench; Volume of fluid (VOF); Image processing; Partial standing internal waves

1. Introduction

Navigation channels and harbor entrances often have trench-like terrain. In many circumstances, fine sediment is easily trapped in such terrain. These fine materials are easily affected by external forces (e.g., dynamic pressures from waves, currents, and the passage of ships over the bottom) and are thus kept in suspension near the bottom, forming a dense layer. A density-stratified fluid consisting of water and a dense fluid is created in the trench. When waves propagate across a submarine trench partially filled with a dense fluid, interfacial waves are generated. It has been observed that when the frequency of the incoming surface waves corresponds to the natural frequency of the interfacial waves in the trench, the amplitude of the internal waves becomes larger than that of the surface waves (Ting and Raichlen, 1988). In these events, the dense fluid in the trench becomes excited into a mode of resonant oscillation. The large amplitude of the interfacial waves results in a large velocity near the boundary, which enhances the erosion process and affects ship maneuverability. An example of this type of dense lower layer can be found in some harbors in the Netherlands if the bottom is defined as a region where the specific gravity of the fluid is larger than 1.2 (Marine Board, 1983). The density-stratified fluid in these channels can influence the kinematics around the perimeter of the trench via interfacial waves generated in the trench. The

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dynamics of interfacial waves significantly influence the operation and maintenance of navigation channels.

Lassiter (1972), Lee and Ayer (1981), Miles (1982), Kirby and Dalrymple (1983), and Ting and Raichlen (1986) studied periodic water waves passing a rectangular trench with a homogeneous fluid in the trench. Lassiter (1972) employed Schwinger's variational method to construct approximate solutions for the reflection and transmission of waves propagating past the submarine trench where the water depths before and after the trench were constant but not necessarily equal. Lee and Ayer found the reflection and transmission coefficients for various trench geometries (1981). Their study focused on wave scattering, where a strong reflection of the incident waves occurred when the ratio of the trench length to the wavelength of the incident wave was approximately 0.5. For a particular symmetric trench where the water depths before and after the trench are equal, it was found that an infinite number of discrete wave frequencies exist at which the incident wave energies are fully transmitted. The maximum and minimum values of the transmission and reflection coefficients appeared periodically, but the effect of the trench on wave energy transmission decreased monotonically as the wavelength decreased. Based on the formulation by Lee and Ayer (1981) and Ting and Raichlen (1986) showed that the wave energies trapped within the trench are very small compared to the energies in the incident waves. Kirby and Dalrymple modified the formulation by Lee and Ayer (1981) to investigate the problem of the propagation of obliquely incident water waves over an asymmetric trench (1983). Recently, the reflection of linear long waves by two scour trenches was investigated analytically (Xie et al., 2011). Hence, the relation between the trench geometry and wave frequencies is important to the energy trapping, which is also related to the formation of energetic interfacial waves.

Generally, there are two independent modes of oscillation about the state of equilibrium in a two-fluid system, namely the internal mode and external (or surface) mode[1] (Parau and Dias, 2001). While the wave at the water surface is in phase with the wave at the interface of the surface mode, the surface wave is 180° out of phase with the interfacial wave for the internal mode. In these two modes, the internal mode is very notable because the internal wave motion is much greater than the surface expression of this mode. Thorpe (1968) extensively studied, both theoretically and experimentally, standing internal waves in a discontinuously/continuously stratified fluid. For the two-layer fluid, the method of analysis was similar to the perturbation scheme used for Stokes waves; the finite amplitude wave solutions were represented in the form of power series expansions with respect to the wave slope as the expansion parameter. Furthermore, Ting and Raichlen (1988) and Ting (1992) experimentally and theoretically studied the excitation of internal waves in a rectangular trench by normally incident surface waves. The research showed that, at the resonance condition, the amplitude of the internal waves was larger than that of the surface waves. The theoretical solutions predicted the wave motions quite well, even for relatively large-amplitude waves in the trench. Of note, two distinct types of internal waves were found in Ting's study (1992), namely standing internal waves and traveling internal waves. However, the finite region (vertical wall) was established at the downstream edge of the trench in that study. Therefore, the total reflected waves immediately occurred when the waves passed over the trench; thus, the effect of the trench could not be fully described. Moreover, the influence of the nonlinear effect of the free surface on the internal waves was not discussed due to the application of linear theory. Compared with the Newtonian fluid, Ting (1994) and Ting and Lemasson (1996) used the Voigt (viscoelastic fluid) bed material to investigate the dynamic response of fluid mud in a trench to water waves. For a soft bed, surface waves with relatively small amplitudes can cause large-amplitude oscillations in the trench, accelerating bed erosion when the frequency of the incident waves corresponds to the natural frequency of mud waves. Further, the difference between the experimental and theoretical results was used to discuss the nonlinear effect for internal waves. Other types of material, such as soil and sand, have also been considered in a two-phase or multi-phase system using analytical solutions, with the interaction between the waves and these materials discussed (Tsai et al., 2009; Hosseininia and Farzaneh, 2010). However, how the incident waves, in conjunction with nonlinearity, can affect the resulting interfacial waves and the formation of external/internal modes remains to be clarified.

In the above studies, the interfacial motion in the density-stratified fluid was captured and calculated via experiments and theoretical models. The quantifications of physical phenomena (e.g., flow field in dense fluid and the nonlinear effect) are not easily extracted from the methods mentioned above. Recently, the interaction between a solitary wave and a trench was studied using a numerical model, where a homogenous fluid was considered (Chang et al., 2011). As in the case of single-phase flow, multi-fluid systems can be numerically modeled with a single set of governing equations in the integral form (Hsu et al., 2003). Moreover, various numerical methods for capturing a sharp fluid interface have been developed, including the volume of fluid (VOF) method, the level set method, the phase-field method, and the front tracking method (Behera and Murali, 2007). These methods have been extensively used to simulate multi-fluid systems. In the present numerical model, the VOF method is used to track the surface waves and interfacial waves in a submarine rectangular trench.

To evaluate the triggering mechanisms of the standing/traveling interfacial waves and the nonlinear effect of the free surface, the present study uses a numerical model and experiments to investigate the dynamic response of interfacial waves generated in a rectangular trench. A VOF-type numerical model (Truchas) is used to trace the free surface and

[1] In this paper, the terminology, surface/interfacial wave, is used to describe waves at the free surface and the interface, respectively (ex: surface and interfacial wave). The terminology, external/internal, is used to describe the independent modes of oscillation. For example, external waves are discussed if the external mode only existed in the interfacial motion.