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# Surface wave disturbance during internal wave propagation over various types of sea bottoms

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ABSTRACT

In this study, we used a numerical model to simulate the propagation of internal waves (IWs) over various topographies, such as those with a flat bottom or bottom with a triangular trench or a ridge, and investigate the development, propagation, and dissipation mechanisms of IWs. Detailed evolution of IWs and vortices and their effects on the disturbance of the ocean surface were studied. The numerical results show that strong mixing and water exchange occur during IW propagation, resulting in severe convergence and dispersion, which lead to strong free surface flow and create noticeable free surface waves. The shapes of free surface waves and IWs have opposing orientations. In addition, there exists a close relationship between IWs and ocean surface waves, which may assist researchers in retrieving the amplitude of IWs by observing the behavior of free surface waves. The resonant interaction of IWs and surface waves was analyzed as IWs passed various types of sea bottom. The results indicate that IWs and surface waves move in the same phase, and the spatial variation of the waves shows that both wave types have the same wavelength.



## 1. Introduction

The water density, temperature, and salinity of oceans and lakes generally vary with depth. Once the water density is vertically stratified into layers, wave perturbation can occur at layer interfaces, generating internal waves (IWs). Tidal motion, ocean currents, and strong winds can trigger IW formation. Mass transport and energy transformation resulting from barotropic flow or the passage of IWs through a sharply varying sea bed result in sediment resuspension into the water column. IWs have been observed in South China Sea and East Sea (Hsu and Ariyaratnam, 2000), San Diego coast of California, USA (Cairns and Williams, 1976), and Andaman Sea in the Indian Ocean (Alpers et al., 1997). They can also be found in lakes such as Fuxian Lake in Yunnan Province, China, and Babine Lake in Colombia (Farmer, 1978). The amplitude of IWs may be several hundred meters, and their length could be as much as several kilometers. Therefore, IWs constitute a large movement of ocean water, and they are of interest in various fields such as biology, military, engineering, and environmental studies.

As early as 1901, Fridtjof Nansen reported finding dead water as his adventure ship entered a sea area covered with fresh water from melting ice. The ship's motion was slowed by an unknown cause. In 1904, Vagn Walfrid Ekman was the first to experimentally verify this phenomenon as the result of IWs. Subsequently, researchers have used various means to investigate IWs, including field observation, deriving theoretical equations to describe IWs, experimental investigation, and numerical simulation. Early field investigations include those of Thrope (1975) in Loch Ness; Farmer (1978) in Babine Lake and Osborne and Burch (1980) in the Andaman Sea. Advances in satellite remote-sensing technology and synthetic aperture radar (SAR) have provided researchers with visible-light images from which to interpret surface roughness and the intensity of light reflections to indirectly describe IWs (Ebbesmeyer and Romea, 1992). Hsu and Ariyaratnam (2000) analyzed image data from an SAR as well as site observation data obtained by using a conductivity–temperature–depth device, acoustic Doppler current profiler, and EK-500 scientific echo sounder system to plot IW distributions. They found that a depression wave might change into an elevation wave as an IW travels toward a shallow water area. After studying IWs in South China Sea, Lin (2001) found that the traveling directions of IWs tend to refract toward shallow water when propagating toward continental shelves with smaller wave heights and shorter wavelengths.

Because site investigations of IW are restricted by weather, cost, and safety factors, laboratory experiments have been conducted increasingly more often, such as in a series of studies by Thrope

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between 1968 and 1999 and a study by Ono (1975). Koop and Butler (1981) investigated solitary IWs and found that Korteweg–de Vries theory agrees well with laboratory measurements based on wave shape parameters. Koop and Butler's suggestions became the basis for several subsequent experimental studies. Wessels and Hutter (1996) further defined the effects of degree of blocking ($B = h_S/H_2$, where $h_S$ and $H_2$ are the height of the block and depth of the lower water layer, respectively). From 2000 to 2008, researchers in National Sun Yat-sen University (J. Hsu et al. – Hsieh et al., 2015; Cheng and Hsu, 2013, 2010; Cheng et al., 2011, 2009; Chen et al., 2008) started a series of experimental measurements in the lab to investigate the propagation and reflection of IWs passing over various bottom bathymetries. The results of lab investigation, however, are limited owing to size of the lab space and its simple geometry, which do not completely describe the real ocean environment. Analytical models have also been reported, for example, Benjamin (1966, 1967) presented a general theoretical treatment of long stationary waves with finite amplitude. More recently, Craig et al. (2010) reported a study on the coupling between IWs and surface waves, focusing on the circumstances under which an IW causes localized bound states with the Schrodinger equation, which are interpreted as surface wave patterns characteristic of the presence of an IW soliton.

With tremendous progress in computing technology, greater numbers of researchers developed numerical models to study IWs, including Muller and Liu (2000), and Vlasenko and Hutter (2002). Fu (2007) adapted a numerical model developed by Lynett and Liu (2002) to simulate IW propagation under weakly nonlinear, weak dissipation, and inviscid conditions. Fu (2008) used code written by Pao (Catholic University of America) to study fully nonlinear IWs in the South China Sea. The results varied greatly from satellite images because coarse meshes were used and real geometrical factors were only partly considered. Although numerical methods for studying IWs are underdeveloped and simulation results require rigorous numerical validation, the advantages of lower cost and space attracted the attention of researchers, and numerical studies in IW research have gradually become more prominent. In the present study, we used a commercial code Fluent (ANSYS) to simulate an IW passing over a horizontal sea bottom and a sea bottom with a trench or triangular ridge. The numerical results obtained were first validated against experimental measurements by Chen (2004) and Kuo (2005). Furthermore, we investigated the development, propagation, and dissipation mechanisms of IWs. The evolution of vortex development with the passage of IWs over a nonhorizontal seabed and the effects of vortices on the disturbance of the sea surface were studied in detail. The relationship between free surface waves and IWs was also analyzed. The remainder of this paper is organized as follows. Section 2 briefly describes the equations of motion of fluid and the boundary conditions programmed into Fluent and the numerical techniques employed in ANSYS Fluent. Section 3 presents the detailed results and provides a comprehensive discussion of the phenomena observed in this study. Our concluding remarks are given in Section 4.

## 2. Numerical method and validation

### 2.1. Numerical method

This research was conducted using Fluent 6.3. The Navier–Stokes equation and the continuity equation were solved to obtain the velocity and pressure fields, respectively. The continuity equation is

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2.1}$$

and the Navier–Stokes equation of a 2D incompressible flow can be written as

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial z^2}\right) - g,$$

where $t$ is time; $u$ and $w$ are, respectively, the velocity components in the $x$ and $z$ directions; $p$ is the pressure; $\rho$ is the fluid density; and $\mu$ is the dynamic viscous coefficient. The following boundary conditions were used in this study:

(1) Wall boundary: impermeable solid boundary with assumption of nonslip conditions
(2) Pressure-inlet boundary: total pressure was set to a constant value in the upstream pressure inlet
(3) Interfacial conditions

Two types of fluid were used in the study, air and water, which had two layers of different densities (998.2 and 1030.0 kg/m$^3$, respectively). The free surface was the air–liquid interface, and a pressure inlet with standard temperature and pressure was used to model the air–sea interface. Fluent uses the volume of fluid (VOF) method (Hirt and Nichols, 1981) to trace and locate the instant sea–air interface and the interface between two liquid layers. The volume fraction of each fluid phase is tracked through every cell. In brief, the following equation is used:

$$\frac{\partial C_q}{\partial t} + v \bullet \nabla C_q = 0 \tag{2.2}$$

where $v = (u(x,z), w(x,z)$ and $C_q$ is a fraction function used to define and calculate the volume ratio of $q$-phase fluid in the computational mesh. In the present study, $q = 0$ for air, 1 for freshwater, 2 for saltwater, 0.5 for water–air interfaces, and 1.5 for freshwater–brine interfaces. A staggered grid was used such that the pressure $p$ was defined at the mesh center, whereas the velocity components $u$ and $v$ were $0.5\Delta x$ behind and $0.5\Delta y$ above the center, respectively. The discretization techniques used to iteratively obtain flow velocity and pressure field were the quadratic upwind interpolation of convective kinematics method and PISO algorithm. To improve the accuracy of the obtained results, we used the second-order upwind scheme.

### 2.2. Numerical implementation and validation

Fig. 1 shows the meshing grid arrangements employed in this study. The meshes around a triangular ridge were triangular meshes, whereas the remainder of the computational domain comprised rectangular meshes.

A solitary wave was generated using the gravity subsidence (gravity collapse) method, which creates a vertical difference in potential (step depth $\eta_0$) on either side of the vertical gate. The size of the numerical wave tank was set as $L = 12$ m, the water depth as $H = H_1 + H_2 = 0.5$ m, and the wave-generation area as $L_m = 0.3$ m; near the gate, the potential difference or step depth was set as $\eta_0 = 0.3$ m on both sides of the gate in the wave-generation area. The boundary conditions at all solid–liquid interfaces were taken as smooth nonslip walls. In the simulation, the gate was made to rise at 0.25 m/s, the same as that in the laboratory conditions used in Kuo (2005). Near the gate, the density distribution levels (step depth) differed on both sides of the gate. The boundary conditions along the gate walls and gate bottom were