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Numerical study on evolution of an internal solitary wave across an idealized shelf with different front slopes

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ABSTRACT

Numerical simulations are performed to investigate the influence of variable front slopes on flow evolution and waveform inversion of a depression ISW (internal solitary wave) over an idealized shelf with variable front slopes. A finite volume based on Cartesian grid method is adopted to solve the Reynolds averaged Navier-Stokes equations using a k-ε model for the turbulent closure. Numerical results exhibit the variations of several pertinent properties of the flow field, in the case with or without waveform inversion on the horizontal plateau of an obstacle. The clockwise vortex is stronger than the counterclockwise one, almost throughout the wave-obstacle interaction. Analysis of the turbulent energy budget reveals that the turbulent production term in the governing equations dominates the wave evolution during a wave-obstacle interaction; otherwise the buoyancy production term and the dissipation term due to viscosity within turbulent eddies play a major role in energy dissipation. In addition, the front slope affects mainly the process and reflection of the wave evolution but has less influence than other physical parameters. Moreover, total wave energy of the leading crest is smaller than that of the leading trough even in the cases with waveform inversion on the plateau.

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1. Introduction

Internal solitary waves (ISWs) have been found in the world ocean, where the submerged shelf topography has a front slope ranging between 1° and 45° [1–4]. Several phenomena (e.g., internal wave breaking, hydraulic jump, vortex formation on the front slope, as well as wave refraction and diffraction in the vicinity of a large island) have also been identified as being associated with ISW propagation across the front slope. In the South China Sea (SCS), ISWs are generated in a density stratified environment by the interaction between tidal currents and local submerged topography, such as the two submerged high ridges across the Luzon Strait between Taiwan and the Philippines. While propagating across the northern SCS, ISWs may undergo numerous transformations and eventually promote waveform inversion on a shallow shelf. In large amplitudes, an ISW has significant ramification not only in marine ecology but also engineering works in the ocean [5–7]. Reports [3,6,8] also conclude that (1) self-generation of the vortices with strong turbulent mixing within a water column, and (2) waveform inversion across a continental shelf are two of the highlights of an ISW across a slope-shelf topography.

The nonlinear process as an ISW propagating over a slope-shelf has been investigated using theoretical descriptions [9–11], field observations [3,8,12–14], laboratory experiments [15–19], and numerical simulations [5,6,20–23]. Among these, Knickerbocker and Newell [9] used a transitional KdV theory and reported that a depression ISW could become unsettle once in shallow water and eventually transformed into an elevation internal wave. In field observations, Hsu and Liu [13] identified the traces of several wave crests of ISWs from SAR imageries taken in the northern SCS in the 1990s, from which waveform inversion was envisaged from the difference in the dark-bright sequence of wave crest patterns. From that, they proposed a depression ISW had a bright band ahead of a dark band in the direction of wave propagation in the deep ocean, while an elevation ISW with a bright band after a darken one in shallow water. Moreover, acoustic Doppler current profiler [8,12,14] and moored acoustic sensors [3] had been deployed to observe large ISW action in the ocean and vortex generation was

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detected as the wave encounters the shelf. However, limited by the complexity in field observations, laboratory experiments had extensively been utilized to study the propagation of an ISW on idealized slope-shelf topography in a stratified two-layer fluid. Among them, the pioneer experiment of Kao et al. [15] had an upper layer thinner than the bottom layer ($h_1 < h_2$) in the wave flume, which could not physically sustain an elevated waveform; while the tests reported by Helfrich and Melville [16] aimed at comparing their laboratory results with a KdV theory. More recently, laboratory studies undertaken by Cheng and Hsu [19], Cheng et al. [17] and Cheng and Hsu [18] had examined the effect of some physical parameters (e.g., depth ratio between upper and lower layer, plateau length and front slope) associated with an ISW propagation and waveform inversion. However, only the laboratory results of waveform evolution using video images and variation of amplitude at specific locations using ultrasonic probes in a wave flume was given, rather the spatiotemporal evolution of some pertinent properties within the flow field and waveform inversion. In order to overcome these shortcomings, numerical models have been adopted to investigate the evolution of density profiles, velocity field and waveform inversion etc. For example, Bourgault et al. adopted 2D numerical model to examine the resuspension, dispersal and transport of mud-like sediment caused by the shoaling and breaking of ISWs on uniform slopes [5]; other research focused on the evolution of the density and vorticity when an ISW propagates across the front slope [6,20,21]. Vlasenko and Hutter produced a correlation formula for wave breaking depth of an ISW on a front slope. Shin adopted a flux-difference splitting scheme and a hybrid Cartesian/immersed boundary method to examine the propagation of an ISW over a foil. However, most numerical studies so far published have emphasized the spatiotemporal variations in waveform, velocity and wave energy of an ISW on a specific front slope, rather on the effect of different front slopes on the evolution of ISW propagation across a slope-shelf topography.

In this study, the evolutions of a depression ISW propagating across an idealized shelf with different front slopes are modeled numerically as a transient two-dimensional, fully nonlinear, viscous flow phenomenon, upon solving the Reynolds averaged Navier-Stokes equations with a k-ε model for the turbulent closure in a fluid system with a pycnocline. In a 2-D Cartesian frame of reference (Fig. 1), the physical domain considered is a rectangular flume, 12 m long (x-axis) and 0.55 m deep (z-axis). The fluid system within the flume consists of two layers with different density and a pycnocline at the interface; and with the same physical conditions (depths, obstacle size and incident wave etc. shown in Table 1) that were reported in Cheng et al. [17]. After successful benchmark verification by comparing the numerical results with that of a laboratory experiment, a series of 21 additional numerical cases are then carried out, using different wave amplitudes, depth ratios between the upper and lower layer (h_1/h_2) and front slope (θ). In all these cases, the depth of the upper layer in the incident section of the flume is less than that of the lower layer ($h_1 < h_2$) in order to generate a depression ISW. The results obtained (e.g., fluid density, wave amplitude, velocity, wave energy, and vorticity) could help provide better understanding for the spatiotemporal evolution of a depression ISW over an idealized shelf.

In this paper, Section 2 describes the numerical methodology and verifications; Section 3 presents the spatiotemporal evolutions of the flow field, vorticity and turbulent kinetic energy, while an ISW propagates over an idealized shelf. Dimensionless analysis is then used in Section 4 to examine the effect of step depth, depth ratio and front slope for the evolution of wave crest to trough ratio, clockwise to counter-clockwise vortex and wave energy; and finally, conclusions are made in Section 5.

2. Numerical methodology

For studying the evolution of an ISW over an idealized shelf in an incompressible free-surface flow with turbulent closure, conservation of mass and momentum is assumed for the fluid motion. Hence, the general mass continuity equation and Reynolds-averaged Navier-Stokes equations (RANS) are utilized to simulate the flow field; and the governing equations [24] are written as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\nu \frac{\partial u_i}{\partial x_j} - \overline{u_i' u_j'}\right) + g_i \frac{\Delta\rho}{\rho_0} \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = \frac{\partial}{\partial x_i}\left(D_m \frac{\partial \rho}{\partial x_i} - \overline{u_i' \rho'}\right) \tag{3}$$

where u_i denotes the mean velocity components (U, W) and u_i' is the fluctuation velocity components (u', w') in x- and z-axis (Fig. 1), respectively; t the time; $\Delta\rho$ the difference of fluid density ($\rho - \rho_0$; ρ_0 is the density in the upper layer; ρ is the fluid density varied along with z-label, seen in Fig. 1); P the dynamic pressure; ν and D_{m} are the kinematic viscosity and molecular diffusivity, respectively. Item $-\overline{u_i' u_j'}$ is the mean Reynolds stresses; $-\overline{u_i' \rho'}$ ($= \frac{\nu_t}{S_{ct}} \frac{\partial \rho}{\partial x_i}$) is the mean turbulent fluxes of the mean density ρ; $g_i = [0, -g]$ is the gravitational acceleration. S_{ct} is the turbulent Schmidt ($= \nu_{\mathrm{t}}/D_{\mathrm{K}}$) [24], in which D_{K} is the eddy diffusivity. The overbar (–) indicates the averaging of fluctuating quantities, and the Reynolds stresses,

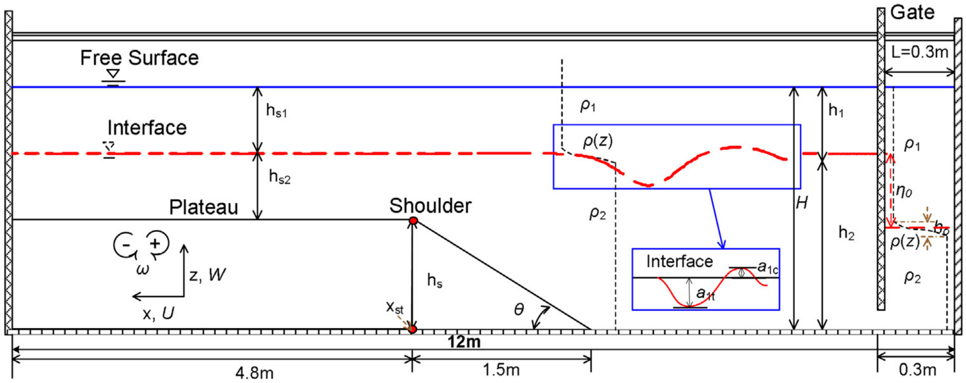

Fig. 1. Schematic diagram showing a depression ISW to be generated by a gravity collapse mechanism (not to scaled and probe locations not shown).

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