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Flow evolution of an internal solitary wave generated by gravity collapse

Chih-Min Hsieh[a], Robert R. Hwang[b,d], John R.-C. Hsu[c,e], Ming-Hung Cheng[d,*]

[a] Department of Maritime Information and Technology, National Kaohsiung Marine University, Kaohsiung 80543, Taiwan, ROC
[b] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan, ROC
[c] Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung 80424, Taiwan, ROC
[d] Department of System Engineering and Naval Architecture, National Taiwan Ocean University, Keelung 20224, Taiwan, ROC
[e] School of Civil and Resource Engineering, University of Western Australia, Crawley, WA 6009, Australia

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ABSTRACT

Numerical simulations are performed to investigate the flow evolution of a depression ISW generated by gravity collapse in a fluid system with a density pycnocline. A finite volume based Cartesian grid method is adopted to directly resolve the Navier–Stokes equations and the general mass continuity equation. Results of the numerical computation are validated by comparing with that of laboratory experiment. Numerical results reveal the initial vortex remains identical for the same step depth but the decrease in its strength is significant as the depth of upper layer increases. However, step depth influences the vertical structure of the initial vortex more than the upper/lower layer depth ratio does on wave generation.

1. Introduction

Internal solitary waves (ISWs) or interfacial waves (IWs) are abundant on the interface of a stratified ocean, where the process of generation, propagation and dissipation associated with them has important impact on many maritime activities and ecological phenomena. For example, a large ISW may affect oil drilling operations [1], produces turbulent mixing [2], causes nutrient pumping [2,3], and induces fish forage [4]. In addition, an ISW with amplitude up to 170 m was once recorded in the South China Sea (SCS) and horizontal velocity difference between the upper and lower layer exceeding 3.4 ms^{-1} could be critical for the safety of structure in the ocean [5].

An ISW in a stratified ocean may be generated by different external forcing, such as tidal flow, irregular ocean floor topography, lee waves, strong wind and atmospheric pressure fluctuations [6]. Despite using advanced equipment in field observations, the devices provide only information for the process of an ISW's evolution at a fixed location, rather a spatial distribution of wave evolution [7].

In most laboratory experiments, an ISW has been generated by a collapse mechanism from a vertical difference in potential (i.e., the interface level) on either side of a removable gate (called *step depth* η_0) [8]. Based on this method in the laboratory, the propagation and transformation of some pertinent physical properties have been presented in the literature [9–11], concerning waveform and wave energy more than the flow field. Although the two important factors (step depth η_0 and depth ratio between the upper and lower layer h_1/h_2 in the wave flume) for the wave generation have been recognized, reports on the detailed process of wave generation and variation in the pertinent properties relating with the flow field remain scarce. In the numerical models available, most researchers adopt an initial waveform based on *KdV* formulation [12,13], with few apply the gravity collapse mechanism [14,15]. However, almost all describe the waveform evolution and the effect of some physical parameters (e.g., water depth ratio and obstacle shape). Although many researchers have recognized the importance of η_0 and h_1/h_2 on ISW generation, the mechanism in which how they affect the flow evolution of an ISW induced by collapse mechanism is seldom examined.

In this study, direct numerical method is used to solve the Navier–Stokes equations and the general mass continuity equation, in order to investigate the evolution and vertical structures of the flow field and the effect of η_0 and h_1/h_2 on a depression ISW

* Corresponding author. Tel.: +886 227898409.
E-mail address: chengminghung@gmail.com (M.-H. Cheng).

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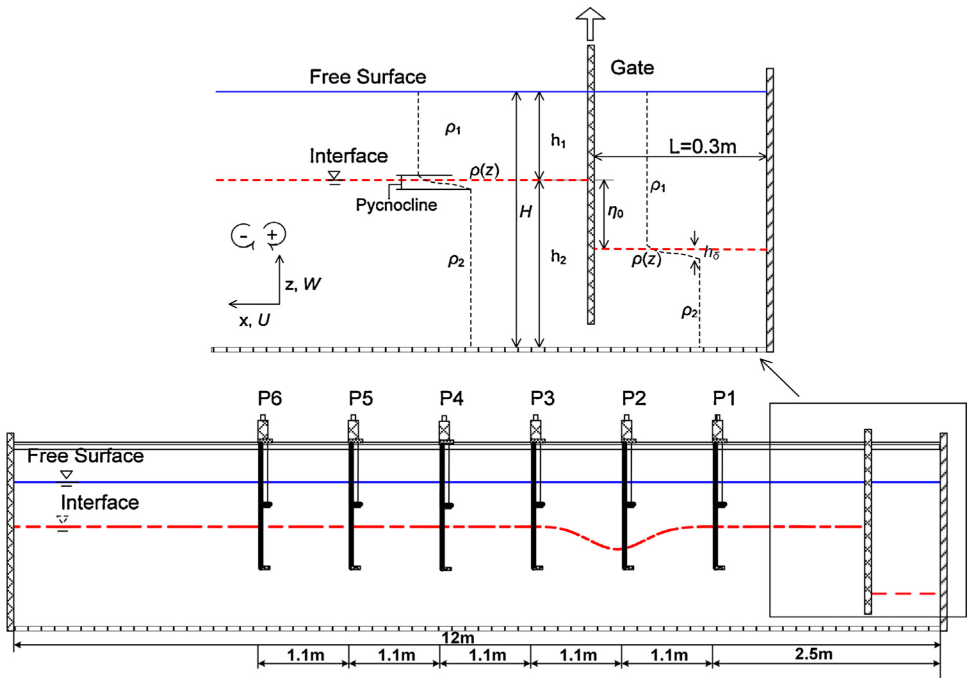

Fig. 1. Schematic diagram showing a depression ISW to be generated by gravity collapse mechanism and locations of ultrasonic probes (P1–P6) and density probe in use.

generated by a gravity collapse mechanism in a fluid system with a pycnocline. A series of numerical cases with variations of these two physical parameters (i.e., η_0 and h_1/h_2) are performed and the results for the spatiotemporal evolutions of iso-density, streamline and vorticity are illustrated and discussed in this paper.

2. Formulation of problem

Flow evolution of a depression ISW generated by gravity collapse mechanism in a fluid system with a density pycnocline is modeled as a transient two-dimensional, fully nonlinear, viscous flow phenomenon. In a Cartesian frame of reference (Fig. 1; omitting the y-axis assuming negligible variation in the direction perpendicular to wave propagation), the physical domain considered is 12 m long (along x-axis) and 0.5 m deep (along z-axis), in which the water body consists of upper and lower layers, as well as a pycnocline at the interface. Notably the above units/dimensions are kept same as used in the experimental setup of Chen et al. (2007) [10], and the physical conditions for all numerical runs are shown in Fig. 1 and Table 1 (i.e., depth and density in upper and lower layers (h_1/h_2; ρ_1/ρ_2), step depth (η_0), pycnocline thickness (h_δ)). Herein, the depth of the upper layer is less than that of the lower layer ($h_1 < h_2$) for generating a depression ISW, and only ISW propagating in the x-direction is considered.

3. Numerical methodology

3.1. Setup of numerical model

An ISW can be generated by the buoyant forces within a fluid system with difference in density. The flow evolution of a depression ISW in different physical conditions (i.e., step depth η_0 and upper/lower layer depth ratio h_1/h_2) is considered in an incompressible free-surface flow problem. The fluid motion follows the basic principle of conservation of mass and momentum. Therefore, the general mass continuity equation and Navier–Stokes equations are utilized to simulation the flow problem. These governing equations [16–19] are written as follows:

$$\nabla \cdot u_i = 0 \tag{1}$$

Table 1
Summary of physical conditions and some numerical results for generating a depression ISW on flat bottom.

Case no.	h_1 (m)	h_2 (m)	η_0 (m)	a_0 (m)	U_0 (ms^{-1})	α	$\omega_{\max}$ (s^{-1})	$\omega_{\min}$ (s^{-1})	E_k (10^{-2} J/m)
Flat_1	0.1	0.4	0.05	0.020	0.032	3.414	1.555	−2.162	0.407
Flat_2	0.1	0.4	0.10	0.038	0.052	1.707	1.062	−5.140	1.648
Flat_3	0.1	0.4	0.15	0.054	0.064	1.138	0.717	−7.357	3.462
Flat_4[a]	0.1	0.4	0.20	0.068	0.074	0.853	1.774	−8.645	5.387
Flat_5	0.1	0.4	0.25	0.080	0.082	0.683	3.788	−9.486	7.748
Flat_6	0.15	0.35	0.05	0.018	0.026	3.414	3.835	−1.979	0.398
Flat_7	0.15	0.35	0.10	0.036	0.041	1.707	2.980	−4.602	1.517
Flat_8	0.15	0.35	0.20	0.064	0.056	0.853	5.748	−8.629	4.493
Flat_9	0.15	0.35	0.25	0.076	0.060	0.683	6.413	−9.561	9.031
Flat_10	0.25	0.25	0.05	0.020	0.015	3.414	5.288	−1.943	0.424
Flat_11	0.25	0.25	0.10	0.034	0.025	1.707	7.502	−4.478	1.604
Flat_12	0.25	0.25	0.15	0.049	0.030	1.138	8.596	−6.914	3.317
Flat_13	0.25	0.25	0.25	0.054	0.031	0.683	11.090	−8.359	6.101

[a] This case is taken as a bench mark for a verification run in the present numerical model (other constant parametric constants are h_δ = 0.04 m; ρ_1 = 996 kg m^{-3}; ρ_2 = 1030 kg m^{-3}).