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Effect of porosity on an internal solitary wave propagating over a porous trapezoidal obstacle

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ABSTRACT

A permeable seabed may influence the evolution of an internal solitary wave propagating on a continental shelf and nearshore. In order to study the porous effect, numerical simulations are performed to investigate the flow field and waveform inversion of a large depression ISW propagating over a porous trapezoidal obstacle. A finite volume based Cartesian grid method is adopted to solve the Reynolds averaged Navier-Stokes equations using a k-ε model for the turbulent closure and porous media model together. Numerical results reveal that waveform inversion weakens significantly, as the porosity of the obstacle increases, except when porosity $n_f < 0.2$. At the same time, the magnitude of vorticity and turbulent energy decrease remarkably due to acute reduction of the production term induced by percolation and wave-pore interaction. Moreover, a skewed hump shaped relation appears between the maximum vorticity and the porosity. For transmitted wave energy on a horizontal plateau, total energy may decrease as $n_f < 0.2$ but increases moderately while $n_f > 0.2$ during a strong wave-obstacle interaction.

1. Introduction

Internal solitary waves (ISWs) in the South China Sea (SCS) are usually generated by the interaction between submerged topography and tidal current in a density stratified environment; wherein an amplitude up to 170 m was once observed with a velocity difference exceeding 2.4 m s^{-1} between its upper and lower water layer (Chang et al., 2008). In addition, a large ISW can cause nutrient pumping and pollution resuspension in the ocean, and affects ecological processes in water depth between 100 and 300 m on Dongsha Atoll (Wang et al., 2007). Beyond that found in the SCS, the episodic sediment resuspension in 60 m water depth in a 3-month data record revealed that long internal waves on the California shelf near Los Angeles might be the principal underlying source for resuspension of the DDT and other toxins previously disposed offshore (Bogucki et al., 1997). The depths cited above are greater than the closure depth for normal wind waves with peak period less than 16 s. Hence, long internal wave packets appear to have important environment implications for coastal waters.

In addition to the generation of strong vortex on a continental shelf, an ISW propagating across the northern SCS also experiences waveform inversion on a shallow shelf (Hsu et al., 2000; Lamb and Xiao, 2014; Orr and Mignerey, 2003; Reeder et al., 2008). During wave shoaling on a shelf-slope, the rear of a depression ISW generates nonlinear oscillations once it enters the shallow water where depth of the upper layer is greater than the lower layer, but it may eventually become elevated, called waveform inversion (Knickerbocker and Newell, 1980; using a transitional KdV theory).

Within the natural environment in the SCS, waveform inversion of a depression ISW had been detected on satellite imageries and moored acoustic source. For example, Hsu et al. (2000) used SAR imageries taken in the 1990s in the northern SCS and identified the traces of several wave crests of ISWs, from which they considered that waveform inversion had occurred from the change in the sequence of its dark-bright wave crest patterns. They suggested that 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 had a bright band after a dark one in shallow water. More recently, Reeder et al. (2008) have also analyzed large internal wave evolution using moored acoustic source in water depth of 116 m on a continental shelf in the northern SCS where an ISW entered shallow water from the shelf edge about 4.5 km away.

Besides field observations, many laboratory experiments have concentrated on the propagation of an ISW on a pseudo slope-shelf

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topography in a stratified two-layer fluid (Kao et al., 1985; Helfrich and Melville, 1986; Helfrich, 1992; Sveen et al., 2002; Cheng and Hsu, 2013, 2014). However, only temporal waveform evolutions associated with amplitude or energy at specific locations were discussed from the results of video images and ultrasonic probes, rather than the spatiotemporal evolution of the flow field and waveform. Although numerical simulations (Arthur and Fringer, 2014; Bourgault et al., 2014; Carr et al., 2011; Grimshaw et al., 2014; Lamb, 2008, 2014; Lamb and Xiao, 2014; Shin, 2013; Talipova et al., 2013; Vlasenko and Hutter, 2002; Warn-Varnas et al., 2010) have also revealed the evolution of density profiles, velocity field and waveform inversion in order to overcome the shortcomings associated with laboratory experiments and field observations, almost all of these studies have focused on the spatiotemporal process of an ISW on an impermeable front slope and the temporal variations in waveform, velocity and wave energy.

However, despite many important phenomena have been revealed as an ISW propagating across a continental shelf based on the results of laboratory experiments and numerical modelings, only impermeable submerged obstacle was treated, and the effect of permeable bed on waveform evolution and inversion was overlooked. Since the topography nearshore or offshore in nature may compose sand or reef seabed with different porosities, especially around the coastal shelf where waveform inversion was observed (Bogucki et al., 1997; Orr and Mignerey, 2003; Reeder et al., 2008), the effect of a permeable seabed on ISW propagation and dissipation has also been considered. For instance, Bryant et al. (1975) measured the sea bottom porosity in the Gulf of Mexico and found porosity (n_f=0.1–0.7) varied with depth; Bennett et al. (1990) investigated Great Bahama Bank and showed the range of porosity (i.e., n_f=0.3–0.6) at different sites; Soulsby (1997) compiled many field measurements and found porosity ranging 0.3–0.46 for natural sand beds by different sediment grading and density. Although the effect of porous obstacle has been vigorously studied for the surface gravity waves in the past two decades by different numerical simulations that solve the Reynolds averaged Navier-Stokes (RANS) equations using a k-ε model (Gui et al., 2015; Hsiao et al., 2010, 2002; Liu et al., 1999; Shao, 2010; Van Gent, 1995; Wu and Hsiao, 2013; Wu et al., 2014); only few are directed to study ISW propagation. In reality, field observations also reveal that a thin porous layer exists within the top of the shelf, rather as homogeneous in porosity assumed in this study in order to examine the strong effect of the porosity on the propagation of a large depression ISW.

Hsieh et al. (2015) have recently used RANS equations with k-ε model to investigate the evolution of a depression ISW propagating over a submerged impermeable ridge. By adding a porous media equation to extending this model, a similar numerical study is carried out with a porous obstacle. In this stud, a laboratory scale wave flume is 12 m long (x-axis), 0.55 m deep (z-axis), and a fluid system consisting of upper and lower layers (h_1 and h_2 respectively) and a pycnocline at the interface (h_δ). An incident ISW of depression is generated by gravity collapse mechanism (Hsieh et al., 2014). An initial step depth (η_0) that represents the difference in the interface level on either side of the vertical gate in the flume is produced (Fig. 1). Upon lifting the gate out of the water surface, a depression ISW is generated and propagates toward a trapezoidal obstacle with variable porosity. To compensate the porous effect on the evolution during weak wave-obstacle interaction, a large step depth equals 0.25 m is used to generate a large ISW in order to match the results in Hsieh et al. (2015). After some successful benchmark verification runs which compare the numerical results with laboratory data, an extra series of numerical cases with different porosities to the same obstacle are then carried out to produce outputs for the spatiotemporal evolutions of isopycnic, vorticity, turbulent kinetic energy and wave energy. Further discussion is given using the results of the numerical simulations, for pertinent physical parameters, such as the maximum amplitude of crest (a_{cmax}) and trough (a_{tmax}), velocity (u_{max} and w_{max}), vorticity (ω_{cw} and ω_{ccw}) and turbulent kinematic energy (K_{max}) during this process (Table 1). Analysis of these results helps provide better understanding into the porous effect on waveform inversion and flow evolution as a large depression ISW propagates over a porous trapezoidal obstacle.

In this paper, Section 2 presents the numerical methodology and benchmark verifications in this study. Section 3 describes the evolutions of a large depression ISW propagating over a porous trapeziodal obstacle with different porosities, as well as displays the resultant physical parameters, which include spatiotemporal variations of isopycnic, waveform, horizontal and vertical velocity, streamline, vorticity, and turbulent kinetic energy. In Section 4, dimensionless analysis is used to discuss the effect of porosity on the pertinent parameters during waveform evolution. Finally, concluding remarks are given in Section 5.

2. Numerical methodology

2.1. Governing equations

In this study, a large ISW in depression is generated by a gravity collapse mechanism, in which the buoyant forces within a straitified two-layer fluid system with a difference in density, and its flow evolution over a porous trapezoidal obstacle is considered within an incompressible free-surface flow regime. The fluid motion is assumed to satisfy the conservation of mass and momentum in a two-dimensional framework and the Reynolds-averaged Navier-Stokes equations (RANS), which are written as follows (Hsieh et al., 2015):

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

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

$$\frac{\partial \rho}{\partial t}+\frac{1}{n_f}\frac{\partial}{\partial x_i}(\rho u_i)=\frac{\partial}{\partial x_i}\left(D_m\frac{\partial \rho}{\partial x_i}-\overline{u_i'\rho'}\right) \tag{3}$$

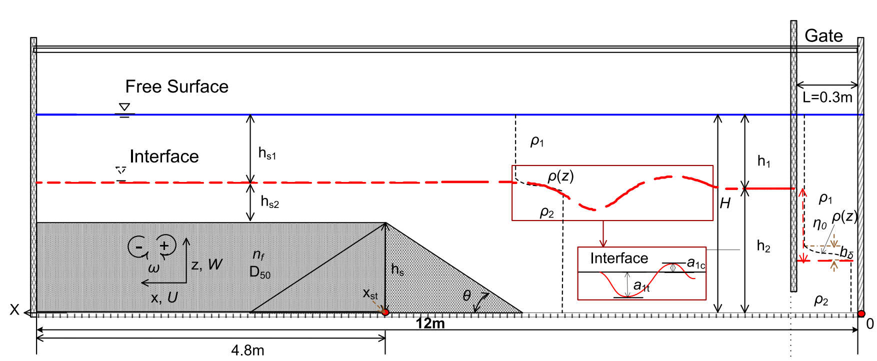

Fig. 1. Schematic diagram showing a depression ISW to be generated by gravity collapse mechanism. (Not to scale).