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Experimental investigation of the load exerted by nonstationary internal solitary waves on a submerged slender body over a slope

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ABSTRACT

Laboratory experiments are performed in a large stratified fluid flume to examine the characteristics of the load on a submerged slender body that is exerted by a nonstationary internal solitary wave (ISW) from its interaction with a gentle slope. The nonstationary ISW over the slope and its load on the body are measured by using multi-channel conductivity-probe arrays and a specially designed force measurement device, respectively, and the body's vertical and horizontal positions on the load are determined by analyzing the effects of the incident ISW's amplitude. The experimental results show that the load on the slender body increases as the incident ISW's amplitude increases; additionally, the effect of oscillations is enhanced because of the ISW's distortion, breaking and fission. The oscillating action from fission waves becomes dominant as the amplitude reaches a certain value. Additionally, the load is correlated with body's vertical position relative to the pycnocline. The magnitudes of the vertical and horizontal forces reach a maximum and minimum in the pycnocline, respectively, and the horizontal force in this direction is the opposite above and below the pycnocline. Compared to a case without a slope, the load on the slender body increases because of the nonstationary ISW, and its effect on the maximum force is transferred to the pycnocline. When the body's horizontal position is located close to the top of the slope, the direction of the horizontal and vertical forces remains consistent, but its acting time becomes longer. In addition, high-frequency actions on the slender body are impacted by nonstationary ISWs near the slope's top.

1. Introduction

An internal solitary wave (ISW) refers to the fluctuation that often occurs in the interior of a stratified fluid. ISWs with low reduced gravity have larger amplitude and lower frequency than sea surface waves, and their waveforms, amplitudes and induced flow fields undergo both non-steady and non-regular variations in time and space [1] during their propagation along the continental shelf or slope, which is defined as the nonstationary ISW in this article. Nonstationary ISWs can intensify the energy exchange between the upper and lower layers of oceans and can cause sudden high-speed flow and even large fluctuations in the interiors of oceans [2,3]. Obviously, high-amplitude nonstationary ISWs could pose serious hazards to oceanic platform structures, underwater vehicles [4].

Numerous in-situ and remote sensing observations have demonstrated that high-amplitude ISWs, which are generated in the Luzon Strait and propagate westward to Dongsha Island, are discovered constantly in the northeastern South China Sea (SCS) [5]. The shoaling effect of ISWs occurs on the shelf, so the horizontal scale of their waveforms gradually becomes wider, the vertical scale of their wave amplitudes becomes smaller, and the induced currents become stronger [6]. Phenomena such as breaking, fission, polarity conversion and high-mode waves may also occur [7–9], and the local vertical mixing and energy dissipation can become intensified. For instance, Lien et al. [9] observed a vertical overturn of ~100 m within an ISW's core in the northern SCS and estimated that the turbulent kinetic energy reached $1.5 \times 10^{-4}\,\mathrm{W\,kg^{-1}}$.

Various experimental studies on the propagation of ISWs over different bottom obstacles have been reported. Kao et al. [10] performed laboratory experiments to examine the propagation of ISWs on a slope/shelf and found that shear instability began to appear on the backside of the wave, with turbulent mixing sometimes occurring afterwards. Helfrich [11] experimentally described the fission of incoming depression waves into several soliton-like waves at

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elevation and their subsequent evolution on a slope. Wessels et al. [12] experimentally studied the interaction of long internal waves with a sill and the resulting energy loss. Michallet et al. [13] detailed the shoaling and breaking of ISWs on a uniform slope and obtained the effective magnitude of the breaking wave's energy loss. Chen et al. [14] conducted a stratification mixing experiment in a wave flume and compared the main behaviors between depression- and elevation-type ISWs that propagated over a submarine ridge. Relevant numerical investigations also demonstrated the results of in-situ observations and laboratory experiments [15,16].

Several studies have examined the dynamic characteristics of the interactions of ISWs with marine structures [17–19]. Various results indicated that ISWs exerted the non-negligible load on cylindrical piles. Cai et al. [17,20] introduced the Morison empirical formula and a modal separation method to estimate the forces and torques that are exerted by ISWs on a cylindrical pile and discussed the effects of background shear flows on the corresponding actions. Xu et al. [18] estimated ISW-induced forces on a small-diameter cylindrical pile by using the Morison equation with the internal wave theory. Si et al. [19] verified that the largest shear force from ISWs on a cylindrical pile occurred at the turning point of the horizontal velocity. Huang et al. [21] proposed a prediction model for ISW loads based on a series of experiments that focused on the interaction of ISWs with a cylindrical pile in a stratified tank. Recently, investigations on the load characteristics of ISWs on other marine structures have been developed [22–25]. You et al. [24] presented experimental results on the interaction of internal waves with a semi-submersible platform and emphasized that the influence of internal waves on marine structures must be considered in practical applications. Wei et al. [25] obtained the characteristics of the interaction between ISWs and a slender body by accurately measuring slight variations in internal wave forces on a slender body in a stratified tank. Most previous studies of the load that is exerted by ISWs have been restricted to the interaction between normal ISWs and some bodies. In fact, ISWs in oceans often appear in a nonstationary form when they propagate along marine topography. At present, few studies of the interaction between nonstationary ISWs and a submerged body have been performed.

In this paper, a series of experiments are conducted in a large, gravitationally stratified flume to obtain the characteristics of the load that is exerted by nonstationary ISWs on a submerged slender body, in which the nonstationary ISWs are generated by means of normal ISW propagation along the bottom topography. The experiments use an alternative approach, namely, the topography is a slope whose inclined angle is chosen based on the shelf topography in the northeastern SCS. The experimental techniques and methods are presented in Section 2. The results and discussion are described in Section 3, and conclusions are presented in Section 4.

2. Experimental methods

The experiments were performed in a wave flume that was 1200 cm long, 120 cm wide and 100 cm deep. A stratified fluid was obtained by using the classical "double-tank" method. During operation, the flume was filled with fresh water to a desired depth, and then a brine solution was slowly injected beneath the lighter fresh water through several small openings along the bottom of the flume until the total water depth D was 80 cm. When a stratified fluid appeared in the flume, a probe that could be moved along the vertical direction was used to measure the vertical density distribution in the fluid. The measuring-point interval in the vicinity of the pycnocline was maintained at 0.05 cm to satisfy the accuracy requirement. Thus, a typical density profile could be obtained, as shown in Fig. 1(a). The definition of the Brunt-Vaisala (B-V) frequency is $N(z) = \sqrt{(g/\rho_1)(\partial\rho/\partial z)}$, where $\rho(z)$ is the density, g is the gravitational acceleration and z is the vertical coordinate. The vertical distribution was depicted in Fig. 1(b), in which a narrow pycnocline with a thickness of 2.0–3.0 cm can be seen. The depth of the maximum B-V frequency value is regarded as the interface between the upper and lower fluids. The ratio of the upper layer's (fresh water) depth h_1 to the lower layer's (brine water) depth h_2 was 1/7, as shown in Fig. 1. Therefore, this stratified fluid was regarded as a two-layer fluid that was bounded by the maximum B-V frequency value.

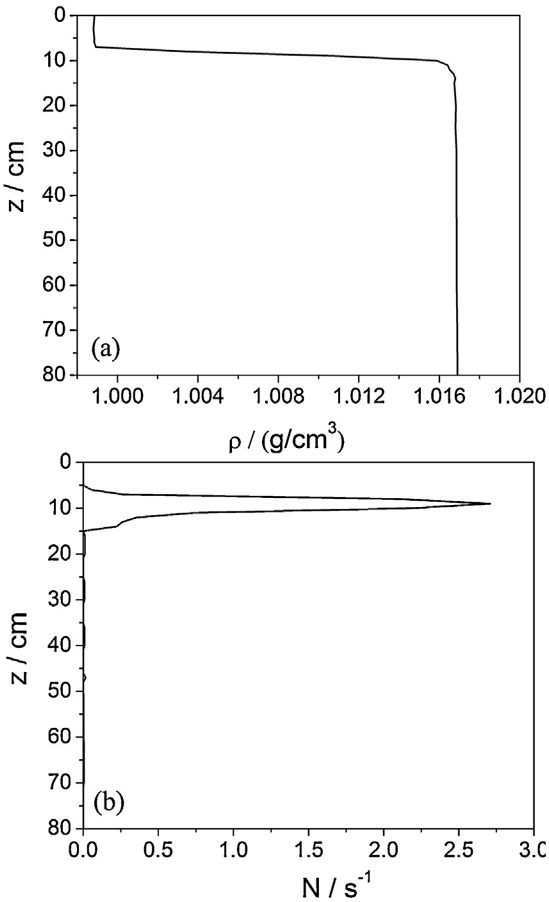

Fig 1. Structure of the two-layer fluid. (a) Vertical distribution of density; (b) vertical distribution of B-V frequency.

The experimental set-up is represented schematically in Fig. 2. ISWs were generated by an effective wave-maker, which followed the mechanism of gravity collapse as described in the pioneer paper of Kao et al. [10]. High-quality depression ISWs can be generated by regulating the step depth η_0 and step length L_0 of the wave-maker in a proper stratified fluid. A wave-absorption facility was introduced at the other end of the flume to maximally reduce the influence of reflected waves on the work region. A 120 cm-wide panel was placed at a certain inclination angle to serve as the simulated gentle-slope topography; the slope angle could be changed according to the actual circumstances. The testing-force model was a slender organic glass body that was 75 cm in length and 9 cm in diameter and was kept in a state of equilibrium, in which the buoyant force equaled the gravitational force before the processing experiments. The coordinate system was defined as shown in Fig. 2, in which $x = 0$ is set at the top of the slope, with x being positive leftward, and $z = 0$ at the surface, with z being positive downward. The notations of H and L represent the maximum height and horizontal length of the slope, respectively, $\varepsilon = H/L$, λ and a represent the slope gradient, wavelength and amplitude of the ISW, respectively.