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Experimental investigation of internal solitary wave forces on a semi-submersible

Min Chen[a,b,c], Ke Chen[a,b,c,*], Yun-Xiang You[a,b,c]

[a] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, 200240 Shanghai, China
[b] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, 200240 Shanghai, China
[c] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, 200240 Shanghai, China

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ABSTRACT

The forces on a semi-submersible induced by internal solitary waves (ISWs) have been investigated. A series of ISWs were generated by a laboratory piston-type wave maker in a density stratified two-layer fluid within a 30-meter-long wave flume. Experiments and ISW theoretical models are compared in terms of frequency-amplitude relationships and wave profiles. The forces and pitch moments on the fixed semi-submersible model were measured. Based on the experimental data, the empirical coefficients *Cm* and *Cd* are obtained as a function of *KC*, Reynolds number and layer depth *h1/h*. The force calculation was also performed based on Morison's equation and pressure integral. There is a good agreement between the calculated results and the measurements. The maximums of the forces and moments increase linearly with the amplitude becoming larger. Besides, the layer depth is found to have a close relationship with the maximum value of the horizontal forces and moments.

1. Introduction

Numerous efforts have been devoted to estimating wave forces accurately over the recent decades. With the development of ocean instrumentation, applied mathematics and remote sensing, ISWs have been observed in the coastal oceans and marginal seas (Perry and Schimke, 1965; Ostrovsky and Stepanyants, 1989; Stanton and Ostrovsky, 1998; Duda et al., 2004; Ramos et al., 2009; Zha et al., 2012; Wang et al., 2013). ISWs have much greater wave amplitude than their surface counterparts and travel thousands of meters below the pycnocline or thermocline (Vlasenko et al., 2010). ISWs are very active in the northern South China Sea (SCS) (Cai et al., 2012), and the largest amplitude of ISWs in the world's oceans is 170 m observed in the SCS (Alford et al., 2015; Lien et al., 2014). Due to the balance between nonlinear and dispersive effects, ISWs keep the shape and speed during their propagation (Osborne and Burch, 1980; Grimshaw et al., 2010). High-amplitude ISWs generate huge wave forces, which cause severe damages to deep-sea oil rigs and platforms (Osborne and Burch, 1980; Ebbesmeyer et al., 1991). Therefore the significant forces on marine structures induced by ISWs must be carefully examined.

In recent years, attentions have been paid to the interaction between ISWs and offshore structures, and the subsequential nonlinear wave forces. Cai et al. (2003, 2006) introduced Morison's empirical method, modal separation and regression analyses to estimate the forces and torques on cylindrical piles exerted by internal solitons, and found that the force contributed by the first mode internal wave dominates the majority of the global force. Cai et al. (2008) demonstrated the effect of shear flows on the forces on cylindrical piles exerted by ISWs. Xie et al. (2010) verified MCC theory for ISWs of very large amplitudes and employed the MCC solution to investigate the load on a small surface-piercing circular cylinder in a two-layer fluid system. Xie et al. (2011) developed a numerical method to estimate the forces on cylindrical piles in a continuously stratified fluid. Zhang and Li (2007) calculated the ISW-induced forces on Spar and semi-submersible platforms based on Morison's equation. Cai et al. (2014) investigated the effect of a seasonal water stratification variation on the force and torque exerted by ISWs, and found that the loads are largely dependent on the stratification. The stronger the water stratification, the larger the force and the torque. More recently, Lü et al. (2016) employed an internal gravity wave model to calculate the force and torque on the small-diameter cylindrical tendon leg exerted by ISWs in a background parabolic current.

However, most of these researches focused on the cylinders and much more attentions should be paid to forces on offshore platforms induced by ISWs. Besides, the values of the empirical coefficients *Cm* and *Cd* used in Morison's equation (Morison et al., 1950) in the ISW

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, 200240 Shanghai, China.
E-mail addresses: MinChen1989@sjtu.edu.cn (M. Chen), raulphan@sjtu.edu.cn (K. Chen).

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circumstance were determined based on surface waves (Lighthill, 1986; Sarpkaya, 1986, 2001, 2005), but the validation of such a determination remains unproved yet.

In the present study, a series of experiments were conducted in a gravitationally stratified flume to investigate the forces on a semi-submersible platform exerted by ISWs. The paper is organized as follows. Section 2 gives a brief description of experimental set-up, including the flume, the two-layer fluid system, the conductivity probes and the three-component force/moment transducer. Section 3 describes three theoretical models of ISWs. In Section 4, results are given for the frequency-amplitude relation and wave profiles of generated ISWs ranging from small to large amplitude in four layer thickness ratios. In Section 5, empirical formulas of the coefficients *Cm* and *Cd* are established from the experimental data; the measured forces are compared with the calculated results based on Morison's equation and pressure integral; and the effects of the amplitude and layer depth on forces are discussed. Finally, conclusions are drawn in Section 6.

2. Experimental set-up

The experiments were conducted in a large-scale wave flume of 30 m long, with a cross-section 1.2 m high by 0.6 m wide. A two-layer fluid of fresh and brine water was prepared by using the classical two-bucket method. The flume was filled with fresh water to a desired depth, then a brine solution was injected slowly beneath the lighter fresh water through several small openings along the bottom of the wave flume until the total water depth h reaching 100 cm. The density of the fresh and brine water was ρ_1=998 kg/m^3 and ρ_2=1025 kg/m^3, respectively. The thickness of the undisturbed upper layer (fresh water) was h_1 and the lower layer (brine water) was h_2. Brine water had to be carefully infused into the two-layer fluid system to ensure uniform diffusion with minimum disturbance and mixing at the interface. When a stratified two-layer fluid was obtained, a density probe that could be moved vertically was used to measure the vertical density distribution. The measuring interval in the vicinity of the pycnocline was maintained at 0.5 cm to ensure the accuracy. A typical density profile is shown in Fig. 1(a). The buoyancy frequency N was calculated as $N=\sqrt{(g/\rho_1)(\partial\rho(z)/\partial z)}$, where$\rho$(z) is the density and g is the gravitational acceleration. The vertical distribution is shown in Fig. 1(b), in which a narrow pycnocline with a thickness of 2–3 cm can be seen. The depth of the maximum buoyancy frequency value is regarded as the interface between the upper and lower layer.

A sketch of the experimental apparatus is plotted in Fig. 2. A reference coordinate system was specified, with the origin located at the start of the flume on the undisturbed interface. The x coordinate is positive to the wave propagation direction while the z coordinate is positive to the vertical upward direction. A wave maker is equipped to generate ISWs in the density stratified two-layer system, which follows the mechanism as described in Huang et al. (2013). High-quality depression ISWs can be generated by pushing two steel plates horizontally, which are placed vertically in the upper and lower layer fluid respectively. The flume is totally covered by a rigid lid to eliminate surface waves in the range where the plates travel. During the tests, the ISW profile was recorded using two arrays of conductivity probes, which were placed at pre-arranged positions along the flume. The first array was set at x=11 m and the second one was located at x=12.9 m. Each array was consisted of 9 conductivity probes with a vertical spacing of 3 cm. The phase speed of an ISW was obtained by $c=\Delta x/\Delta t$, in which Δx is the distance between two arrays and Δt is the time lag of wave peaks. A wave absorption facility is fixed downstream to avoid the wave reflection.

The semi-submersible model was mounted stiffly below a rigid frame at x=13.7 m. As shown in Fig. 3, the model consists of 6 columns with the diameter of 0.07 m and 2 pontoons of 0.55 m long, with a 0.1 m x 0.05 m cross-section. The spacing of the columns is 0.18 m. The platform also contains 3 horizontal braces with the diameter of 0.018 m and 14 diagonal braces with the diameter of 0.01 m, which are connected with the columns. The draft of the semi-submersible model is d=0.13 m.

A three-component force/moment transducer was fixed between the semi-submersible and the rigid frame to measure the forces and moments exerted by a depression ISW. The force point of the transducer is 0.24 m above the free surface. Electrical signals were recorded to indicate the force/moment variation on the semi-submersible in the signal acquisition and processing system. The relationship between the force/moment variation and the electrical signals were calibrated before the experiment.

3. ISW theoretical models

A one-dimensional ISW propagating along the interface between two homogeneous incompressible and inviscid fluid of different density is considered. From the original Euler equations under the sole assumption that the waves are long compared to the undisturbed thickness of one of the fluid layers, Choi and Camassa (1999) derived the following strongly nonlinear internal wave equation, which is called MCC equation:

$$(\zeta_X)^2=\left[\frac{3g(\rho_2-\rho_1)}{c_{MCC}{}^2(\rho_1h_1^2-\rho_2h_2^2)}\right]\frac{\zeta^2(\zeta-a_-)(\zeta-a_+)}{(\zeta-a_*)} \tag{1}$$

Here a_* is given by

$$a_*=-\frac{h_1h_2(\rho_1h_1+\rho_2h_2)}{\rho_1h_1^2+\rho_2h_2^2} \tag{2}$$

and $a_\pm$ are the roots of a quadratic equation,

$$\zeta^2+q_1\zeta+q_2=0 \tag{3}$$

with q_1 and q_2 defined as

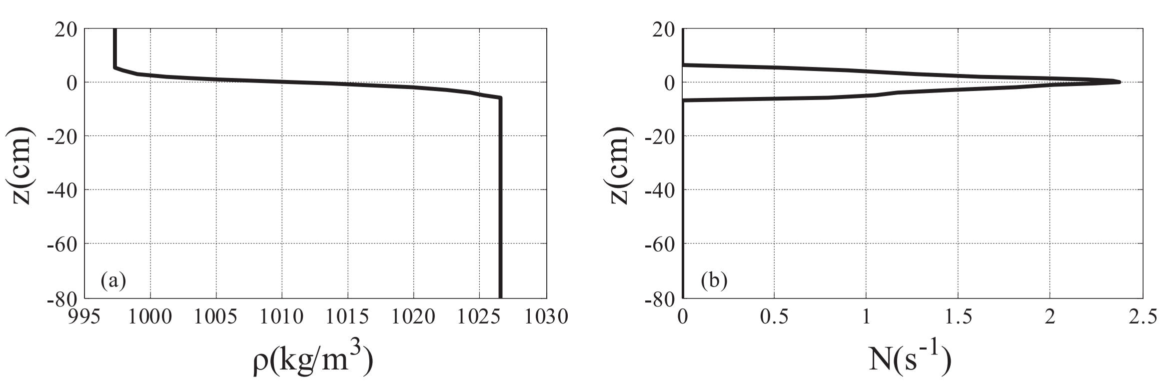

Fig. 1. The two-layer fluid of h_1/ h_2=20/80: (a) a density profile; (b) vertical distribution of the buoyancy frequency.