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A numerical and experimental study of internal solitary wave loads on semi-submersible platforms

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ABSTRACT

Using a double-plate wave maker, a series of laboratory experiments of internal solitary wave (ISW) loads on semi-submersible platforms were conducted in a density stratified fluid tank. Combined with experimental results, a numerical flume based on the Navier-Stokes equations in a two-layer fluid is developed to simulate nonlinear interactions between ISWs and a semi-submersible platform. The numerical results of horizontal and vertical forces, as well as torques on the semi-submersible platform also agree well with the experimental measurements. Besides, the numerical results indicate that the horizontal and vertical forces on the semi-submersible platform due to ISWs can be divided into three components, namely the wave pressure-difference forces, viscous pressure-difference forces, and the frictional force which is negligible. For the horizontal force, the wave and viscous pressure-difference components are of the same order, implying that the viscous effect is significant. For the vertical force, the contribution of the viscous pressure-difference is not important. Moreover, the diffraction effect is significant for horizontal force and insignificant for vertical force. Hence, it is feasible to estimate the vertical load using the Froude-Krylov approach.

1. Introduction

A large number of observations show that internal solitary waves (ISWs) occur frequently and exist widely in the ocean due to density stratification arising from salinity and temperature variations (Apel et al., 1985), which present significant hazards in coastal and oceanic regions where offshore petroleum exploration, production and sub-sea storage activities are in progress. (Osborne and Burch, 1980). For instance, in 1990 a sudden strong current accompanied by an internal wave caused a cable breakage in the extended test period of the Liuhua oilfield in the South China Sea (Bole et al., 1994). Therefore, drilling rigs should be built to withstand ISW loads in the areas where internal solitons may occur (Ablowitz and Clarkson, 1991).

A semi-submersible floating structure can serve as a drilling platform or an offshore wind turbine foundation. There is a large number of experimental and numerical investigations on the performance of this type of platform under the action of wind, waves and currents, and methods and software have been developed to calculate the hydrodynamic loads (Faltinsen, 1993; Kvittem et al., 2012). Nonetheless, there are relatively fewer studies on the loading mechanism of ISWs on floating structures. In general, previous researches were mainly focused on cylinder structures and adopted the Morison formula (Morison et al., 1950) to calculate ISW loads (Cai et al., 2003, 2008, 2006; Si et al., 2012; Song et al., 2011). However, the geometry of the semi-submersible platform is much more complicated than a cylinder thus it is difficult to directly calculate the ISW load by the Morison formula. Apparently, by modifying its coefficients, the Morison formula can still be used to estimate the loads on the cylindrical components of platforms, such as columns, horizontal and diagonal braces. For instance, Huang et al. (2013) and Chen et al. (2017) developed two sets of modified coefficients of the Morison formula by fitting the experimental data. However, these modified coefficients are not universal and certainly depend on the model settings. It is therefore questionable to extend the modified coefficients to other circumstances. Owing to the practical significance of the problem and the aforementioned discussion, a lot of ISW hydrodynamic issues on floating platforms should be clarified, including the mechanism of various load components, the influence of viscosity, and so on.

With the enhancement of computing capability, CFD simulations

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provide an effective way to analyze the problem mentioned above. As a first step towards a comprehensive understanding, one of the key issues is to develop an accurate and controllable numerical flume for the interaction between ISWs and structures. Previously Wang et al. (2017) proposed a new method to generate ISWs by adding a mass source/sink term to the continuity equation, which has been proved effective and accurate. However, special attentions should be paid to such issues as whether the numerical waveform can match the desired one in the presence of platforms, the reliability of simulated ISW loads, and so on. In the present paper, based on wave generation method proposed and with the aid of laboratory experiments, we will develop a numerical flume to calculate ISW loads on semi-submersible platforms. Furthermore, the components of the ISW loads accounting for wave pressure, fluid viscosity and wave diffraction as well will be discussed.

The present paper is organized as follows. Section 2 briefly describes the developed numerical flume. Section 3 introduces the experimental facility and procedure. Section 4 presents the numerical results, including wave properties and the ISW load characteristics on the semi-submersible platform. Finally, conclusions are given in Section 5.

2. Numerical methods

The present numerical experiments use the full Navier-Stokes equations to simulate the nonlinear interactions between ISWs and a semi-submersible platform. The ISWs are obtained by adding a mass source/sink term to the continuity equation.

2.1. Governing equations

For an incompressible fluid of density ρ_i, the velocity components (u_i, v_i, w_i) in Cartesian coordinates *Oxyz* (its origin is at the interface, see Fig. 1) and the pressure P_i satisfy the continuity equation and the Navier-Stokes equations:

$$u_{ix} + v_{iy} + w_{iz} = 0, \tag{1}$$

$$u_{it} + u_i u_{ix} + v_i u_{iy} + w_i u_{iz} = -p_{ix}/\rho_i + \nu\left(u_{ixx} + u_{iyy} + u_{izz}\right), \tag{2}$$

$$v_{it} + u_i v_{ix} + v_i v_{iy} + w_i v_{iz} = -p_{iy}/\rho_i + \nu\left(v_{ixx} + v_{iyy} + v_{izz}\right), \tag{3}$$

$$w_{it} + u_i w_{ix} + v_i w_{iy} + w_i w_{iz} = -p_{iz}/\rho_i + \nu\left(w_{ixx} + w_{iyy} + w_{izz}\right) - g, \tag{4}$$

where g is the gravitational acceleration, the subscripts with respect to space and time represent partial differentiation, and $i = 1$ (i=2) denotes the upper (lower) layer fluid.

In order to generate ISWs by using the mass source method, Eq. (1) is modified as

$$u_{ix} + v_{iy} + w_{iz} = \begin{cases} 0, & (x,y,z) \notin \Omega \\ S_i(x,y,z,t)/\rho_i, & (x,y,z) \in \Omega \end{cases}, \tag{5}$$

where the additional mass source term $S_i(x, y, z, t)$ is a nonzero function only in the source region Ω.

The computational domain is shown in Fig. 1, which consists of three regions: the mass source region, wave propagation region and dissipation region. Demarcated by ISW interface, the source region can be divided into two subregions Ω_1 and Ω_2, which respectively denote the source region and the sink region. Fluxes between the source and the sink are forced to cancel each other in order to ensure the conservation of mass in the computational domain.

For simplicity, we assume that the mass source functions vary with time only (namely, S_i is independent of spatial variables). We consider the interface fluctuation in the mass source region during the wave generation process, and define $S_i(t)$ as:

$$S_1(t) = -\rho_1 c \frac{\zeta(t)}{h_1 - \zeta(t)} \frac{1}{\Delta x}, \tag{6}$$

$$S_2(t) = \rho_2 c \frac{\zeta(t)}{h_2 + \zeta(t)} \frac{1}{\Delta x}, \tag{7}$$

where c denotes the phase speed, Δx is the width of the mass source region, and $\zeta(t)$ is interface displacement of an ISW (Wang et al., 2017).

2.2. Boundary and initial conditions

The rigid-lid approximation is adopted on the top in the present paper. It follows that the impermeability condition should be satisfied at the top and bottom of the fluid domain:

$$w_1|_{z=h_1} = 0, \quad w_2|_{z=-h_2} = 0. \tag{8}$$

Moreover, the surface of the platform is set to the impermeability boundary, the forces and torque on the surface are monitored during the simulation.

The normal velocity is continuous, and so is the pressure, at the interface $z = \zeta(x, y, t)$ which give the boundary conditions:

$$\zeta_t + u_1\zeta_x + v_1\zeta_y = w_1, \quad \zeta_t + u_2\zeta_x + v_2\zeta_y = w_2, \quad p_1 = p_2. \tag{9}$$

Only right-traveling ISWs are considered, so a symmetry condition is posed on the left boundary. The right boundary is specified as a smooth non-slip wall. In order to avoid wave reflection at the end, a buffering region is allocated to dissipate ISWs in the numerical flume, which is realized by adding a source term to the momentum equation in the vertical direction:

$$w_{it} + u_i w_{ix} + v_i w_{iy} + w_i w_{iz} = -p_{iz}/\rho_i + \nu\left(w_{ixx} + w_{iyy} + w_{izz}\right) - g - \delta(x) w, \tag{10}$$

where the damping function $\delta(x)$ is nonzero only in the dissipation region, otherwise $\delta(x) = 0$. In the present paper, we choose $\delta(x)$ as a linear function:

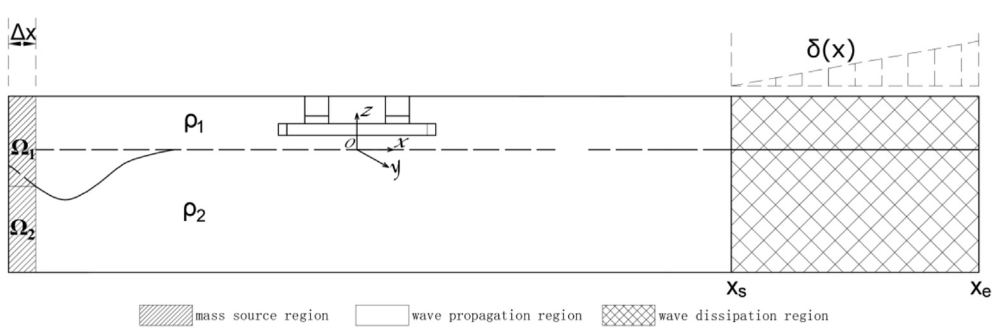

Fig. 1. The front view of the 3D computation domain.