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Investigation of wave forces on partially submerged horizontal cylinders by numerical simulation

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ABSTRACT

Wave forces on partially submerged fixed cylinders are investigated by numerical simulation; the numerical wave tank is based on the Navier–Stokes equation and VOF method spatially discretized using finite elements. Cylinders with circular and squared cross sections are used in this investigation. The features of typical force curves in a wave cycle, the magnitude of wave forces, influence of relative axis depth of cylinder, relative wave amplitude and relative wave length on the wave forces are investigated. The numerical results are compared with those calculated by a modified Morrison's equation considering a varying immersed volume of cylinder. The comparison shows modified Morrison's equation tends to underestimate the wave forces.

1. Introduction

Wave forces acting on horizontal cylinders near the sea surface are of important engineering significance and have been studied extensively by both experimental and numerical means in past decades. If no wave breaking and wave overtopping occur, and the Keulegan–Carpenter (KC) number is fairly small so that the viscosity effect is negligible, potential flow theory based models can be used to study the wave loads on bodies. Ogilvie (1963) gave second-order theoretical solutions of wave force on horizontal cylinder submerged under a free surface. Chaplin (1984) carried out an experimental work on this problem. If the wave force on a fixed cylinder be classified as a special case of wave–body interaction, then numerous works in this category based on potential flow theory in past decades can be referenced, such as Koo and Kim (2004), Liu and Teng (2010) etc., most of them relating to the field of naval architecture. More recently, Abbasnia and Ghiasi (2013) used a high-order boundary element method (BEM) to study fully nonlinear wave interaction with a fixed submerged single cylinder, dual cylinders and cylinder arrays.

For relatively small size cylinders, i.e. the viscosity effect is important, the well known Morison's equation is widely used to estimate the wave forces. In this case wave reflection and diffraction effects due to the existence of the cylinder are usually negligible. Morison's equation was originally proposed for the horizontal force acting on a vertical pile in waves. It regards the wave force as the sum of drag and inertial forces with corresponding coefficients C_D and C_M. Although Morison's equation has been widely adopted by engineers in evaluating the wave forces on cylinders, it is still necessary to research this topic further, especially when wave surface plays a role. The mechanism of the wave forces is then more complicate due to the wave surface effect.

Dixon et al. (1979) and Dixon (1980) have carried out series of experiments at The University of Edinburgh where they show that under certain circumstances the vertical force on horizontal cylinders close to the wave surface is often downwards for the entire wave cycle. This result leads to negative inertial coefficients C_M which should always be positive according to the theory behind Morison's equation. Dixon et al. (1979) have modified Morison's equation to adapt it to the case of a partially submerged horizontal cylinder by introducing a varying immersed volume of the cylinder, and considering the buoyancy effect. In spite of the fact that fairly rough approximations are used, such as ignoring the wave steepness effect in calculating immersed volume, this modified Morison's equation works well at least for small values of wave amplitude and wave steepness.

From then on, research on wave loading on horizontal cylinders near the sea surface is reported from time to time. Easson et al. (1985) measured the force spectrum from partially submerged circular cylinders in random seas. Venugopal et al. (2006) measured wave forces on horizontally submerged rectangular cylinders which are placed close to wave surface, and then derived drag and inertia coefficients. In recent years, numerical models based on viscous fluid theory emerged as a robust tool of study in this area. Zhu et al. (2001) established an adaptive finite element

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model of viscous incompressible fluid with free surface, and tested it by simulating progressive waves over submerged cylinders placed half way between the still water level and the bottom. Bihs and Ong (2013) validated their numerical model which solves URANS equations together with the k–ω turbulence model and level set method by comparing calculated vertical wave forces on partially-submerged circular cylinders in free surface waves with the experimental data of Dixon et al. (1979). They found that when the relative wave amplitude was small so that no wave overtopping occurs, the numerical vertical forces agree with experimental data well, otherwise there are discrepancies on the time of peak forces occurring.

In this paper wave forces on horizontal cylinders with both circular and square sectional shapes and partially submerged in water are investigated numerically. The typical variations of the forces in a wave cycle, and the magnitudes of peak forces are discussed. The influences of cylinder geometrical and wave parameters on wave forces are discussed as well. The numerically predicted wave forces are compared with those calculated by Morison's equation with varying immersed volume of cylinder but constant force coefficients.

2. Numerical model

2.1. Numerical wave tank

A two-dimensional numerical wave flume based on the Navier–Stokes equations for incompressible viscous fluid is established. The governing equations are spatially discretized by the finite element method and the volume of fluid (VOF) method is applied to trace the motion of the fluid. The governing equations consist of continuity equation and Navier–Stokes equations combined with a sub-grid stress (SGS) turbulent model as follows:

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

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+(\upsilon+\upsilon_T)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)+f_i \tag{2}$$

$$\upsilon_T=(c_s\Delta)^2\left[\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]^{\frac{1}{2}} \tag{3}$$

The subscript i, $j=1$, 2 represents the directions of Cartesian coordinates; υ is the kinematic viscosity of fluid and υ_T is the eddy viscosity; $c_s=0.1$ is the Smagorinsky constant; Δ is the filter scale of the SGS model and is set to the grid dimension as $\Delta=S^{1/2}$, where S is the area of grid element; u is the velocity; p is the pressure; and f is the volumetric force (i.e. gravity in this paper).

The VOF method is widely used in the numerical simulations involving free surface flows. Since its first presentation by Hirt and Nichlos (1981), many variations have been developed to improve its performance. These variations are mainly focused on the way of conveying the volume of fluid function F which is governed by the equation below:

$$\frac{\partial F}{\partial t}+u_j\frac{\partial F}{\partial x_j}=0 \tag{4}$$

In contrast to the conventional donor–accepter type algorithm, Ashgriz et al. (2004) present a computational Lagrangian–Eulerian advection remap algorithm, known as the CLEAR-VOF model. The idea of this algorithm is to move the fluid portion of an element in a Lagrangian sense, and redistribute it locally in the Eulerian fixed mesh. The CLEAR-VOF algorithm is used to track the motion of water in this paper.

The finite element discretized Navier–Stokes equation is marching in time with a three-step algorithm, comprised of evaluating the velocities with momentum equations explicitly and solving a Poisson equation of pressure implicitly, *cf.* Jiang et al. (1992).

At the boundary of wave generation, Stokes second-order waves are generated following Dong and Huang (2004)'s method and the displacement ξ of the piston of the wave generator is given as:

$$\xi(t)=-\xi_0\left[\cos\,\omega t+\frac{a}{2h_0n_1}\left(\frac{3}{4\,\sin\,h^2kh_0}-\frac{n_1}{2}\right)\sin\,\omega t\right] \tag{5}$$

$$\xi_0=\frac{an_1}{\tan\,hkh_0},\quad n_1=\frac{1}{2}\left(1+\frac{2kh_0}{\sin\,h2kh_0}\right) \tag{6}$$

where h_0 is the still water depth at the wave generation boundary; ω is the angular frequency of the wave, k the wave number and a the wave amplitude. Thus the horizontal component of the wave generator's velocity can be derived from Eq. (4) as:

$$U(t)=\frac{\partial\xi}{\partial t}=\xi_0\left[\sin\,\omega t+\frac{a}{2h_0n_1}\left(\frac{3}{4\,\sin\,h^2kh_0}-\frac{n_1}{2}\right)\cos\,\omega t\right] \tag{7}$$

When a wave passes the cylinder and finally hits the end wall of the flume, it must be absorbed so that no reflection waves go back to the cylinder. This can be done by placing a wave absorber at the end of the flume, the piston of the wave absorber moving as:

$$U_{ab}(t)=-\Delta\xi_0\left[\sin\,\omega t+\frac{a}{2h_0n_1}\left(\frac{3}{4\,\sin\,h^2kh_0}-\frac{n_1}{2}\right)\cos\,\omega t\right],\quad \Delta\xi_0=\eta(t)-\mathrm{SWL} \tag{8}$$

in which $\Delta\xi$ is the difference between water elevation and the still water line at the wave absorber. In a similar way, a slight reflection backwards from the cylinder can be absorbed by a correction on the wave generator's motion by measuring how much the water elevation differs from the predicted value. This actually turns the wave generator at the left end of the flume to be a wave generator–absorber.

2.2. Validation of numerical model

The above numerical wave flume has been used by the authors in studying the breaking wave forces on the vertical wall of a breakwater (Yuan et al., 2010), as sketched in Fig. 1, although no turbulence closure applied then. In that work, the breakwater consisted of a vertical wall structure mounted on a trapezoidal foundation; water depths d in the flume are 0.3 and 0.35 m; the water depth above the foundation d_1, the widths of the foundation shoulder b are 0.14 m and 0.15 m respectively for all cases; the wave period T varies from 1.0 s to 1.2 s; the wave height H varies from 0.09 m to 0.11 m. Both physical model tests and numerical simulations are conducted. The numerical results of pressure distribution on the vertical wall agree well with measured data. For more details refer to Yuan et al. (2010). Later an SGS model is applied to the original numerical model, which forms the exact numerical model used in this paper. The numerical tests are

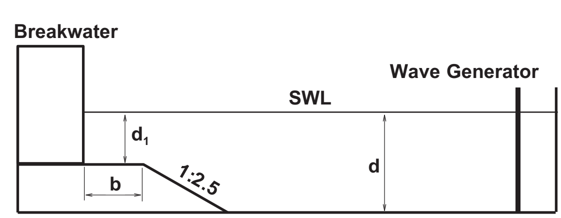

Fig. 1. Layout of flume model test for wave force on breakwater.