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Study of interaction between wave-current and the horizontal cylinder located near the free surface

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ABSTRACT

In this paper, the authors experimentally and numerically study the interaction between wave-current and the horizontal cylinder near the free surface. The experiments are conducted in the Circulating Water Channel with varying axis depths of cylinder. Considering the same wave height and different wave lengths, two regular waves are generated combined with current using a flap-type wave maker. Also, the numerical model based on the RANS equations is solved by the finite volume method, in which the RNG $k-\varepsilon$ model is adopted to simulate the turbulence while the VOF method is used to capture the free surface. In this study, the free surface deformation due to wave reflection and blockage is investigated firstly. Then, the typical features of the wave-current force on the cylinder with various axis depths are studied. The peak values of the force are also discussed by comparison with those calculated by the modified Morison's equation. Besides, the vorticity field around the fully submerged cylinder is discussed in detail. It is found that the wave-current force value is affected by both wave reflection and wave blockage under lower cylinder submergence. To be detailed, the force value increases due to wave reflection while decreases because of wave blockage. With regard to the partially submerged cylinder, wave reflection plays a dominant role compared with wave blockage. Therefore, the measured force value is larger than the theoretical one by modified Morison's equation. However, for the fully submerged cylinder, its wave blockage is more notable in contrast with dramatically reduced wave reflection, resulting in a lower measured force value compared with theoretical one.

1. Introduction

In real seas, wave-current interaction is a common phenomenon. So offshore structures in operation most probably encounter these combined real seas. While for offshore structures, horizontal cylinders such as offshore pipelines and oil platforms are popular components and will interact with such seas. Therefore, the research on its interaction with wave-current is of great engineering significance to the design of offshore structures.

Over the past years, extensive investigations have been made concerning hydrodynamic forces on horizontal cylinders. For totally submerged horizontal cylinder, the well known Morison's equation (Morison et al. [1]) has been widely used in calculating wave forces. By introducing a varying immersed volume of cylinder and considering the buoyancy effect, Dixon et al. [2] modified Morison's equation to the calculation of the force on partially submerged horizontal cylinder. However, in this modified Morison's equation the interaction between cylinder and wave effects, such as wave reflection or wave blockage, was not taken into account. Moreover, the effect of wave steepness was also ignored in calculating the immersed volume of the cylinder. In this way, the modified Morison's equation would become inapplicable, and this results in bad agreements between the theoretical forces value and measured ones as the wave height and wave steepness increased. For partially submerged horizontal cylinder, Chen et al. [3] developed a numerical model, which demonstrated that the maximum relative errors between their numerical results and the modified Morison's equation went up to 50% for both horizontal and vertical wave forces. This meant that the interaction between wave and the horizontal cylinder close to the free surface was complicated. Therefore it is necessary to further investigate this issue, especially when the current is taken into consideration.

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In recent years, several studies have been conducted regarding the interaction between wave and the horizontal cylinder close to the free surface. Oshkai and Rockwell [4] used particle image velocimetry (PIV) to investigate the patterns of vorticity in the interaction between regular wave and a submerged horizontal cylinder. The effect of the submergence depth of cylinder was discussed. This study revealed the patterns of the vorticity around the cylinder in detail. Koh and Cho [5] performed fully nonlinear potential flow simulations of the inviscid drift force caused by nonlinear waves on a submerged horizontal cylinder. It indicated that both the magnitude of negative drift force and the higher-harmonic amplitudes averaged over the transmitted wave region became larger with the decrease of submergence depth of the cylinder. Bihs and Ong [6] and Ong et al. [7] performed two-dimensional (2D) numerical simulations using of the Unsteady Reynolds-Averaged Navier-Stokes equations to investigate the flows past partially submerged circular cylinders in free surface waves. The free surface elevations and vorticity fields around the horizontal cylinders have been investigated. Bozkaya and Kocabiyik [8] conducted 2D numerical simulation to investigate the free surface wave interaction with an oscillating cylinder. The effect of the submergence depth on the lift coefficient and the corresponding equivorticity patterns are discussed in detail. According to the simulated results, two new locked-on states of vortex formation were observed in the near wake region. In recently years, numerical studies about solitary wave (Xiao et al. [9]) and focused wave (Gao et al. [10]) interaction with horizontal cylinders near the free surface have been carried out by solving the Reynolds-averaged Navier-Stokes (RANS) equations. For partially submerged cylinder, the free surface tracking is one of the most important steps in RANS simulation of its interaction with wave. To do this work, some typical methods have been employed, such as the volume of fluid method (Xiao et al. [9]), level set method (Ong et al. [7]) and SPH method (Wen et al. [11]). However, for the complex interaction between wave and cylinder, problems remain, such as the disruption of the free-surface and air-water mixing, adequate surface boundary conditions, as described by Brocchini and Peregrine [12] and Brocchini [13]. And these factors should be added in the equation for better simulation of the turbulence.

Above researches show that the submergence depth of cylinder is an important parameter in the interaction between wave and the horizontal cylinder close to the surface. Also, so does the interaction between steady current and cylinder near the free surface. Recently, several studies involving the influence of submergence depth on the interaction between current and horizontal cylinder have been carried out.

Liang et al. [14] investigated the force and vortex shedding generated by a 2D horizontal cylinder beneath a free surface using the mesh-free viscous discrete vortex method. As the horizontal cylinder approached the free surface, it was found that the center line of the wake vorticity moved downwards and diffusion occurred for a low gap ratio. The effect of the gap ratio on drag coefficient and lift coefficient were discussed in this study. Ozdil and Akilli [15] investigated the flow characteristics around a horizontal cylinder located at different elevations between bottom and free surface using PIV technique. Reichl et al. [16] performed numerical simulation to study the 2D flow past a cylinder close to a free surface at a Reynolds number of 180. Based on the simulation results, the wake behaviors for gap ratios between 0.1 and 5.0 were investigated. Lin and Huang [17] applied a Lagrangian numerical framework to study 2D free surface flow induced by a submerged moving cylinder. A series of computations were carried out to investigate the effects of Froude number, the depth of submergence and still water depth on the free-surface deformation and the wake formation.

Obviously, the submergence depth can exert significant influences on the interaction between wave-current and the horizontal cylinder close to the surface. However, previous researches on this issue have concentrated mostly on deeply submerged cylinders, while the effects of wave reflection and blockage are usually neglected. To investigate the forces on horizontal cylinders in waves and currents, Chaplin and Subbiah [18] conducted some experiments in which the still water depth of the water channel was 5 m and the axis depth of the cylinder was more than 1.75 m. Then Venugopal et al. [19] carried out an experimental investigation to measure the combined wave and current loads on horizontally submerged square and rectangular cylinders. Their experiments were conducted at a water depth of 2.2 m and the center of the cylinder was located at 0.47 m from the still water level. Furthermore, Li and Lin [20] developed a two-dimensional numerical tank to compute the hydrodynamic forces and coefficients induced by waves and currents on a submerged cylinder. The drag and inertia coefficients induced by waves and wave-current flows were compared and the effect of current on the coefficients was discussed as well. Later, a 2D fully nonlinear numerical wave flume was developed by Ning et al. [21] to investigate higher harmonics induced by a submerged horizontal cylinder in the presence of uniform current. The effects of current and cylinder's submergence on harmonics waves were discussed in detail, proving that the second free harmonics were significantly enhanced by the opposing current and small submergence.

The horizontal cylinders used in above researches were all fully submerged in water. According to the studies on the interaction between wave (or current) and cylinder, axis depth becomes an important parameter only under the condition that the cylinder is close to the free surface. Nevertheless, few efforts have been made so far to investigate the interaction between wave-current and the horizontal cylinder near the free surface. Therefore, a deeper understanding is needed to learn how the axis depth affects the interaction between wave-current and horizontal cylinder.

In this paper, the interaction between wave-current and a horizontal cylinder near the free surface is experimentally and numerically studied. Meanwhile, the influences of wave reflection and blockage are concerned on the interaction between wave-current and cylinders with varying axis depths. Also, the free surface deformation, wave-current forces with various axis depths and the vortex field around the cylinder are discussed in detail.

2. Experimental arrangement

The experiments are carried out in a Circulating Water Channel at Shanghai Jiao Tong University. For this channel, the length and height are 24.6 m and 7.4 m respectively. And its working section is 8.0 m in length and 3.0 m in width, and is operated with a still water depth of 1.6 m. Besides, a oscillating flap type wave maker is located at the upstream of the channel, while a honeycomb type wave absorber is positioned at the another end. The wave absorber can absorb the energy of incident waves and allow uniform current to pass through with very low energy loss.

The overview of the experimental arrangement is provided in Fig. 1. With a diameter of 0.06 m and a length of 2.98 m (0.02 m shorter than the width of the channel), the cylinder used in this experiment is made of aluminum and positioned horizontally near the free surface, extending along the entire width of the channel. In addition, the distance between the cylinder and the wave maker is 4.0 m. The cylinder is fixed on a steel bracket that is bolted to a six-axis load cell, while the load cell is fastened on the support system located above the wave channel. Fig. 2 presents the schematic diagram of the experimental arrangement. The distance between the center of the cylinder and the still water line is defined as the axis depth, d. A resistance wire wave gauge is located at the distance of 0.3 m from the cylinder in the experiment.