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Model experiments on wave elevation around a four-cylinder structure

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ABSTRACT

Column-supported structures are commonly used in offshore industries. The prediction of the free surface elevation in the vicinity of the supporting columns is important for structural safety and air gap design. Because the tension leg platform is normally supported by four vertical columns, model experiments are carried out to study the diffraction of regular waves by a four-cylinder structure. The experiments are designed to measure the free surface elevation at multiple locations close to the cylinder surfaces. By analysing the measured data, the amplitudes of the first-order and second-order harmonic wave elevations are obtained. To validate the diffraction theory with regard to predicting the free surface elevation, the experimental and numerical results are compared and show that the second-order diffraction theory is effective in predicting the free surface elevation, even for steep waves. The important phenomenon of near-trapping is also investigated in the experiment. For a specific incident wave frequency, near-standing wave motion can be observed inside the structure. Different wave headings are also investigated to describe the dependence of first-order and second-order near-trapping phenomena on the incident wave direction.

1. Introduction

Column-supported structures, such as tension leg platforms (TLPs) and semisubmersibles, are widely used in the offshore industries. As the distance between neighbouring columns is typically small, the hydrodynamic interaction between the columns is significant, and at certain frequencies, an important phenomenon known as near-trapping could occur. When this occurs, only a small amount of scattered wave energy radiates outwards, and a near standing wave with a rather large amplification of free surface oscillations can be observed near the cylinders. These magnifications are particularly large at the fluid-body interface with associated high induced pressures. If these phenomena were to occur in practice, equipment would likely be damaged, impacting production. Damage to the lowest decks of offshore platforms has been reported by Eatock Taylor and Wu (1997) and Swan et al. (1997).

The problem of the linear and non-linear interactions between waves and an array of cylinders has been studied by many authors. Most studies have been primarily focused on the interference effects between the cylinders, and the results have been generally obtained in the framework of inviscid flow. Havelock (1940) developed an analytical solution for the diffraction of incident regular waves from a single cylinder; this solution was then extended to multiple cylinders by Ohkusu (1974). Kagemoto and Yue (1986) considered three-dimensional water-wave diffraction and radiation by a structure consisting of a number of separate members in the context of linearized potential flow; they developed an effective interaction theory based algebraically on the diffraction characteristics of single members only. Linton and Evans (1990) improved the direct matrix method proposed by Spring and Monkmeyer (1974) and solved the scattering of water waves by an array of N bottom-mounted vertical circular cylinders under the assumption of the linear water wave theory. Ghalayini and Williams (1991) and Moubayed and Williams (1995) analysed hydrodynamic properties for an array of four bottom-mounted cylinders using the indirect method of Lighthill (1979) and Molin (1979). Evans and Porter (1997) made numerical calculations for bottom-mounted cylinders with axes at the corners of a regular polygon. They showed that at certain frequencies, the loads on single cylinders in the array can be considerably amplified compared to the isolated cylinder case examined by Mac Camy and Fuchs (1954). In that work, this phenomenon was explained by the occurrence of near-trapping in the zone internal to the polygon. The increased forces appeared to arise when the incident waves excited the near-trapped mode, and are in agreement with the amplified forces in linear arrays described in Maniar and Newman (1997). Evans and Porter (1997) found that this phenomenon is associated with the specific ratios of the incident wavelength λ to the cylinder radius a (i.e., the λ/a parameter) and the distance between neighbouring cylinder centres d to the cylinder radius a (i.e., the d/a parameter). Malenica et al. (1999) solved the problem

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of the second-order water wave diffraction of an incident monochromatic wave field by an array of bottom-mounted circular cylinders using a semi-analytical approach and extended the studies of near-trapping in an array of cylinders to the second order. They suggested that a near-trapping phenomenon exists for second-order waves in an array of cylinders at half the wave frequency at which the corresponding linear near-trapped mode occurs. Huang (2004) developed a semi-analytical solution for the second-order wave diffraction by an array of cylinders in monochromatic waves that yields simple expressions for potentials in the vicinity of cylinders. Eatock Taylor (2007) showed the linear wave amplitudes in the vicinity of a four-cylinder structure for different incident wave directions at a frequency corresponding to a near-trapped mode. The maximum value in the case of $\beta=45^\circ$ was found to drop off with increasing or decreasing β, where β was defined as the incident wave angle and measured from a side of the square. It was suggested that the degree to which a near-trapped mode is excited is related to the incident wave directions. Wang and Wu (2007) employed the time domain method to analyse the interactions of water waves and an array of cylinders. The results for various configurations are provided to show the effect of the interaction and their behaviour near the trapped mode. Walker et al. (2008) studied the diffraction of monochromatic waves by an array of four bottom-mounted cylinders and a gravity-based structure in detail. In this study, a design wave called NewWave is proposed as a realistic model for large ocean waves and is used as the incident wave field in the wave–structure diffraction analysis. Teng and Cong (2012) investigated wave diffraction by a square array of truncated cylinders using the second-order theory; numerical results showed that the second-order near-trapping phenomenon can occur inside the truncated cylinder array. Bai et al. (2014) simulated the wave diffraction around an array of fixed vertical circular cylinders in a numerical wave tank by using a fully nonlinear model in the time domain.

Many theoretical experiments on various multi-column structures have already been performed. Swan et al. (1997) presented the results of a physical model study of waves around the Brent Bravo gravity-based structure, which consists of closely placed legs. Measurements of the water surface elevation in the vicinity of the model structure show that the closely spaced legs give considerable wave–structure interaction. The measured local wave elevations are higher than those expected, which suggests the presence of significant nonlinearities. Scolan and Malenica (1998) investigated the diffraction of regular waves around an array of four vertical bottom-mounted cylinders. Highly localized second-order wave elevations in the spacing between the two front columns were observed; these phenomena are explained by the existence of near-trapped modes. Giorgio and Fabrizio (2000) presented results of experimental tests on the interaction between regular waves of moderate steepness and an array of four vertical bottom-mounted cylinders. These results highlight the occurrence of large oscillations of the free surface. Ohl et al. (2001a, 2001b) performed an experimental study on the wave diffraction produced by arrays of vertical bottom-mounted circular cylinders. In this study, the second-order harmonic free surface elevations at different wave headings were extracted in the context of near-trapping, and the second-order near-trapping was observed to affect the magnitude of local free surface oscillations as well as the scattered far field radiation. Kagemoto et al. (2002) presented an experimental study on regular wave interaction with an array of 50 cylinders. They found that viscous dissipative effects take place within the boundary layers at the cylinder walls and in the wave period range of the Neumann trapped mode, significantly less resonance was observed than predicted by the linearized potential flow theory. Giorgio et al. (2005) extended the work of Giorgio and Fabrizio (2000) to the second order, showing a large amplification of the second-order wave run-up in the experiment with waves travelling along the diagonal of the square. Kagemoto et al. (2013) presented experimental results on the free surface displacements between two rows of vertical circular cylinders in head waves and showed that in waves of certain periods, large second-order free surface displacements could be induced.

Although the near-trapping phenomenon in a four-cylinder structure has been studied by many authors, there are some issues that require further study. First, previous investigations of the first-order and second-order near-trapping phenomena focused on the case of waves travelling along the diagonal of the square; however, whether this phenomenon can occur under other wave headings has not been studied in depth. Second, because the second-order diffraction theory is usually used as an effective tool to study the interaction between waves and maritime structures, its validation in predicting the free surface elevation needs to be strictly examined. This paper presents the results of an experimental study in which the wave elevations arising at multiple locations in the vicinity of the four bottom-mounted cylinders were recorded for a wide range of wave conditions. The purpose of this study is to investigate the dependence of the first-order and second-order near-trapping phenomena on the incident wave direction and check the performance of the diffraction theory in predicting the free surface elevation. Numerical computations based on the potential flow theory are also implemented using QTFDUT; numerical accuracy and convergence are also addressed. QTFDUT is a hydrodynamic analysis program, which utilizes Teng and Eatock Taylor's (1995) higher order boundary element method (HOBEM) to solve the three-dimensional diffraction problem to the second order. Then, the experimental and numerical results are compared, focussing on the variation of the wave elevation when the incident wave frequency is near a critical frequency. The behaviour of the measured wave elevation versus ka shows clearly the occurrence of the first-order and second-order near-trapping phenomena. The effects of alterations in wave steepness on the results are considered, and for each wave period, the wave steepness kA was set to three different values. Three wave headings (i.e., 45°, 22.5° and 0°) are considered in the experiment. The results from different wave headings show the dependence of the near-trapping phenomenon on the incident wave direction.

In the following sections, the concept of wave elevation is first introduced in Section 2. Following a description of the wave diffraction experiment in Section 3, results and discussions are presented in Section 4. Finally, conclusions are presented in Section 5.

2. Expression for wave elevation

Consider the diffraction of a plane monochromatic wave of amplitude A, angular frequency ω, by a fixed body in a water depth h. Assuming ideal fluid and small wave amplitude, the velocity potential, solution of Laplace's equation in the fluid domain, can be expanded in a perturbation series in terms of the wave slope parameter ε., yielding

$$\Phi=\varepsilon\Phi^{(1)}+\varepsilon^2\Phi^{(2)}+o(\varepsilon^3) \tag{1}$$

The first-order and second-order potentials will have the following forms:

$$\Phi^{(1)}(\mathbf{x},t)=\mathrm{Re}\{\phi^{(1)}(\mathbf{x})e^{-i\omega t}\}, \tag{2}$$

$$\Phi^{(2)}(\mathbf{x},t)=\overline{\phi}^{(2)}(\mathbf{x})+\mathrm{Re}\{\phi^{(2)}(\mathbf{x})e^{-2i\omega t}\}. \tag{3}$$

In Eq. (3), $\overline{\phi}^{(2)}(\mathbf{x})$ does not contribute to the free surface elevation and is thus not required in this analysis. At each order, ϕ is decomposed into incident (ϕ_I) and diffracted (ϕ_D) potentials: $\phi^{(i)}=\phi_I^{(i)}+\phi_D^{(i)}$, $i=1,\ 2$. The incident potentials are given from