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Experimental investigation of the interaction of multidirectional irregular waves with a large cylinder

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ABSTRACT

Experimental investigations of the interaction of multidirectional irregular waves with a large, vertical bottom-mounted cylinder have been carried out. In the experiments, the ratio of the significant wave height to the water depth has values of 0.08, 0.12, and 0.16, and the relative size of the cylinder with respect to the wavelength varies from 0.44 to 1.26. Recently, many researchers have studied wave loading on large structures. However, there is a lack of high-quality experimental data that can be used for verification. In this paper, experimental measurements of the wave run-up at different locations and wave load on a large cylinder are presented. The results show that the directional spreading parameter has a significant effect on the interaction of multidirectional irregular waves with cylinder. These results may provide a reference for the design of engineering structures and be regarded as basic data for numerical verification.

1. Introduction

Increasing numbers of marine structures are being built for the purpose of developing marine resources. Most of these structures are composed of cylinders. There are, basically, two different approaches to evaluating the hydrodynamic wave forces acting on a cylinder, one based on Morison's equation and the other on diffraction theory. The interaction of regular waves with a slender cylinder can be evaluated based on the formulation proposed by Morison et al. (1950). Morison's equation is a semi-empirical equation for the in-line horizontal force per unit length on a vertical cylinder. The total force is represented as the sum of a linear inertial component and a non-linear drag component. Generally, Morison's equation is used under the condition $D/L \leqq 0.15$ (D is the diameter of a cylinder and L is the wave length) in such case the effect of the wave diffraction can be ignored. However, when $D/L > 0.15$ for the case of a large cylinder, the effects of the wave diffraction are dominant and the wave diffraction theory should be used. For this case, a superposition method was used by MacCamy and Fuchs (1954) to obtain a linear solution based on the assumption that the incident wave has a small steepness. Chakrabatri and Tam (1975) experimentally studied on the wave pressure distribution on the cylinder and found that the linear diffraction theory to be reasonably accurate for the ratio of wave height and water depth being smaller than or equal to 0.25 and the range of ka (k is the wave number and a is the cylinder radius) being between 0 and 3. Isaacson (1978) presented an approximate expression for the wave run-up at different locations on a cylinder. Niedzwecki and Duggal (1992) performed a small-scale experimental study to investigate the wave run-up on rigid full-length and truncated circular cylinders under regular and random sea conditions, and presented a semi-empirical formula for the maximum run-up on a cylinder.

Nonlinear effects in wave diffraction due to a cylinder have been discussed by many researchers (e.g., Eatock Taylor and Hung, 1987; Newman, 1996; Kriebel, 1990). The authors used second-order diffraction theory to study the nonlinear interaction of regular waves with a vertical circular cylinder. Kriebel (1992, 1998) investigated the wave run-up and wave force carried out in 22 laboratory experiments. It was found that both the measured and the predicted maximum forces exceeded the predictions of the linear theory by 5–15%, and the measured maximum wave run-up exceeded the predictions of the linear theory by 44%. The predictions of the second-order theory for the wave run-up around a large-diameter vertical cylinder and for the wave load on it were more consistent with the experimental results than were the predictions of the linear theory. Wang and Wu (2010) developed a fully nonlinear numerical wave tank to simulate three-dimensional waves and cylinder array interactions by the finite element method. Morgan and Zang (2010) developed numerical model using the open source CFD software suite OpenFOAM for the simulation of focused wave packets interacting with a vertical cylinder, and the results had good agreement with experimental data. Paulsen et al. (2014) numerically investigated the steep regular water waves on a vertical circular cylinder at

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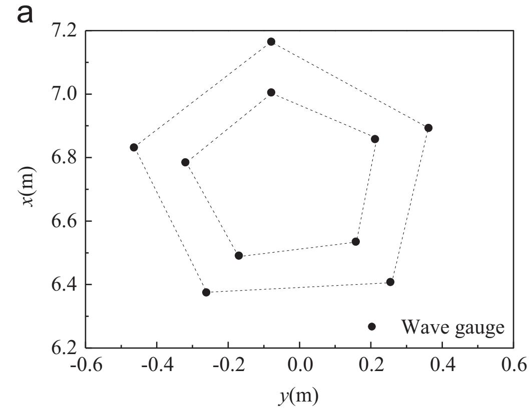
finite depth by solving the two-phase incompressible Navier–Stokes equations, and the physics of the secondary load cycle and the influence factors on it were discussed.

However, most of the researches were based on unidirectional waves, whereas in fact sea waves are multidirectional. Lee et al. (2002, 2007) used a numerical model to predict the interaction of multidirectional random surface waves with rectangular submarine pits, and found that the minimum diffraction coefficients for multidirectional random waves were greater than the regular wave values. Yu et al. (2000) conducted a series of physical experiments to study the refraction and diffraction of multidirectional random waves through a gap in a breakwater. Li et al. (2000) studied numerically the diffraction of multidirectional irregular waves around a semi-infinite breakwater and through a gap in a breakwater, and good agreement was observed between the numerical and experimental results. Yu et al. (1996) investigated the wave force due to multidirectional random waves on a small vertical cylinder by experiment. The variation of various hydrodynamic coefficients with KC number and wave directional spreading were investigated. The few studies show that the wave directionality has important effects on the interaction of waves and structures. However, little research has been conducted on the load induced by multidirectional waves on large vertical cylinders. Huntington and Thompson (1976) studied experimentally the transfer functions for pressure and force, and their results agreed with theoretical results. Mizutani et al. (1998) carried out hydrodynamic experiments to study the forces induced by multidirectional waves on cylinders. Niedzwecki et al. (2001) studied experimentally the dynamic response of a mini-Tension Leg Platform under multidirectional wave conditions. A finite element model with unstructured triangular elements based on modified Boussinesq equations was developed by Liu et al. (2010, 2012), and the effects of the wave directionality on waves incident on a group of cylinders and on the wave run-up on the cylinders were investigated. Li et al. (2012, 2014) performed an experiment on the interaction of multidirectional focused waves with a vertical cylinder. The relationship between the directionality of multidirectional focused wave and wave loads on the cylinder was discussed.

Accurate predictions of the wave run-up and wave force on large cylinders are extremely important for design purposes. Wave directionality is a very important feature for real sea conditions. In order to improve the scientific understanding on the effect of wave directionality on the wave run-up and wave load on cylinders, we have carried out systematic experiments on the action of directional waves on a cylinder and cylinder groups. In this paper, experimental results for the multidirectional wave run-up and force on a large vertical cylinder are presented. Various wave parameters, including the relative dimension, the wave steepness, and especially the wave directionality, are considered. The relationships between the wave parameters and the wave run-up and force are investigated. It is hoped that the results will provide a reference for the design of appropriate engineering structures and for verification of numerical models.

2. Experimental arrangement and wave parameters

A laboratory experiment was carried out in a wave basin at the State Key Laboratory of Coastal and Offshore Engineering (SLCOE), Dalian University of Technology, China. The basin is 55.0 m long, 34.0 m wide and 0.7 m deep. A multidirectional wave-maker system was installed on one side of the basin. The wave-maker system included 70 segments, each 1.0 m high and 0.40 m wide, resulting in a system with a total length of 28.0 m. To adapt the infinite extent of the fluid for the wave–structures interaction, wave absorbers were arranged along the other three sides of the basin to absorb incoming waves and prevent the wave reflections from the boundary of the wave basin.



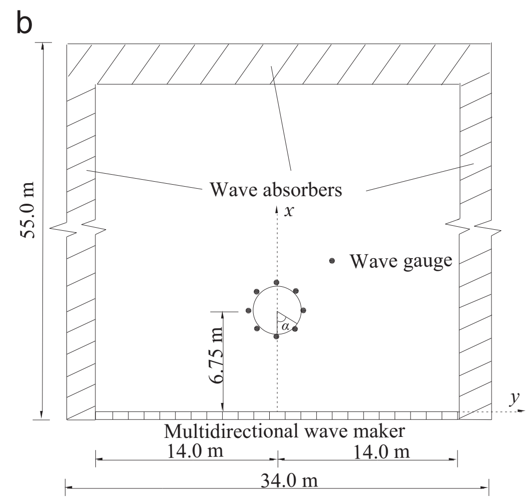


Fig. 1. Physical layout of the experiment; (a) wave gauge array used to analyze the directional spectrum, (b) the arrangement of wave gauges around the cylinder.

As the research mainly focused on the effect of the wave directionality on the wave action on a large cylinder, the water depth was kept constant at 0.5 m in the experiment.

Fig. 1 gives the experimental arrangement. The multidirectional waves in the valid area of the wave basin were recorded, and the data was used to analyze the directional spectrum by a Bayesian method (Hashimoto et al., 1987). The wave gauge array used for this measurement, consisting of ten wave gauges, is shown in Fig. 1(a).

Fig. 1(b) shows a sketch of the physical layout of the main experiment. In this experiment, the cylinder has a radius $a=0.2$ m and a height of 0.85 m to avoid overtopping by waves. It was fixed at the position (6.75 m, 0.0 m). Eight wave gauges were arranged around the cylinder to measure the wave run-up on the cylinder. The angles α defined in Fig. 1(b) are 0° (toward the wave maker), 45°, 90°, 135°, 180°, 225°, 270°, and 315°, and the distance between the wave gauges and the cylinder surface is 0.5 cm.

A model of the force-measuring device is shown in Fig. 2. The cylinder was fixed to a rigid frame via a forcemeter. The gap between the floor of the wave basin and the bottom of the cylinder was 0.5 cm. The purpose of this gap was to avoid attachment of the cylinder to the floor, which might affect the accuracy of the experimental results. The natural frequency of the cylinder in the water is 9.7 Hz, which is much larger than the wave frequencies used in the experiment. This means that the cylinder will not resonate when the waves interact with it.