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Benchmark computations of wave run-up on single cylinder and four cylinders by naoe-FOAM-SJTU solver

Hongjian Cao, Decheng Wan*

State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

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ABSTRACT

The benchmark simulations of wave run-up on a fixed single truncated circular cylinder and four circular cylinders are presented in this paper. Our in-house CFD solver naoe-FOAM-SJTU is adopted which is an unsteady two-phase CFD code based on the open source package OpenFOAM. The Navier-Stokes equations are employed as the governing equations, and the volume of fluid (VOF) method is applied for capturing the free surface. Monochromatic incident waves with the specified wave period and wave height are simulated and wave run-up heights around the cylinder are computed and recorded with numerical virtual wave probes. The relationship between the wave run-up heights and the incident wave parameters are analyzed. The numerical results indicate that the presented naoe-FOAM-SJTU solver can provide accurate predictions for the wave run-up on one fixed cylinder and four cylinders, which has been proved by the comparison of simulated results with experimental data.

1. Introduction

Wave run-up is the phenomenon of wave uprush on large vertical supporting cylinders of offshore structures. Wave run-up height is defined as the maximum vertical wave elevation to the still water surface, which is considerable larger than the incident wave crest especially in steep waves. It is a very important factor for the design of a safe deck elevation if large loads of wave impact on deck are to be avoided. Wave run-up generally occurs along with the strongly nonlinear phenomena such as wave impact, wave turning over and even wave breaking and spray. All these factors lead to the difficulty of accurately predicting the wave run-up value. Development of an effective and accurate numerical tool for the prediction of wave run-up and wave impact loads on supporting cylinders is both necessary and inevitable for the optimal design of offshore structures.

Numerous experimental and numerical investigations on wave run-up on a single vertical cylinder have been reported over the last several decades. In the early days, the approximate results of maximum wave run-up on a single cylinder according to linear diffraction theory proposed by MacCamy and Fuchs [1] are given as

$$\frac{R}{\eta_{\max}} = \left[1 + 4(ka)^2\right]^{1/2} \qquad (1)$$

where $\eta_{\max}$ denotes the incident wave crest elevation; k denotes the wavenumber; a denotes the radius of the circular cylinder. However, the linear diffraction method is not sufficient for predicting wave run-up accurately. Therefore, the second order diffraction theory was applied for the wave run-up calculation by Kriebel [2] and compared with his experiments, but the numerical results of wave run-up were still under-predicted especially for steep waves.

Proposing empirical formula based on experimental work is another way to predict wave run-up height. The first notable experiment of wave run-up on cylinders was conducted by Hallermeier [3], and the velocity stagnation head method was suggested for calculating the wave run-up height, which was given as

$$R = \eta_{\max} + \frac{u^2}{2g} \qquad (2)$$

where u denotes the horizontal velocity of water particles. This method can give reasonable results for long waves. In addition, a series of experimental work on wave run-up problems was also performed by Niedzwecki and Duggal [4], Martin et al. [5], Mase et al. [6], Nielsen [7], Morris-Thomas [8], Morris-Thomas and Thi-

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* Corresponding author.
E-mail addresses: dcwan@sjtu.edu.cn, wan_decheng@126.com (D. Wan).

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agarajan [9], De Vos et al. [10], Myrhaug and Holmedal [11], Lykke Andersen et al. [12], Ramirez et al. [13].

The rapid advance of computational fluid dynamics (CFD) technology during the last several decades has deeply affected the offshore structure design process. CFD simulation has become an efficient tool for the investigation and superior understanding of the complex physical phenomena. Numerous previous numerical simulations have also been performed on wave run-up problems. Yang & Ertekin [14] studied the nonlinear wave diffraction by a vertical cylinder numerically. Buchmann et al. [15] used the second-order boundary element model for the wave run-up problem. Trulsen and Teigen [16] applied the fully nonlinear potential method for computing the wave scattering around a vertical cylinder. Kristiansen et al. [17] performed a validation of second-order analysis approach for the prediction of diffracted wave elevation around a vertical cylinder. Sheikh and Swan [18] investigated the interaction between steep waves and vertical surface-piercing column. Lee et al. [19] simulated the wave run-up on a vertical cylinder by a 3-dimensional VOF method based on a two-step projection algorithm, and discussed the nonlinear wave-cylinder interaction. Danmeier et al. [20] compared the wave run-up results from the second-order diffraction code (WAMIT) and the fully nonlinear CFD program (ComFLOW) with experiments. The regular wave run-up on a single cylinder was also carried out numerically in the previous work. Cao and Wan [21] showed that the obtained results of wave run-up was reasonable but not accurate enough especially under steep waves when compared with those from Nielsen [7], as linear wave was used as the incident wave condition.

Investigation of wave run-up on multiple cylinders is also extremely important especially for the design of an offshore platform supported by multiple columns. Previously, many experiments were carried out to study the wave run-up on the platform columns. Niedzwecki and Huston [22] studied the wave run-up on a four-column TLP in regular wave conditions. Nielsen [7] investigated the air-gap and wave run-up on a four-column floating platform. Mavrakos et al. [23] analyzed the wave run-up on a scaled TLP model experimentally. Contento et al. [24] studied the wave run-up on an array of vertical cylinders and showed the occurrence of the second-order near trapping phenomena. Simos et al. [25] performed a series of tests for small-scale columns under regular waves, focusing on the air gap response. Izadparast and Niedzwecki [26] studied the distributions of wave run-up on a TLP model with a developed three-parameter distribution model. All the work shows the significance of investigating the wave run-up phenomena. Meanwhile, numerous numerical investigations have been conducted on the interaction between wave and multiple cylinders. Ma et al. [27] investigated the full nonlinear interaction between vertical cylinders and steep waves with finite element method. Stansberg & Kristiansen [28] investigated the nonlinear wave-column interaction in steep waves with second-order numerical model. Wang & Wu [29] studied the fully nonlinear interactions between water waves and vertical cylinder arrays based on finite element method. Bai et al. [30] studied the wave diffraction around an array of fixed vertical cylinder, and investigated the nonlinear properties of the near-trapping phenomenon associated with multiple cylinders. The investigations both with experiments and numerical models indicated that there is an urgent demand for a more efficient and accurate solver for the wave run-up prediction.

The objective of the paper is to apply the in-house CFD solver naoe-FOAM-SJTU to the benchmark computation of wave run-up on a single cylinder and multiple cylinders, considering the strongly nonlinear effects under extremely large and steep waves. All the simulations are performed in a full-scale numerical wave tank established by the numerical wave tank module of naoe-FOAM-SJTU solver. The solver is an unsteady two-phase viscous fluids flow solver employing Navier-Stokes equations as the governing equations and the volume of fluid (VOF) method for capturing the free surface. More details about naoe-FOAM-SJTU solver can refer to references [31–38]. By comparing the numerical results with corresponding experimental data, the accuracy of present solver is validated and more detailed flow field information is presented to have a deeper insight into the wave run-up phenomena.

This paper is organized as follows: the research work on the wave run-up on cylinders is reviewed firstly. The numerical methods proposed in the presented work are introduced in next section. Then, numerical simulations are performed and results of the wave run-up height around the cylinder are analyzed and discussed. Finally, a brief conclusion is drawn.

2. Numerical methods

2.1. Governing equations

Both air and water are assumed as incompressible viscous fluids. The Navier-Stokes equations are employed as the governing equations as follows:

$$\nabla \cdot \vec{u} = 0 \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\vec{u}) + \nabla \cdot (\rho\vec{u}\vec{u}) - \nabla \cdot \left(\mu\left(\nabla\vec{u} + \nabla\vec{u}^T\right)\right) = -\nabla p + \rho\vec{g} + \vec{F}_S \tag{4}$$

where $\vec{u}$, p, ρ, $\mu$and $\vec{g}$ denote the velocity, pressure, density, dynamic viscosity and acceleration of gravity respectively. $\vec{F}_S$ is the source term for wave damping in the wave damping zone to avoid wave reflection from the outlet boundary. The linear and quadratic formulas are often used for wave damping, and the quadratic version is expressed as follows:

$$\vec{F}_S(x) = \begin{cases} -\rho\vec{u}\mu_S\left(\dfrac{x - x_0}{l_S}\right)^2 & \text{if} x_0 < x \le (x_0 + l_S) \\ 0 \ \text{if} x \le x_0 & \end{cases} \tag{5}$$

where μ_S denotes a constant parameter to adjust the wave damping effect; x_0 is the start position of the wave damping zone; l_S is the length of wave damping zone.

2.2. Interface capturing approach

The VOF method with interface compression technique proposed by Ruche [39] is used for capturing the water-air interface which is determined by solving the volume fraction function. Its governing equation is as follows:

$$\frac{\partial\alpha}{\partial t} + \nabla \cdot (\alpha\vec{u}) = 0 \tag{6}$$

where α denotes the volume fraction of one fluid in a cell, which has the value$0 \le \alpha \le 1$. The iso-contour of $\alpha = 0.5$ is considered as the free surface of water. The physical properties of the fluid are calculated as the weighted averages based on the volume fraction in one cell and shown as follows:

$$\begin{cases} \rho = \alpha\rho_1 + (1 - \alpha)\rho_2 \\ \mu = \alpha\mu_1 + (1 - \alpha)\mu_2 \end{cases} \tag{7}$$

in which, ρ_1 and ρ_2 are the densities of the water and air, respectively; μ_1 and μ_2 are the dynamic viscosities of the water and air, respectively.

2.3. Discretization schemes

The finite volume method (FVM) is used for solving the governing equations including Eqs. (3), (4), (6). The computational domain is discretized into numerous cells, and the flow field variables are

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