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Numerical and experimental investigation of breaking wave interaction with a vertical slender cylinder

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Abstract

Offshore wind turbine substructures consisting of cylindrical members are exposed to highly non-linear and breaking waves in shallow waters [1]. Those structures experience extreme impulsive loads of short duration from breaking waves that can cause permanent structural damage[2]. The main purpose of the present paper is to investigate the wave impact forces on a slender cylinder from plunging breaking waves in shallow waters both experimentally and numerically. The present study consists of two major parts: laboratory measurements and numerical simulations. The laboratory experiments are performed with regular waves. Plunging breaking waves are generated and free surface elevations are measured around the cylinder. Next, numerical simulations are carried out in the three-dimensional numerical wave tank REEF3D. The model is based on the incompressible Reynolds-averaged Navier-Stokes equations together with the $k - \omega$ for turbulence and the level set method for free surface. The numerical results are compared with the laboratory measurements in order to validate the numerical model. A good agreement between the computed results and the experimental data is seen for the breaking wave properties. Further, the breaking wave forces and the free surface deformations during the interaction of plunging breaking waves with a vertical cylinder are investigated and they are reasonably well represented in the numerical simulations.

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1. Introduction

Offshore wind energy is gaining spotlight as a potentially huge, clean and renewable energy source. Currently, most of the offshore wind farms have been developed in shallow waters of depths between 5 to 30m. Offshore wind turbine (OWT) substructures consisting of cylindrical members are exposed to highly non-linear and breaking waves in shallow waters [1]. Wave impacts exert high intensive loads on structures and the load durations are shorter or

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comparable with the natural period of the structures. In particular, a shorter rise time wave impact event can cause more intense impact force on a structure. Moreover, the forces from breaking waves are the largest and exert the most severe loads, causing permanent structural damage to structural members. In some cases, this loading condition governs the design of the OWT substructures[1]. Monopile is the most common foundation type for offshore wind turbines in shallow waters [3]. In addition, hydrodynamic loads from highly nonlinear shallow water waves have a significant influence on the fatigue life of OWT [4]. Specifically, understanding the physical processes during the wave breaking has always been a key factor in the estimation of hydrodynamic loads on OWT substructures.

Wave breaking is a natural process involving transformation of wave energy into turbulent energy leading to a rapid transition of the free surface, that exerts massive hydrodynamic loads on marine structures [5]. A wave undergoes deformation, i.e. the wave height and local wave steepness increase as it propagates over decreasing water depth, leading to an increase in the forward momentum. Further, the slope of the wave front and the crest particle velocity increases continuously until the wave breaks. When the breaking wave interacts with a vertical cylinder, a rapid change in the forward momentum occurs, causing an impact force on it in a very short duration [6]. The shape of the wave profile and the wave celerity at breaking are important considerations for describing the wave impact force. Numerous studies have investigated the nonlinear hydrodynamic loads from breaking waves on offshore structures in deep waters (e.g. [7,8]).

Several experimental studies have been carried out to investigate the interaction between breaking waves and a vertical cylinder (e.g. [6,9–12]). The studies also show that the application of the Morison equation [13] to estimate the breaking wave force on a fixed vertical cylinder is not straight forward, but the equation can be used to predict the total breaking wave force by including a separate impact force term. However, the inputs concerning the wave shape and the breaking wave celerity need to be known in order to determine the theoretical total force from breaking waves [6,9,11]. Numerical modelling of of breaking waves and the interaction with OWT substructures are subjected to significant uncertainties since the underlying physical processes are still not fully understood. The evolution of breaking waves and their interaction with structures can be modelled numerically with computational fluid dynamics (CFD) models based on the Navier-Stokes equations. A number of numerical investigations have been attempted to model breaking waves and the associated flow characteristics in shallow waters (e.g. [14–19]). A few numerical studies have been carried out to investigate the interaction between breaking waves and structures [3,20,21]. Although these investigations reported many interesting results, little work has examined the characteristics of breaking wave forces and the resulting free surface flow features around a structure.

The main purpose of the present paper is to investigate the interaction of plunging breaking waves with a vertical slender cylinder in shallow waters both experimentally and numerically. The present study consists of two major parts: laboratory measurements and numerical simulations. First, the laboratory experiments are performed with regular waves in a 33m long glass wave flume. Plunging breaking waves are generated and free surface elevations along the wave tank and the wave impact forces are measured. Next, numerical simulations are conducted in the three-dimensional numerical wave tank REEF3D [17,22]. The numerical model is based on the incompressible Reynolds-averaged Navier-Stokes equations together with the $k - \omega$ for turbulence and the level set method for the free surface. The numerical results are compared with the laboratory measurements in order to validate the numerical model. A good agreement between the computed results and the experimental data is seen for the characteristics of breaking waves and the wave celerity at breaking. Further, the numerical study examines the wave celerity at breaking, the pressure distribution, and the free surface deformations during the interaction of breaking waves with a cylinder. In addition, the breaking wave forces for waves with different frequencies are also presented and discussed.

2. Numerical model

In the present study, the open source CFD model REEF3D has been used to simulate breaking waves and their interaction with a slender cylinder. The present numerical model has been thoroughly validated and tested for several hydrodynamic problems such as waves breaking over slopes [17,19], waves breaking over an impermeable slope [18] and non-breaking wave forces on vertical cylinders [22,23]. The model has also been validated for modeling breaking wave forces [24,25] and utilized to investigate the breaking forces on slender vertical cylinders under different wave impact scenarios and the flow features around them. The present numerical model uses higher-order numerical schemes in order to achieve good numerical accuracy and stability. The governing equations of the model are the