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# A CFD model for simulating wave run-ups and wave loads in case of different wind turbine foundations influenced by nonlinear waves

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ABSTRACT

A hydrodynamic simulation of wave run-up heights and wave loads on three types of wind turbine foundations, *i.e.* monopile, gravity-based and tripod support structures, was conducted using a RANS solver and employing k-ε turbulent closure. Due to the contribution of the present CFD model, a semi-empirical formula is calibrated based on velocity stagnation head theory for crest kinematics. Eventually, the results indicate that the difference among the maximum normalized run-up heights of these support structures is smaller for lower wave steepness than those for higher wave steepness. In contrast, it is shown that the difference among the wave loads of these foundations is larger for lower wave steepness than those for higher wave steepness. A calibrated run-up parameter is also obtained by means of numerical simulation and found that the value of calibrated run-up parameter becomes smaller accompanied with larger values of wave steepness and the maximum normalized run-up height. It is relevant that the tendency of run-up heights is positively correlated with higher nonlinearity, whereas an opposite trend is observed in the relationship between larger calibrated run-up parameter and lower nonlinearity.

## 1. Introduction

In the near future the relative shallow waters in the Taiwan Strait are subject to an intense planning and construction of offshore renewable energies, mainly offshore wind farms. An undesirable consequence of constrained heave motion of sea water for the offshore wind turbine is the breakwater effect. Subsequently, the wave progresses against a vertically fixed structure causing a local upwelling or wave run-up. In ocean engineering, run-up can be defined as the “green water” level on the surface of the cylinder. For the design of offshore wind turbines, the minimum value of the air-gap, which is the distance between the water level and the underside of the deck, and the probability of its exceedance within the lifetime of the structure are always required. It is known in the harsh sea conditions that the wave run-up may cause sea water to the underside of decks and thus increase the probability of deck impact and consequent damage. As for the influence of run-up prediction on the minimum air-gap, under-estimation usually results into higher exceedance of the minimum air gap, whereas over-estimation leads to a result of increasing the deck height with consequential increases in structural weight and cost.

The maximum run-up on the circular cylinders for different wind turbine foundations (or support structures) could be realized by their underwater geometry. The monopile support structure is a relatively simple design by which the tower is supported by the monopile. Monopiles are currently the most commonly used foundation in the offshore wind farm due to their ease of installation in shallow to medium water depth. This type of structure is well suited for sites with water depth ranging from 0 to 30 m. A gravity-based support structure, which is also used for offshore wind farms, is a support structure held in place by gravity. The gravity-based support structure is suited for the water depth greater than 20 m. While offshore wind farms are growing size and moving towards deeper waters, the gravity-based support structure is usually considered competitive in comparison with other support structures. The tripod support structure is considered to be a relatively lightweight three-legged steel jacket compared to a standard lattice structure. The piles are driven 10–20 m into the seabed. It is known that the advantages of the tripod support structure are the suitability for larger water depths, and a minimum of preparations required at the site before installation.

The high waves exhibit significant nonlinear behaviors, and wave amplification due to the interaction with cylinders of different turbine foundations must be accounted for in an air-gap calculation. Therefore,

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the approach, in this study, would be demonstrated by nonlinear waves through a series of numerical experiments and is based on the velocity stagnation head theory together with Stokes second order wave theory. For clarifying the effect of wave nonlinearity on run-up, the wave steepness parameter $ka$ is adopted (Chatjigeorgiou and Mavrakos, 2007; Kriebel, 1987). It was indicated that the wave run-up in high waves can be reached up to 50% more than the initial wave amplitude. Another important parameter examining the harmonic components of the wave run-up around circular (Morris-Thomas and Thiagarajan, 2004) and non-circular cylinders (Thiagarajan and Repalle, 2013) was discussed by adopting the scattering parameter $kA$. It was shown that an increasing value of each harmonic is proportional to increasing scattering parameter $kA$.

In order to estimate the wave run-up height, a formula based on the velocity stagnation head theory has often been adopted for adjustment to data. It is assumed in the velocity stagnation head theory that the water particles at the wave crest convert the kinetic energy into potential energy by rising the stagnation head of the crest elevation up the cylinder. Hallermeier (1976) originally proposed the wave run-up height according to the velocity stagnation head theory at the time instant that the wave crest impinges a slender circular cylinder. Another application was by implementing the experiments for regular and irregular waves and using the velocity stagnation head theory multiplied by an adjusting factor to formulate the measured run-up heights (De Vos et al., 2007). Based on the Stokes second order theory for regular waves, it is found that the value of the adjusting factor m is 2.71 for a monopole and 4.45 for a cone foundation. In order to give good correlation between predicted run-up velocities and impact pressures on the structure, a 40% increase of the calibrated factor was suggested (Andersen et al., 2011) as a result of underestimation of the run-up heights for breaking or nearly breaking waves measured by the wave gauges.

In the former studies, the computational fluid dynamics (CFD) has been employed to extensively model free-surface elevation. A well-known method for simulating free-surface elevation is the Volume of Fluid (VOF) method. In the VOF method, each cell in the domain is assigned a volume fraction (0 for gas and 1 for liquid), and the interface is defined by cells in which the volume fraction varies between 0 and 1. A commercial software, FLUENT, is equipped with capability to model flow interface using the VOF method. The application of CFD tools to model wave run-up on circular cylinders is presented by Repalle et al. (2007) and Thiagarajan and Repalle (2013). On the other hand, a numerical study (Iwanowski et al., 2009) was conducted to predict the wave-in-deck load due to extreme waves on jacket platform near to free surface of the water. A second-order numerical model has been proposed by comparing the experimental data to investigate the run-up heights within a radius distance around fixed vertical column (Stansberg and Kristiansen, 2005). It was found in their analysis that first harmonic amplitudes are under predicted whereas second harmonics are generally predicted.

Accurate estimations of the run-up heights and wave loads on the wind turbine foundations are definitely important for design purposes. In order to realize the effects of wave nonlinearity and scattering on run-up heights and wave loads on the wind turbine foundations, a series of numerical experiments were carried out by FLUENT to investigate the relationship between waves and structures. According to the simulation results, run-up formulae based on velocity stagnation head theory are developed by analyzing the calibrated $m$ factors for different wind turbine foundations.

Another significant issue is that modeling the wave-structure interaction is actually a complex 3D free-surface flow with moving run-up boundaries on the foundations. Essentially, the total force acting on the structure is composed of inertial force, drag force and impact force. The first two components can be evaluated by Morison equation (Morison et al., 1950) appropriately, and the last component may be induced by wave breaking. The impact force acts for a very short time and is also called slamming, which has to consider the wave nonlinearity and the distribution of water particle velocities around the structure. It is known that the turbulent intensity becomes evident when Reynolds No. ($R_e$) reaches $5\times10^5$ (Schetz and Fuhs, 1999). In our cases, evident turbulence in the vicinity of the foundations and near the free surface need to be treated due to higher $R_e$ ( > O(7)) of nonlinear wave-induced velocities. Therefore, Reynolds Averaged Navier–Stokes (RANS) equations with k-ε closure model are suggested in this study for describing flow motions accurately. In the RANS equations, only the ensemble-averaged flow motion is resolved. The turbulence effects appear in the momentum equations for the mean flow and are represented by Reynolds stresses, which are often modeled by an eddy-viscosity model, *i.e.* k-ε closure model.

In this manuscript, Section 1 introduces motivation and background of this study; Section 2 mentions the governing equations, numerical methods, the Stokes second order wave theory and semi-empirical run-up formula; Section 3 mainly shows the verification and results of numerical simulation. Eventually, the concluding remarks would be summarized in Section 4.

## 2. Numerical model

In this section, the governing equations and boundary conditions used to establish the 3-D numerical model for regular wave propagation over the foundations are presented. The model was based on the CFD tool FLUENT, with the finite volume approach to solve the governing equations. User-Defined Functions (UDFs) written in C programming language, which can enhance the capability of FLUENT, were used to implement the uni-directional regular boundary condition and wave absorber over the sloping bed.

### 2.1. Governing equation

In order to take the turbulent flow into account, the variables in Navier Stokes equation are decomposed in to mean and fluctuating part. Thus, substituting the flow variables of governing equation will result in Reynolds Averaged Navier Stokes (RANS) equation. Supposing that the right-handed Cartesian coordinate system o-xyz is defined with the origin on the undisturbed free surface, the continuity equation and the tensorial form of RANS equation can be written as:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_j} = 0,\ \ i, j = 1, 2, 3 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}(-\rho u'_i u'_j) \tag{2}$$

where $i$, $j$ are tensor indices and $\delta_{ij}$ is Kronecker delta. $u$ and $u'$ represent the mean and fluctuating parts of velocity components of the fluid particles. $g$ is the gravitational accelerations, $p$ is the pressure term, and $\rho$ is the volume-fraction-averaged density in the form.

Boussinesq hypothesis relates the Reynolds stresses to the mean velocity gradient, which is given as

$$-\rho u'_i u'_j = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \tag{3}$$

where $\mu_t$ is the turbulent viscosity, $k$ is the kinetic energy. The hypothesis would be used in the following turbulence model, *i.e.* $k$-$\varepsilon$ model. Furthermore, the Re-Normalization Group (RNG) $k$-$\varepsilon$ model (Yakhot et al., 1992), which is one of the variants of $k$-$\varepsilon$ models, is adopted to account for the effects of smaller scales of motion. The RNG $k$-$\varepsilon$ turbulence model is a three-dimensional model, which holds two more additional transport equations, *i.e.* one for turbulent kinetic energy $k$ and one for turbulence dissipation rate $\varepsilon$, which are evaluated