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Simulating the wave-induced response of a submerged wave-energy converter using a non-hydrostatic wave-flow model

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ABSTRACT

With the increasing interest in wave energy, and when moving towards commercial-scale wave-energy projects, a detailed understanding of the interactions between single and arrays of wave-energy converters (WECs) with the ambient wave and flow field becomes imperative for both design and operational purposes, as well as assessment of their environmental impacts. This work presents a new numerical approach to simulate the nonlinear evolution of the waves and their interactions with a submerged wave-energy converter at the scale of a realistic coastal region. The numerical approach is based on the non-hydrostatic framework, and implemented in the open-source SWASH model, which provides an efficient tool to simulate the nonlinear evolution of waves over realistic coastal bathymetries. Here, we present a numerical extension to the non-hydrostatic approach to account for interactions between waves and a submerged point absorber, and to capture the response of such a wave energy device. Model results are compared with an analytical solution based on potential flow theory, a CFD simulation, and experimental data to validate its capabilities in simulating the wave-WEC interactions for both linear and nonlinear wave conditions. Overall, the results of this validation demonstrate that the model captures the wave-structure interactions and the body response with satisfactory accuracy. Notably, the results also indicate that a coarse vertical resolution was sufficient to capture these dynamics, making the model sufficiently computationally efficient to simulate the interaction of waves and WECs over large scales. As a consequence, this new modelling approach should provide a promising new alternative to simulate the interactions between nonlinear wave fields and submerged point absorbers at the scale of a realistic coastal region.

1. Introduction

Ocean waves provide a vast marine energy source that has the potential to contribute to the future renewable energy mix. To harness the power of the waves, numerous types of Wave Energy Converters (WECs) have been and are currently under development. Despite a vast number of different technologies, all designs require a large number of devices, arranged in a so-called wave farm, to extract a substantial amount of energy.

Wave farms of considerable size (say 10 to 100 devices) will likely alter both the wave field and circulation patterns in their vicinity. Devices that are arranged in arrays will also interact with each other through both scattered and radiated waves. This can subsequently impact the power generated by the individual devices, known as the “park effect” (e.g., Babarit, 2013), whereby the power take-off of N devices will not necessarily be equal to N times the power take-off of a solitary device. Furthermore, the disturbance of wave and current fields can also potentially alter the natural conditions in the coastal zone (e.g., causing erosion or accretion of adjacent beaches), and adversely affect recreational activities (e.g., surfing) in surrounding areas. Adverse environmental effects thereby pose considerable risks in terms of financial costs for wave energy developers, and can also damage the public perception of a wave farm and wave energy more generally. A thorough understanding of both the park effect and the environmental impact is therefore of critical importance for the wave energy industry when moving towards wave farms of substantial size.

To date, no commercial-scale wave farms have been constructed, and field evidence regarding these aspects is essentially non-existent. Furthermore, laboratory studies on this subject are limited (Day et al., 2015) – apart from a few exceptions (e.g., Stratigaki et al., 2014; Özkan-Haller et al., 2017) – as they are very costly to conduct at the relevant temporal and spatial scale. Consequently, our understanding of park

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effects and environmental impacts by wave farms primarily relies on numerical modelling (see, for example, Wolgamot and Fitzgerald (2015) and Folley (2016) for detailed overviews of available numerical tools).

Traditionally, the local interactions between waves and floating structures have been modelled based on the potential flow equations, either solved analytically or by means of the Boundary Element Method (BEM). These techniques have also found widespread use in the wave energy community (e.g., Mavrakos and McIver, 1997; Li and Yu, 2012; Folley, 2016). They are primarily suited to resolve the details of the wave-WEC interactions (i.e., the near-field effects), and have mainly been used to study and maximise the power output of (arrays of) WECs (e.g., Wolgamot et al., 2012; Babarit et al., 2012). They are however not specifically designed to simulate the larger scale impact of WEC farms (or far-field effects), especially at the scales which are relevant when considering the environmental impact. For example, they do not account for all physical processes that are relevant to understand potential coastal impacts of wave farms (e.g., the evolution of waves over variable bathymetry, nonlinear wave interactions, and wave breaking).

For this type of application, alternative methods have been developed. The most commonly applied approach to simulate how wave farms may modify coastal wave fields is based on phase-averaged (or spectral) wave models (e.g., Gonzalez-Santamaria et al., 2013; Abanades et al., 2014; Iglesias and Carballo, 2014; Bergillos et al., 2018). With spectral wave models, the spatial and temporal evolution of the statistical properties of a wave field are modelled through the wave action balance equation, including various source terms to account for wave-related processes (e.g., wind generation, nonlinear wave interactions, and wave breaking). The impact of the energy extraction by the WECs on the wave field is typically modelled as a reduction in wave energy (or wave height) in the lee of the wave farm (Millar et al., 2007; Smith et al., 2012; Chang et al., 2016), where the energy extraction can be obtained from experiments or models that resolve the wave-structure interactions (e.g., the BEM). As phase-averaged models parametrise the relevant physical processes, they thereby do not fully represent the processes that determine the wave-WEC interactions and the wave transformation in coastal waters (e.g., diffraction and nonlinear wave-wave interactions). For example, the parametrizations of the WEC energy extraction do not account for the scattering and radiation of waves by the WEC (e.g., Özkan-Haller et al., 2017). The absence of such processes may consequently result in unrealistic predictions of the environmental impact of wave farms.

As an alternative, several studies proposed the use of a phase-resolving wave model to simulate the disturbance of the wave field by a wave farm (e.g., Beels et al., 2010a; b; Greenwood et al., 2016; Troch and Stratigaki, 2016). With the most advanced version of this approach (Troch and Stratigaki, 2016; Verbrugghe et al., 2017), the impact of the wave farm on the wave field is modelled combining a BEM code to simulate the wave-structure interactions, and a phase-resolving wave model based on the potential flow equations to simulate the evolution of the waves on coastal scales (either through the mild-slope equations, Radder and Dingemans, 1985, or fully nonlinear potential flow theory, Engsig-Karup et al., 2009). In this manner, the model aims to resolve the relevant physical processes in the vicinity of the device (e.g., the radiation of waves by the motions of the WEC), and the wave processes that act on larger scales (e.g., shoaling and diffraction). However, this approach relies on the coupling with a linear wave-structure interaction model, formally restricting this method to small wave amplitudes. Furthermore, simulating the impacts of wave farms on the nearshore circulation patterns that drive the shoreline response (i.e., the erosion or accretion of a beach) will require a coupling between this approach and a circulation model.

For more extreme wave conditions, Computational Fluid Dynamic (CFD) models are better suited to simulate the wave-WEC interactions (e.g., Agamloh et al., 2008; Chen et al., 2017; Crespo et al., 2017; Ransley et al., 2017; Bharath et al., 2018; Devolder et al., 2018). Such models can resolve the detailed turbulent flow field around the WEC, and can ideally account for all relevant physical processes that affect the wave-structure interactions. Given their detail, they require considerable computational resources which restricts their application to small spatial and temporal scales, and consequently to a single or small number of devices. CFD models are therefore at present not suited to resolve the impact of WEC farms at the spatial and temporal scales of interest.

In this work we pursue an alternative approach to numerically simulate the impact of WECs on the incident wave field, including the park effects and downstream environmental impacts of wave farms, at both relatively large scales (i.e., the nonlinear evolution of the waves over variable bathymetry and the wave-induced currents) and small scale (i.e., the wave-structure interactions). Our numerical methodology is based on the non-hydrostatic approach (e.g., Yamazaki et al., 2009; Ma et al., 2012; Ai and Jin, 2012), and implemented in the non-hydrostatic wave-flow model SWASH[1] (Zijlema et al., 2011). Non-hydrostatic wave-flow models have become a popular tool to simulate the nonlinear wave evolution and wave-induced currents in nearshore regions due to their efficiency in resolving these dynamics at coastal scales (e.g., Rijnsdorp et al., 2015, 2017; Gomes et al., 2016; García-Medina et al., 2017, and many others).

This paper present a new extension to the non-hydrostatic approach to account for the interactions between the waves and a single submerged point absorber (Section 2 and 3). To demonstrate the capabilities of the approach in simulating these interactions and the wave-induced response of the submerged device, model predictions are compared to an analytical solution based on potential flow theory for linear waves, and laboratory and numerical experiments for nonlinear wave conditions (Section 4). This work thereby provides the first step towards simulating the interactions between the waves and a WEC at the scale of a realistic coastal region using a non-hydrostatic wave-flow model (Section 5–6). Although the present work focuses on submerged point absorber devices, we envision that the numerical approach can be expanded to include other devices (e.g., floating point absorbers, bottom-mounted flaps, and oscillating water columns), pushing our modelling capabilities towards accurate predictions of large-scale impacts by arrays of generic WECs.

2. Governing equations

2.1. Fluid motion

The governing equations of the model are the Reynolds-Averaged Navier-Stokes equations for an incompressible fluid of constant density ρ. The fluid is bounded by the bottom $z = -d(x, y)$, the free-surface $z = \zeta(x, y, t)$, and a submerged obstacle with its top and bottom at $z = -S_t(x, y, t)$ and $z = -S_b(x, y, t)$, respectively; where t is time and $\langle x, y, z\rangle$ are the Cartesian coordinates (see Fig. 1). Using the Einstein summation convention, the governing equations are,

$$\frac{\partial u_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} + \frac{\partial p}{\partial x_i} + g_i = \frac{\partial \tau_{ij}}{\partial x_j}, \tag{2}$$

where i and j are equal to $\langle 1,2,3\rangle$, with $\langle x_1, x_2, x_3\rangle = \langle x, y, z\rangle$, g_i represents the contribution of the gravitational acceleration $\langle 0,0, g\rangle$, u_i is the velocity component of $\vec{u}$ in the x_i direction, τ_{ij} represents the turbulent stresses (which are estimated based on the eddy viscosity approximation), and p is the total pressure normalised by the reference density ρ. The total normalised pressure is defined as ; in which the first

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[1] Simulating WAves till SHore, available under the GNU GPL license at http://swash.sourceforge.net/.