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Modelling performance of a small array of Wave Energy Converters: Comparison of Spectral and Boussinesq models

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ABSTRACT

This paper presents results from numerical simulations of three Oscillating Wave Surge Converters (OWSC) using two different computational models, Boussinesq wave (BW) and Spectral wave (SW) of the commercial software suite MIKE. The simulation of a shallow water wave farm applies alternative methods for implementing a frequency dependent absorption in both the BW and SW models, where energy extraction is based on experimental data from a scaled Oyster device. The effects of including wave diffraction within the SW model is tested by using diffraction smoothing steps and various directional wave conditions. The results of this study reveal important information on the models realms of validity that is heavily dependent on the incident sea state and the removal of diffraction for the SW model. This yields an increase in simulation accuracy for far-field disturbances when diffraction is entirely removed. This highlights specific conditions where the BW and SW model may thrive but also regions where reduced performance is observed. The results presented in this paper have not been validated with real sea site wave device array performance, however, the methodology described would be useful to device developers to arrive at preliminary decisions on array configurations and to minimise negative environmental impacts.

1. Introduction

The use of Boussinesq Wave (BW) and Spectral Wave (SW) models for the simulation of Wave Energy Converter (WEC) arrays and regional impact based studies has increased over the years. This has led to the further development of the simulation of hypothetical devices and arrays. Early studies such as [1–5] use large supra-grid blocks that were representative of several devices. The removal of energy was often assigned through a constant coefficient with no frequency or directional dependencies. These studies provided the first real attempt at the quantification of regional scale wave-device interactions. More recently, studies have been carried out that include a more detailed approach [6–10], where increased model resolution and computational resource has enabled a better simulation of WECs in both the BW and SW models.

The Boussinesq wave model has previously been applied to simulate regions in and around harbours. However, its application in the previously mentioned literature provides a reasonable representation of the propagation of wave disturbances. The numerical implementation of an array of Wave Dragon devices was applied in a MILDwave model [9,11,12]. This uses a sponge layer within the domain to reflect, absorb and transmit waves as they propagate across the domain. The use of sponge regions allows a readily controllable medium, where sponge thickness and density determine the level of reflection, absorption and transmission of a device. By applying a spatially variable sponge value these studies replicated the different wave-device interaction from the reflecting arms and the main body housing the power take off unit. The basic simulation of WECs is described in detail in Refs. [9], the results of which show reasonable wave disturbance patterns that are simplistically validated using a few generic terms. The method of implementing WECs is shown to be highly adaptable, but does exclude the capability to account for directional and frequency dependent device interactions. Ways to include these factors were discussed by simulating each directional and frequency component separately. This work was later reapplied using Mike21 BW model

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where porosity layers were applied to replicate the extraction of wave energy [13]. This study combined the numerical implementation of devices with a physical scale model. These results indicate that the numerical representation of the device shows a poor agreement to the experimental data in the extreme near field. However, when the distance behind the device was extended into the mid-field region a much better agreement was observed.

The numerical simulation of multiple DEXA devices was conducted using porosity layers within Mike21 BW wave model [14,15]. These studies used experimental data from a 1:60th scale model to calibrate the reflection, absorption and transmission for the devices. The results of additional sea states were tested where the porosity was set to a value of 0.9. The comparison between the numerical and experimental results indicates a very similar transmission of wave energy where a difference of less than 3.5% is shown for the first row of devices. The agreement between the numerical and experimental reflection coefficients was much poorer, with a difference ranging between 16 and 34%. The authors of the present paper observed that by adjusting the laminar and turbulent resistance coefficients within the Boussinesq model a better agreement was achieved between the numerical and experimental results, as this allowed the wave transmission to remain in agreement by altering the reflection component. Like the previous studies this method of replicating a WEC using a porosity layer neglects the effects of a device dependent frequency absorption characteristic.

The SW model's flexibility and wide application in a large number of studies has resulted in further development of methods for implementing WECs when compared with the BW model. The numerical simplifications of the spectral wave model, larger areas and ability to simulate large number of devices often makes spectral wave models a more advantageous tool. This is illustrated by a case study shown in Refs. [8,16] where device layout and distance to shore are tested using a basic device absorption coefficient to consider the propagation of the wake effects. Including the influence of varying frequency that allows a more advanced treatment. This has been applied within the SWAN model for an array of point absorbers [17]. The use of SWAN in this case allowed the modification of model source code to account for the presence of wave energy devices. This code was later modified and focused on array layouts [6]. This work was adapted and implemented within MIKE21's SW model where the addition of a device specific directional dependent absorption was applied for bottom mounted hinge-flap devices [7]. A modification of the SWAN code has been developed by Sandia National Lab (SNL) to promote a more user friendly software that allows users to select from multiple types of WEC absorption patterns. This allows SNL-SWAN to simulate devices with a constant transmission coefficient, a WEC power matrix or using a relative capture width curve. However, the effect of a directionally spread sea state is yet to be accounted in the device absorption.

This paper builds on the previous work used to implement a small array of OWSC (Oscillating Wave Surge Converters) and applies a device specific frequency dependent transmission within both Mike21's Spectral and Boussinesq wave models. This study is the first of its kind that allows a direct comparison between two identical device arrays to quantify difference in surrounding wave field, additional innovative material is also presented on the methods used to achieve device-like absorption. Due to the numerical differences from the phase resolving and phase averaging simulations the spatial wave disturbance is reviewed and the effects of the inclusion of model parameters are addressed.

2. Numerical wave model description

2.1. Mike21 Boussinesq Wave (BW) model

The Boussinesq wave model used for this work to investigate the potential impact of WECs on the surrounding wave climate is commercially marketed by the Danish Hydraulic Institute (DHI), Denmark. The BW model used here applies the enhanced Boussinesq equation that permits the propagation of irregular waves over varying bathymetry. A linear dispersion coefficient (B = 1/15) is used that allows the propagation of irregular waves from deep to shallow water. This applies a linear relationship in deep water that reverts back to the standard classical Boussinesq equations in shallow water. When this method is compared to Stokes first order wave theory the phase celerity and wave group velocity showed a good agreement [18,19]. The numerical representation of x and y formulation for the x- momentum is represented by

$$n\frac{\partial P}{\partial t}+\frac{\partial}{\partial x}\left(\frac{P^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{PQ}{h}\right)+\frac{\partial R_{xx}}{\partial x}+\frac{\partial R_{xy}}{\partial x}+n^2gh\frac{\partial \xi}{\partial x}+\ldots n^2P\left[\alpha+\beta\frac{\sqrt{P^2+Q^2}}{h}\right]+\frac{gQ\sqrt{P^2+Q^2}}{h^2C^2}+n\psi_1\psi_1=0 \quad (1)$$

And the y- momentum is represented by

$$n\frac{\partial P}{\partial t}+\frac{\partial}{\partial y}\left(\frac{Q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{PQ}{h}\right)+\frac{\partial R_{xx}}{\partial x}+\frac{\partial R_{xy}}{\partial x}+n^2gh\frac{\partial \xi}{\partial y}+\ldots n^2Q\left[\alpha+\beta\frac{\sqrt{P^2+Q^2}}{h}\right]+\frac{gQ\sqrt{P^2+Q^2}}{h^2C^2}+n\psi_2\psi_2=0 \quad (2)$$

Where P is flux density in x direction (m^2s), Q is flux density in y direction (m^2s), t is time (s), n is porosity, C is Chezy resistance ($m^{0.5}/s$), α and β are the laminar and turbulent flow resistance coefficients for a porous structure, ξ is Surface elevation above datum (m), ψ_1, ψ_2 are dispersive Boussinesq terms for the x and y terms respectively and R_{xx}, R_{xy} are the excess momenta from surface rollers. More information on the mathematical derivation of ψ_n and the R terms can be found at [20]. The BW model can simulate processes such as shoaling, refraction, diffraction, wave breaking, and, includes frequency and directional spreading and nonlinear