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An approximate solution for the wave energy shadow in the lee of an array of overtopping type wave energy converters

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ABSTRACT

In this study we investigate how the wave energy deficit in the lee of an array of overtopping type wave energy converting devices (WECs), redistributes with distance from the array due to the natural variability of the wave climate and wave structure interactions. Wave directional spreading has previously been identified as the dominant mechanism that disperses the wave energy deficit, reducing the maximum wave height reduction with increasing distance from the array. In addition to this when waves pass by objects such as an overtopping type WEC device, diffracted waves re-distribute the incident wave energy and create a complex interference pattern. The effect of wave energy redistribution from diffraction on the wave energy shadow in the near and far field is less obvious. In this study, we present an approximate analytical solution that describes the diffracted and transmitted wave field about a single row array of overtopping type WECs, under random wave conditions. This is achieved with multiple superpositions of the analytical solutions for monochromatic unidirectional waves about a semi-infinite breakwater, extended to account for partial reflection and transmission. The solution is used to investigate the sensitivity of the far field wave energy shadow to the array configuration, level of energy extraction, incident wave climate, and diffraction. Our results suggest that diffraction spreads part of the wave energy passing through the array, away from the direct shadow region of the array. This, in part, counteracts the dispersion of the wave energy deficit from directional spreading.

1. Introduction

A Wave Energy Converter (WEC) converts the kinetic and potential energy in the incident wave in one of two distinct ways. Either a volume of water with a positive potential energy is captured from the system (overtopping type device), or wave motion cause the components of the device to move relative to each other so that a destructively interfering wave is generated (point absorber or attenuator). The extraction of wave energy from the system produces a wave energy deficit or shadow down wave. The ability to predict the shadow is of topical interest due to the significant stake holder concerns about potential impacts from wave shadowing arising from wave energy device installations. Waves play a key role in mass transport, assist in mixing and force sediment transport, therefore, quantifying the wave energy reduction and identifying induced wave height gradients would help us to assess the environmental impact of a WEC array on the nearby coastal ocean and shoreline. To minimise environmental impacts, it is desirable that the wave energy deficit redistributes over the widest area in the shortest distance to minimise wave height reductions at any one location, or vice versa if shore protection is a desired goal of the wave energy development. In addition the ability to predict the wave shadow and interference pattern about devices will reveal locations of low energy within the device array due to negative interference and shadowing. A specific spatial arrangement of devices that avoids placing devices in these low energy locations would maximise the collective performance of the array.

For an overtopping type WEC the spatial distribution of the wave energy deficit is affected by wave directional spreading, diffraction and refraction. Wave directional spreading describes the degree of lateral transmission of wave energy in a given sea state. A broader directional spread would disperse the energy deficit over a wider region and, vice versa, as shown in Black (2007). This mechanism is analogous to the dull shadow cast by an object illuminated by diffuse light or the sharp shadow cast by an object illuminated by a point source. The sharp gradient in wave height at the edge of an overtopping type WEC device, from the wave termination at the device, will induce diffraction. This diffraction effect propagates wave energy into the lee region of the WEC initially. Refraction due to bathymetry or ambient current change would deflect the direction of the incident and scattered waves, and therefore alter the wave energy shadows location and distribution at the coast.

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Some recent studies have been carried out to investigate the wave height reduction in the lee of WEC arrays. Millar et al. (2007) used the third generation phase averaged spectral wave model SWAN to investigate the effects of the scale of energy extraction and incident wave parameters on the far field wave energy deficit. As phase is not resolved in SWAN and the individual WEC devices not delineated the redistribution of energy by diffraction and radiation is not accounted for. The wave height reduction was predicted to reduce monotonically with distance from the array for a final wave maximum reduction 25 km behind the array of less than 1% of the incident wave height.

Venugopal and Smith (2007) used the Boussinesq wave model, Mike21 BW to assess the resultant wave field about a single row of overtopping type WECs which partially reflect energy to achieve a wave energy deficit in the down wave region rather than by specifically extracting it. Redistribution of wave energy from diffraction is considered but the distance from the array to the shore is 2 km which is short compared to some proposed offshore wave array installations.

Palha et al. (2009) used the parabolic mild slope wave model REF/DIF to assess the wave shadow in the lee of a series of large energy sinks that represent clusters of devices. Wave structure interactions and the resultant redistribution of wave energy are not considered fully. Individual devices are not delineated so that waves diffract only about the edges of the energy sink regions (WEC clusters) and not the individual devices.

Beels et al. (2010) used the time dependent mild slope wave model MILDwave to assess the wave shadow in the lee of a 2D array of Wave dragon overtopping type WEC devices. The devices where implemented within the model as porous layers, the shape of which capture the geometry of the Wave Dragon device. The porous layers specifically reflect and transmit wave energy at the reflecting wings of the structure and extract, reflect, and transmit energy at the main body. The degree of reflection, absorption and transmission are dependent on the draft of the wings and body, the freeboard of the main body and the incident wave height and period.

Nørgaard and Andersen (2012) assessed the shore protection benefits that might be achieved by placing an array of Wave Dragon overtopping type WEC in the relatively near-shore region using the Boussinesq wave model, Mike21 BW. The devices where implemented in essentially the same way as Beels et al. (2010) using frequency dependent sponge layers. They also considered lower resolution approximations of the devices as rectangular porous, permeable, breakwater type structures. For these approximate devices the total variable reflection, absorption and transmission characteristics of the detailed device, were averaged across the device. It was found that in the moderate-field (2 km from the devices) the low resolution approximate representation of the WEC provides excellent accuracy when compared to the more accurate geometrical and variable absorption, transmission and reflection, representation of the Wave Dragon device. In the very near-field there was significant local fluctuations in the wave field for the two device representations but the general wave energy distribution was comparable.

The studies that consider WEC arrays located far offshore (Millar et al., 2007; Palha et al., 2009) do not properly account for or resolve diffraction. The studies that do resolve diffraction about the individual devices do not consider arrays far offshore (Beels et al., 2010; Nørgaard and Andersen, 2012; Venugopal and Smith, 2007). As such the effect of re-distribution of wave energy over larger distances from scattered waves remains unclear. It is also difficult to cross compare these studies to check for consistency as their models and model implementations are often significantly different from each other.

The motivation for this study was to develop an accessible engineering tool for scaling the far-field wave energy deficit in the lee of an array of overtopping type WEC devices, without the; domain size, resolution and simulation time, restrictions of a time-stepping phase resolving model and the wave diffraction and interference limitations of a spectral model. Radiated waves associated with point absorber type WEC devices are not considered here in order to exclude the wave energy redistribution due to wave radiation, and to avoid the numerically challenging problem of near trapping of waves associated with an array of point absorbers. This allows us to focus on the effect of wave energy redistribution from diffraction.

A number of analytical solutions and modelling schemes have been proposed for describing the diffracted wave field about solid, porous, dissipating type structures. These include the Pos and Kilner's (1987) application of the mild slope equations using a finite element method, the eigenvalue expansion approach of Dalrymple and Martin (1990). McIver (2005) presents the mathematically exact solution for a series of permeable or porous breakwater segments using the boundary element method and an application of the Green's theorem to describe the problem in terms of an integral equation.

In this study we use the computationally efficient classical solution of Penney and Price (1952) for the diffracted wave field about a semi-infinite breakwater, as a basic building block for the full solution. By making multiple superposition's and by applying reflection and transmission coefficients, the Penney and Price solution can be used to describe the wave shadow and interference pattern in the lee of a segmented transmitting and reflecting breakwater series. We use this to approximate a single row array of overtopping type WECs because the degree of absorption and transmission across the breakwater can be set to equal to that of the WEC in a similar manner to Nørgaard and Andersen's (2012) representation of a simple overtopping WEC device. The approach presented here contain some approximations that affect the accuracy of the solution in the region very close to the array and these will be discussed in more detail later. However, because of the comparatively short calculation time this solution provides a useful alternative for assessing the moderate to far field wave energy shadow for a high resolution spectral/directional wave climate. Also the solution does not require familiarity with the advanced mathematical techniques associated with the mathematically exact boundary element method of McIver (2005) and does not have the computational time or domain size/boundary limitations of a time stepping Mildslope or Boussinesq type models.

The objectives of this study were twofold: (1) to construct an approximate analytical solution for the wave field about a single row of overtopping type WEC devices that is sufficiently computationally efficient to scale the very far field wave energy shadow; (2) to investigate the effects of wave directional spreading, incident wave spectrum, diffraction and array configuration on the down-wave, wave energy deficit and interference pattern.

2. Wave diffraction solutions at structures

A WEC array does not remove energy uniformly across the whole wave front passing through the array as modelled in Millar et al. (2007), Black (2007) and, in part, Palha et al. (2009). Instead for an array of overtopping devices wave energy is removed from sections of the wave front by the WEC devices. A breakwater segment with width equal to the overtopping device and with a transmission coefficient equal to the devices will remove the same amount of wave energy from a section of the wave front. As such it has been a common practice to represent an overtopping WEC device as a segmented dissipating or porous breakwater type structure. This method was adopted by Venugopal and Smith (2007), Beels et al. (2010) and Nørgaard and Andersen's (2012).