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The impact of wave energy converter arrays on wave-induced forcing in the surf zone

Annika O'Dea [a,*], Merrick C. Haller [a], H. Tuba Özkan-Haller [b]

[a] School of Civil & Construction Engineering, Oregon State University, 101 Kearney Hall, Corvallis, OR, 97331, USA
[b] College of Earth, Ocean, & Atmospheric Sciences, Oregon State University, 104 CEOAS Administration Building, Corvallis, OR, 97331, USA

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ABSTRACT

An alternative metric for assessing nearshore hydrodynamic impact due to Wave Energy Converter (WEC) arrays is presented that is based on the modeled changes in alongshore radiation stress gradients in the lee of the array. The metric is developed using a previously observed relationship between measured radiation stresses and alongshore current magnitudes. Next, a parametric study is conducted using the spectral model SWAN to analyze the nearshore impact of different WEC array designs. A realistic range of array configurations, locations, and incident wave conditions are examined and conditions that generate alongshore radiation stress gradients exceeding a chosen impact threshold on a uniform beach are identified. Finally, the methodology is applied to two permitted WEC test sites to assess the applicability of the results to sites with more realistic bathymetries. For these sites, the overall trends seen in the changes in wave height, direction, and radiation stress gradients in the lee of the array are similar to those seen in the parametric study. However, interactions between the wave field and real bathymetry induce additional alongshore variability in wave-induced forcing. Results indicate that array-induced changes can exceed the natural variability up to 15% of the time with certain array designs and locations.

1. Introduction

For wave energy extraction to be commercially viable at utility scales, wave energy converters (WECs) will need to be deployed in arrays that include several to hundreds of devices. Understanding the potential impacts of WEC arrays on marine ecosystems and the coastal environment is crucial in order to ensure the sustainability and success of the nascent marine energy industry. For WECs designed for offshore sites (depth $\geq$ 35 m), nearshore effects primarily arrive via the modified wave field created in the lee of a WEC array.

Interactions between WEC devices and the incident wave field can be separated into interactions that modify the wave field within the array (near-field interactions) and those that alter the wave climate in the lee of the array (far-field effects) (Özkan-Haller et al., 2017). The far-field effects of WEC arrays include a redirection of waves and a reduction in wave height in the lee of the array, referred to as the wave shadow. The extent and significance of the far-field effects of WEC arrays are a function of the array design, its location, and the incident wave conditions. Quantifying the changes in the far-field wave conditions as a result of WEC arrays is the first step in determining whether the WEC arrays will influence nearshore processes.

The far-field effects of WEC arrays have been investigated using spectral models (primarily the wave model SWAN, Booij et al., 1999) in past studies. Although spectral models of this type do not capture the near-field scattering processes that occur in WEC arrays and handle diffraction in an approximate fashion, they are less computationally expensive than phase-resolving models and thus can be applied to large domains, a necessity when studying far-field effects. Özkan-Haller et al. (2017) compared the results of model simulations of WEC arrays using both a phase-resolving model (WAMIT) and SWAN. Their results showed that SWAN can be effective at modeling the wave shadows in the lee of WEC arrays when the majority of wave energy lies at periods near or above the peak period of WEC energy extraction.

Most past studies conducted using spectral models have represented an array as a single or multiple partially transmissible objects with a frequency-independent transmission coefficient (Millar et al., 2007; Rusu and Soares, 2013; Carballo and Iglesias, 2013; Abanades et al., 2014a, 2014b, 2015a, 2015b; and Iglesias and Carballo, 2014). However, use of a frequency-independent transmission coefficient fails to capture the frequency-dependent energy extraction characteristics that are inherent to WEC devices. The amount of energy that WEC devices extract is a function of the device's power transfer function (PTF), defined as the

* Corresponding author.
E-mail addresses: odeaa@oregonstate.edu (A. O'Dea), merrick.haller@oregonstate.edu (M.C. Haller), ozkan@coas.oregonstate.edu (H.T. Özkan-Haller).

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proportion of available wave power extracted at each frequency by a particular device. Smith et al. (2012) altered the SWAN source code to allow for a frequency-dependent extraction of energy using a theoretical PTF to assess the far-field effects of WEC arrays in the UK. In the present work, WEC devices are represented in SWAN through the external modification of the wave spectra at individual device locations within a WEC array using an experimentally determined, frequency dependent PTF established in an earlier laboratory study that utilized an array of point-absorber WECs operating mostly in heave (Rhinefrank et al., 2013; Özkan-Haller et al., 2017).

Changes in wave height and direction in the lee of WEC arrays imply a change in nearshore forcing; yet, the forcing terms in the nearshore hydrodynamic balances are more directly quantified through the spatial gradients in radiation stress (Svendsen, 2006). These gradients in radiation stress drive alongshore currents, rip currents, and nearshore sediment transport. Although some recent studies on far-field effects of WEC arrays have coupled spectral wave models with current or sediment transport/morphologic models (Rusu and Soares, 2013; Gonzalez-Santamaria et al., 2013; Mendoza et al., 2014; Abanades et al., 2014a; Abanades et al., 2014b; Abanades et al., 2015a; Abanades et al., 2015b), many studies have only focused on the differences in wave height (or wave power) and direction in the lee of the array (Millar et al., 2007; Carballo and Iglesias, 2013; Palha et al., 2010; Smith et al., 2012; and Iglesias and Carballo, 2014).

In order to assess nearshore impact, Iglesias and Carballo (2014) used indicators based on relative and absolute changes in wave power at the 10 m depth contour. Such an approach depends on changes in wave height but does not include changes in wave-induced nearshore forcing directly. In a follow-on approach, Abanades et al. (2014a; 2014b; 2015a; 2015b) modeled the response of a beach in Cornwall, England to storm conditions both with and without a WEC array using a wave propagation model (SWAN) and a coupled coastal processes model (Xbeach). To interpret the observed differences in predicted beach response, they defined impact indicators based on changes in the sea bed level and net erosion rates (2014a; 2014b; 2015a), and the reduction in wave heights at fixed distances (2, 4, and 6 km) in the lee of the array (2015a), or change in wave power along a given contour and changes to the morphological classification of the beach due to the presence of the array (2015b).

In all such applications, the designer must choose a particular threshold for impact that is representative of something useful or relevant to the study area. Changes in wave parameters are an obvious choice. Additionally, coupling wave and coastal process models can provide detailed information of the potential changes to nearshore currents and sediment transport due to WEC arrays; however, this is a more computational expensive approach. In the present study, we propose an alternative threshold for hydrodynamic impact based on changes in nearshore hydrodynamic forcing parameters. Since these parameters are calculated directly from the wave information, this is a computationally inexpensive method for characterizing nearshore impact that is directly focused on the driver of physical change in the nearshore.

Independent of the specific criterion, the impact of WEC arrays will ultimately depend on the characteristics of the array (number of devices, array configuration, and distance from shore) and the characteristics of the site (wave climate, bathymetry). However, the use of generalized descriptions of the impacts of WEC arrays as a basic guideline in the design process would allow for a more rapid assessment of candidate sites. One goal of this study is to assess nearshore impacts of WEC arrays on a generic nearshore environment in order to draw general conclusions that could be used to facilitate the preliminary design and development of future arrays.

This study can be separated into three parts. The objective of the first part is to develop and test a threshold metric for alongshore force, F_y, that would link changes in the wave climate to meaningful changes in nearshore processes. Using this proposed threshold for alongshore force, the objective of the second part is to determine how array spacing and distance from shore influence the nearshore forcing, and to determine which array designs and incident wave conditions generate alongshore forces that exceed the F_y threshold established in the previous section. As a final objective, we ask the question as to whether natural bathymetric and climatologic variability at actual field test sites will exceed the variability induced by the WEC array. In the final part we conduct a similar assessment of two existing wave energy sites in order to determine whether the general conclusions made in the idealized study are valid at field sites with realistic bathymetries.

2. Methodology for assessing nearshore impact

Changes in wave parameters (such as wave height and direction) induced by the energy extraction of WEC arrays will alter the wave-induced radiation stresses, which are defined as the excess flux of momentum due to the presence of waves (Longuet-Higgins and Stewart, 1964). Here, the SWAN wave model is used to simulate wave transformation in the lee of WEC arrays and to calculate the cross-shore and alongshore wave radiation stress gradients.

2.1. Model overview

SWAN is a third-generation spectral wave model and uses the spectral action balance equation to calculate the transformation of wave spectra across realistic bathymetry. The spectral action balance is shown in Equation (1),

$$\frac{\partial N}{\partial t}+\frac{\partial c_x N}{\partial x}+\frac{\partial c_y N}{\partial y}+\frac{\partial c_\sigma N}{\partial \sigma}+\frac{\partial c_\theta N}{\partial \theta}=S_{tot} \quad (1)$$

where N is the wave action, c_x and c_y are the velocity components of N in geographical space, θ is the wave direction, σ is the relative frequency, and c_σ and c_θ are the propagation velocities of N in σ- and θ-space. In this study, the coordinate system is defined such that the positive x-axis is pointing onshore and the y-axis is parallel to the shoreline, with the origin located at the offshore edge of the model domain. The term S_{tot} represents the sum of the physical processes that result in the generation, redistribution, and dissipation of wave energy. The physical processes represented in SWAN include the processes of wave growth through energy transfer from wind (energy generation), nonlinear transfer of wave energy through quadruplet and triad interactions (energy redistribution), as well as the loss of energy through wave breaking, bottom friction, and white-capping (energy dissipation). García-Medina et al. (2013) previously demonstrated that neither bottom friction nor wind input are dominant processes for SWAN simulations over the shelf in the Pacific Northwest. Hence, following their lead, we only include depth-induced breaking in our SWAN simulations, as it is the most relevant physical dissipation mechanism and the primary process leading to wave-induced currents.

Although diffraction can be approximated by SWAN with a phase-decoupled refraction-diffraction approximation (Holthuijsen et al., 2003), the spatial resolution used in this model was significantly finer (9 m, smallest nested grid) than the suggested resolution for the activation of diffraction, (SWAN team, 2006a), and the model did not converge when diffraction was activated. In order to use the SWAN diffraction approximation, it would have been necessary to coarsen the spatial resolution of the domain, which essentially requires treating the WEC array as a single object, similar to past studies. Previous studies have demonstrated that diffraction is much less important when the input wave spectrum contains realistic directional spreading (Özkan-Haller et al., 2017), as was done here. For these reasons, the SWAN diffraction approximation was not utilized in this study.

2.2. Wave forcing

Spatial gradients in radiation stresses result in cross-shore and