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Numerical modeling of the effects of wave energy converter characteristics on nearshore wave conditions

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ABSTRACT

Modeled nearshore wave propagation was investigated downstream of simulated wave energy converters (WECs) to evaluate overall near- and far-field effects of WEC arrays. Model sensitivity to WEC characteristics and WEC array deployment scenarios was evaluated using a modified version of an industry standard wave model, Simulating WAves Nearshore (SWAN), which allows the incorporation of device-specific WEC characteristics to specify obstacle transmission. The sensitivity study illustrated that WEC device type and subsequently its size directly resulted in wave height variations in the lee of the WEC array. Wave heights decreased up to 30% between modeled scenarios with and without WECs for large arrays (100 devices) of relatively sizable devices (26 m in diameter) with peak power generation near to the modeled incident wave height. Other WEC types resulted in less than 15% differences in modeled wave height with and without WECs, with lesser influence for WECs less than 10 m in diameter. Wave directions and periods were largely insensitive to changes in parameters. However, additional model parameterization and analysis are required to fully explore the model sensitivity of peak wave period and mean wave direction to the varying of the parameters.

1. Introduction

In order to effectively convert wave energy into commercial-scale onshore electrical power, arrays of multiple wave energy converter (WEC) devices are necessary. The deployment of WEC arrays will likely begin small (pilot-scale or ~10 devices) but could feasibly number in the hundreds of individual devices at commercial-scale. As the industry progresses from pilot- to commercial-scale, an understanding of the effects of WEC arrays leeward of the deployment site and on the nearshore environment will become increasingly important. WEC arrays have the potential to alter nearshore wave propagation and circulation patterns and possibly modify sediment transport patterns (e.g., [12]), which could have detrimental effects on ecological processes and local socioeconomic services. To help accelerate the realization of commercial-scale wave power, it is necessary to evaluate the potential environmental effects of WEC arrays and inform environmental assessments associated with the regulatory process (e.g., [8,15,28]).

At present, due to the lack of deployed WEC farms, direct measurements of the effects of WEC arrays on nearshore wave propagation are not available. Wave model simulations however, can provide the groundwork for completing such environmental assessments by investigating the sensitivity of predictive model results to differing WEC characteristics over anticipated wave conditions. The understanding developed here will allow investigators to conduct predictive environmental assessments with increased confidence and reduced uncertainty in future phases of WEC development.

1.1. Background

Baseline versions of spectral wave models, such as TOMAWAC [29] and SWAN (Simulating WAves Nearshore) [4,20] do not have the inherent capabilities needed for modeling far-field effects of arrays of WECs. These codes effectively model a WEC as an obstacle with a constant, user-specified transmission coefficient [9,11] applied across the entire frequency spectrum. Transmission coefficients determine the amount of wave energy that is absorbed

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and subsequently allowed to transmit past the obstacles, or WECs.

In a study presented by Millar et al. [16], potential WEC farm effects on shoreline change were modeled at the Wave Hub site using the native SWAN model and transmission coefficients set at 0%, 40%, 70%, and 90% (corresponding to 100%, 60%, 30%, and 10% wave energy absorption). Millar et al. [16] concluded that wave heights inshore of WECs decrease linearly with increasing wave energy transmission. Bento et al. [3] also simulated WECs as SWAN obstacles with the same transmission coefficients at three different incoming wave directions along the Portuguese coast during two different seasons. They similarly found decreases in significant wave and swell height with increased energy absorption immediately in the lee of the simulated WEC farm.

Several other studies by Rusu and Guedes Soares (e.g., [24–26]) evaluated WEC and WEC farm effects on the Portuguese coast and neighboring archipelagos. Iglesias and Carballo [14] determined impact indicators to describe the influence of WEC farm distance to shore on nearshore wave characteristics using constant transmission coefficients determined from laboratory studies. Wave farm configuration sensitivity analysis was performed for the Pelamis WEC by Palha et al. [17]. Chang et al. [6] evaluated the sensitivity of the native SWAN model to a variety of model parameters with and without a WEC array (transmission coefficient, frequency spreading, directional spreading, and WEC device spacing within the array) and concluded that changes in significant wave height in the lee of a simulated WEC array are most sensitive to wave energy transmission.

While these studies provided insight on wave propagation in the presence of an array of obstacles, they did not take into account WEC device-specific characteristics in the specification of the SWAN model's obstacle transmission coefficients. For example, a later review of the study by Millar et al. [16] determined that the application of constant obstacle transmission coefficients to model WECs was not well understood and there was not sufficient guidance on how to appropriately account for WEC power performance [1]. This directly motivated the work accomplished by Smith et al. [27]; who modified the SWAN code to account for the frequency- and directionally-dependent power absorption of WECs. With Smith's modifications to SWAN, WEC power performance can be modeled by user-defined frequency- and directionally-depended power transfer functions. Using this model, the effects of deploying wave farms at the Wave Hub site were re-assessed [27].

The development of the SNL-SWAN (Sandia National Laboratories – SWAN) code builds upon the work performed by Smith et al. [27] by further modifying the native SWAN code to allow for direct importation of WEC power performance data in the form of relative capture width (RCW) curves, or power matrices. RCW curves and power matrices are the current industry standard practice for defining WEC power production (e.g., [13]) (RCW curves are analogous to turbine power curves in the wind industry). The incorporation of RCW curves or power matrices removes any uncertainties related to arbitrarily chosen transmission coefficient values. Rather, the transmission coefficients (or WEC power absorption) are calculated directly by SNL-SWAN based on user-defined WEC power performance data. This approach has been verified by comparison to other codes and has undergone preliminary validation by comparison to experimental wave tank data [18,23].

1.2. *Objectives*

The present study incorporates SNL-SWAN, a modified version of an industry standard wave modeling tool, SWAN to simulate wave propagation through a hypothetical WEC array deployment site on the California coast. The primary objective of the SNL-SWAN sensitivity study is to investigate the potential effects of a range of WEC devices on leeward and nearshore wave propagation. To accomplish this goal, the following tasks are undertaken:

- Evaluate the modified wave propagation model, SNL-SWAN, which allows the incorporation of device-specific WEC characteristics.
- Perform model sensitivity analysis using SNL-SWAN to examine the effects of WEC characteristics (WEC device type and size, number of WECs, and WEC device spacing within the WEC array) on near-field and far-field wave conditions in the lee of the WEC devices.

2. Methods

2.1. *SNL-SWAN*

SNL-SWAN was developed to more accurately evaluate WEC farm effects on wave propagation by incorporating a WEC module that accounts for device-specific WEC power performance. Based on the user specified power performance, SNL-SWAN calculates transmission coefficients that are associated with a WEC's power performance. Several methods of determining the transmission coefficient are employed in Version 1.0 of SNL-SWAN. The five methods are employed through switches (specified in the SNL-SWAN input file) in the SNL-SWAN WEC module, where:

Switch 0) SNL-SWAN uses the standard SWAN obstacle treatment [10]. The transmission coefficient value, K_t, is a constant value entered into the SWAN input file and applied across all wave frequencies. The transmission coefficient represents the ratio of wave heights incident to and in the lee of the obstacle (or WEC) (Eq. (1)).

$$K_t = \frac{H_{lee}}{H_{incident}} \tag{1}$$

Switch 1) SNL-SWAN computes the transmission coefficient from a user-supplied WEC power matrix (Table 1 shows an example power matrix for a particular WEC). A power ratio is then calculated at the peak wave period based on the absorbed wave power from the WEC power matrix (supplied by the user) and the incident wave power (determined from SNL-SWAN). The transmission coefficient used by SNL-SWAN is calculated based on this power ratio at the peak wave period, as shown in Eq. (2), and is applied as a constant value across all wave frequencies.

$$K_t^2 = \frac{P_{Lee}}{P_{Incident}} = \frac{P_{Incident} - P_{Absorbed}}{P_{Incident}} = 1 - \frac{P_{Absorbed}}{P_{Incident}} \tag{2}$$

Switch 2) SNL-SWAN computes the transmission coefficient from a user-supplied WEC RCW curve. The transmission coefficient used by SNL-SWAN is calculated based on the RCW value from the curve given the peak incident wave period, as shown in Eq. (3), and

Table 1
Power matrix computed for a floating two-body heaving converter (select wave periods and heights shown) [2].

		T_p (s)							
		3	5	7	9	11	13	15	17
H_s (m)	1	2.38	11.41	24.59	43.58	53.08	34.42	19.86	11.78
	2	0	45.28	100.01	153.17	150.81	126.08	60.69	48.03
	3	0	96.17	204.65	357.25	352.72	248.15	136.67	112.52
	4	0	0	366.25	550.98	530.82	419.89	268.44	193.75
	5	0	0	514.29	824.37	617.58	512.41	384.04	257.61
	6	0	0	710.80	973.55	838.26	648.39	501.78	388.41
	7	0	0	781.16	1000	1000	959.05	573.85	449.84