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DEVELOPMENT AND RELEASE OF THE OPEN-SOURCE WAVE CLIMATE ENVIRONMENT ASSESSMENT TOOL SNL-SWAN

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INTRODUCTION

Accurately assessing potential far-field environmental impacts due to wave energy converter (WEC) arrays is needed for commercialization of wave energy. One of the barriers to development is how to assess environmental concerns related to the potential effects these arrays will have on the near- and far-field wave climate. In order for projects in the United States to be approved, regulatory agencies must perform an Environmental Assessment proving little to no environmental impact. However, little is known about the environmental impacts of such wave farms as utility-scale WEC arrays have not yet made it to the market. As a result, the environmental impacts of wave farms are largely determined by numerical wave models capable of modeling large areas (i.e., spectral wave models). Therefore a validated, publicly available wave model that accurately predicts the effects due to WEC-arrays is crucial to WEC commercialization

Existing spectral wave models are limited in their ability to model WECs. They typically model WECs as obstacles with a constant amount of energy absorption across all frequencies. This approach does not accurately account for the WEC's performance, which is often tuned maximize energy capture for certain periods or sea states. Sandia National Laboratories has modified the open source spectral wave model Simulation WAves Nearshore [1] (SWAN), to include a validated WEC Module that more realistically models the frequency and sea state dependent energy absorption of WECs. SNL-SWAN is an open source code available for download and use by developers, licensing agencies, and other interested parties.

This extended abstract will provide an update on code developments since the initial release of SNL-SWAN v1.0 in Oct, 2014. It will focus on the new model features and modifications that are incorporated in SNL-SWAN v1.1 (planned to be released Fall 2015). The significant modifications for SNL-SWAN Version 1.1 include the following:

- An output file for power absorbed by each WEC obstacle
- Directional dependent WEC power extraction
- Incorporation of a frequency dependent reflection coefficient term
- An update to transmission coefficients determined by WEC power matrix

Additionally, this abstract will present an example application of using the SNL-SWAN v1.1 model to assess wave farm impacts on the nearshore environment.

BACKGROUND

Presently, the baseline versions of spectral models such as SWAN and TOMOWAC parameterize obstacles by applying a constant transmission coefficient across the entire frequency spectrum. However, typically WECs behave and absorb energy differently per incident wave frequencies [2]. Several studies implementing frequency dependent WEC parameterizations to examine far-field effects have been completed and utilize several models. For example, Silverthorne [3] modified the TOMAWAC source code and added a frequency and directional dependence for transmisivity to model representative WEC performance (RCW) curves. Smith [4] built upon previous work [5] at the WaveHub site in England

and modified the SWAN source code to include frequency and directional dependent WEC power source terms. However, none of the spectral model studies above were able to be validated against observational data. With the intent of optimizing array design, Child [6] modeled WEC arrays using Garrad Hassan's code WaveFarmer, which was developed from the baseline spectral solver TOMAWAC. WaveFarmer is a commercial code whose source code is not publicly available. The authors herein sought to further the previous WEC array work by developing the open source code, SNL-SWAN, and validating the code by comparison to experimental data.

SNL-SWAN works differently than baseline SWAN in that it determines the transmission coefficient (Kt) of a WEC based on WEC power performance data, and the incident wave climate within the model. WEC power performance data can be input as either a power matrix, or a relative capture width (RCW) curve. This type of WEC performance data may be obtained through experimental data or other numerical modeling efforts. The power matrix can be defined in terms of significant wave height (H_s) and peak wave period (T_p), or for regular waves as wave height (H) and period (T). An example power matrix is shown in Table 1. Device power flux values in this table are populated by either physical experiments or numerical modeling (using WEC codes such as WEC-Sim, WaveDyn, InWave, etc) for all wave height and wave period combinations.

TABLE 1 - SAMPLE WEC POWER MATRIX

Mean Power Flux [kW/m]		T_p [s]														
		0.5222	0.6963	0.8704	1.0445	1.2185	1.3926	1.5667	1.7408	1.9149	2.0889	2.2630	2.4371	2.6112	2.7852	2.9593
	0.0152	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	0.0303	0.0001	0.0001	0.0002	0.0003	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
	0.0455	0.0000	0.0003	0.0004	0.0006	0.0007	0.0007	0.0004	0.0004	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001
	0.0606	0.0000	0.0004	0.0006	0.0010	0.0013	0.0011	0.0007	0.0005	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001
	0.0758	0.0000	0.0000	0.0010	0.0015	0.0017	0.0014	0.0011	0.0008	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0002
	0.0909	0.0000	0.0000	0.0014	0.0020	0.0024	0.0021	0.0013	0.0010	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002
	0.1061	0.0000	0.0000	0.0017	0.0028	0.0032	0.0026	0.0019	0.0013	0.0009	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003
H_s [m]	0.1212	0.0000	0.0000	0.0000	0.0035	0.0035	0.0033	0.0023	0.0017	0.0012	0.0009	0.0008	0.0005	0.0005	0.0004	0.0003
	0.1364	0.0000	0.0000	0.0000	0.0041	0.0048	0.0038	0.0024	0.0019	0.0015	0.0012	0.0010	0.0007	0.0006	0.0005	0.0004
	0.1515	0.0000	0.0000	0.0000	0.0051	0.0059	0.0044	0.0031	0.0022	0.0018	0.0014	0.0011	0.0009	0.0007	0.0006	0.0005
	0.1667	0.0000	0.0000	0.0000	0.0060	0.0061	0.0052	0.0039	0.0027	0.0022	0.0015	0.0013	0.0010	0.0008	0.0006	0.0006
	0.1818	0.0000	0.0000	0.0000	0.0000	0.0074	0.0061	0.0041	0.0031	0.0021	0.0019	0.0014	0.0011	0.0009	0.0007	0.0006
	0.1970	0.0000	0.0000	0.0000	0.0000	0.0094	0.0066	0.0045	0.0031	0.0025	0.0020	0.0015	0.0013	0.0010	0.0008	0.0007
	0.2121	0.0000	0.0000	0.0000	0.0000	0.0106	0.0077	0.0052	0.0039	0.0030	0.0025	0.0016	0.0014	0.0012	0.0009	0.0008
	0.2273	0.0000	0.0000	0.0000	0.0000	0.0103	0.0090	0.0059	0.0045	0.0033	0.0024	0.0021	0.0015	0.0012	0.0010	0.0010

The RCW curve is defined by equation 1.

$$RCW = \frac{P_{absorbed}}{P_{incident,flux} CW} \qquad (1)$$

Where $P_{absorbed}$ is the amount of power absorbed at each frequency, $P_{incident,flux}$ is the power flux of the incident wave field at each frequency and CW is a characteristic width (typically equal to device width). The absorbed power is determined either experimentally or numerically. Available power flux is computed for the incident wave field. An example RCW curve is shown in Figure 1.

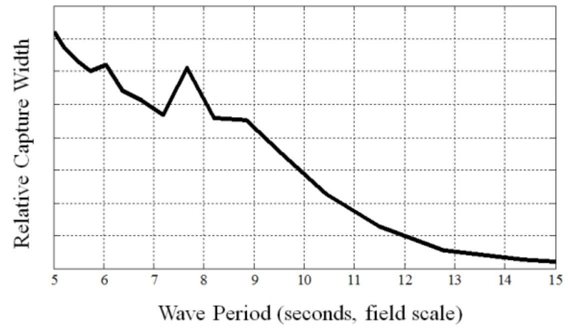

FIGURE 1 - CONCEPTUAL RELATIVE CAPTURE WIDTH PLOT AT LAB SCALE (NOTE: NOT ACTUAL DEVICE RCW CURVE).

The transmission coefficient, Kt, can be determined in four different ways based on the power performance data and incident wave conditions. These options for the WEC obstacle case type, herein referred to as an "Obcase" are detailed in previous work by the authors [7]. The Obcase of choice is identified in the INPUT file, and the differences between obcases are summarized in Table 2 below.

TABLE 2. SUMMARY OF SNL-SWAN OBCASES

OBCASE	DESCRIPTION
0	Baseline SWAN, K_t^2 is determined by OBSTACLE in INPUT file. A constant value for this coefficient is used across all frequencies.
1	WEC power matrix to calculate the effective transmission coefficient. K_t^2 is calculated and a constant value for this coefficient is used across all frequencies.
2	WEC relative capture width curve to calculate the effective transmission coefficient. K_t^2 is again calculated using the provided curve, and a constant value is used across all frequencies.
3	WEC power matrix to calculate the effective transmission coefficient. K_t^2 is calculated independently for each frequency, resulting in a frequency dependent obstacle transmission coefficient.
4	WEC relative capture width curve to calculate the effective transmission coefficient. K_t^2 is calculated independently for each frequency, resulting in a frequency dependent obstacle transmission coefficient.

In each Obcase, the Kt value is determined by SNL-SWAN is used as an energy sink in the spectral action balance equation. Kt is shown in red within this equation in Equation 2.

$$\left(\frac{1}{\Delta t} + \left(D_{x,1} + D_{x,2}\right)c^{+}_{x,i,,j} + \left(D_{y,1} + D_{y,2}\right)c^{+}_{y,i,,j}\right) N^{+}_{i,,j} - \frac{N^{-}_{i,,j}}{\Delta t} - D_{x,1}\left(c_x \boldsymbol{K_{t,1}}^{2} N\right)^{+}_{i-1,j} - D_{y,1}\left(c_y \boldsymbol{K_{t,1}}^{2} N\right)^{+}_{i-1,j} - D_{x,2}\left(c_x \boldsymbol{K_{t,2}}^{2} N\right)^{+}_{i,j-1} - D_{y,2}\left(c_y \boldsymbol{K_{t,2}}^{2} N\right)^{+}_{i,j-1} = S^{+}_{i,j} \qquad (2)$$

Where N is the action density in space and time, D terms represent rates of energy dissipation, c terms represent propagation velocities, and S is the source/sink term.

After modifications were made to the code, SNL-SWAN code underwent extensive verification through comparison to baseline SWAN [8], the Oregon State University version of SWAN, and University of Exeter's version of SWAN [4] to ensure the code functions properly.

NEW CODE FEATURES

Based on user feedback and internal development discussions regarding SNL-SWAN v1.0, several more features have been added to SNL-SWAN v1.1. These features will be included into the upcoming release, planned in Fall 2015.

WEC Power Absorption Output

SNL-SWAN v1.1 includes an output file of absorbed wave power for the incident wave condition, at each WEC obstacle. The absorbed power is calculated directly from the amount of energy removed from the wave spectra along the obstacle face. Absorbed power is output in Watts for each WEC obstacle.

Directional Dependent Power Extraction

SNL-SWAN v1.1 includes the option of including a binary directional dependence option. At input wave angles, the device no longer absorbs energy. For example, if a certain WEC only extracts energy at +/-30 degrees to normal, no power would be absorbed angles greater than thirty degrees off of normal. At wave directions outside this threshold, there is full (100%) wave transmission.

Frequency Dependent Obstacle Reflection

The motivation for including a frequency dependent reflection coefficient in SNL-SWAN is to provide a tool that can be used as a parameterization for losses in the lee of an array due to factors other than power absorption (such as wave scattering). Earlier work has shown that other factors are a relatively significant contributor to reducing wave heights in the lee of a WEC array [2, 9]. The goal of including this mechanism in SNL-SWAN is not to accurately simulate interactions between WECs on a small scale, but instead to provide a way to parameterize the re-distribution of waves interacting with WECs in a larger scale spectral wave model. At present there is no standard frequency dependent reflection coefficient input. The reflection curve could possibly be determined by numerical modeling or laboratory testing.

EXAMPLE WEC-MODULE IMPLEMENTATION

SNL-SWAN implementation is dependent on available data, and user intent. The following section gives an example of SNL-SWAN implementation using a power matrix.

The format of the power matrix is dependent on Obcase and available data. If using Obcase 1, the power matrix should be populated with values

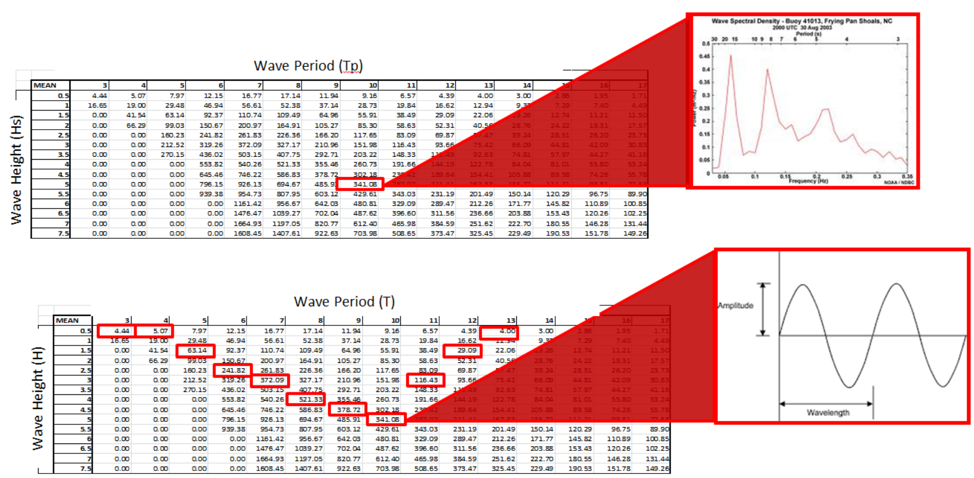

FIGURE 2. OBCASE 1 AND OBCASE 3 KT DETERMINATION VISUALIZATION.

that represent power extraction for the full frequency spectrum (i.e. bulk power measurements for a sea state). To correctly select Obcase 3, which enables frequency dependent obstacles, the use must have a power matrix populated with data collected using a range of regular wave cases (wave height and wave period combinations). In this way the power performances for a unique wave period (rather than the entire spectra) and monochromatic (regular) wave height is used to determine Kt for each frequency bin. Therefore, in SNL-SWAN v1.1 wave height for Obcase 3 is calculated for each binned frequency as shown in equation 3. Obcase 1 calculates the significant wave height of the overall spectrum, Hm0, as shown in equation 4.

$$H = \sqrt{2S(f)df} \tag{3}$$

$$H_{m0} = 4\sqrt{m_0} \tag{4}$$

An example of the Obcase differences and modifications are shown in Figure 2, where the Obcase 1 is shown in the top panel, and Obcase 3 is shown on the bottom panel. As shown in Figure 3, Obcase 1 uses a single cell to determine the Kt value, whereas Obcase 3 calls several cells in the power matrix.

Figure 3 shows SNL-SWAN v1.1 applied to a conceptual WEC-array outside Santa Cruz which has been developed for conceptual comparative purposes. The left panel shows the percent change in significant wave height using Obcase1, and the right panel shows percent change in significant wave height using Obcase3. These results show differences in wave height due to differing wave spectra shapes caused by the variable transmission coefficient at the WEC devices as opposed to a constant transmission coefficient. Differences in model results between Obcase 1 and Obcase 3 will vary dependent on the device and the incident wave climate. Selected model inputs are summarized in Table 3. SNL-SWAN has also computed an estimate of power absorbed by each WEC in Watts, and is output as a text file (not shown here).

In the case that an RCW curve was chosen as the WEC power absorption input, the selected Obcase would be either Obcase 2 (constant Kt) or Obcase 4 (frequency dependent Kt).

TABLE 3. SELECTED CONCEPTUAL EXAMPLE INPUT PARAMETERS.

INPUT	PARAMETER
WECS	10
Spacing	6 Diameters
Location	Santa Cruz, CA
Hs	1.7 meters
Direction	205 Degrees From North
Tp	12.5 seconds
OBCASE	#1, #3
DEVICE	Idealized floating three-body oscillating flap-type

CONCLUSIONS

Based on user feedback, new features have been added to SNL-SWAN. These features are intended in part to improve assessment of large scale environmental effects studies due to the presence of wave farms by including directional dependence and a tuning parameter for scattered waves. The addition of WEC power output is also intended for an estimate of WEC power output for modeled sea states, and can be used for preliminary wave farm layout optimization. It should be noted that SNL-SWAN is not intended to

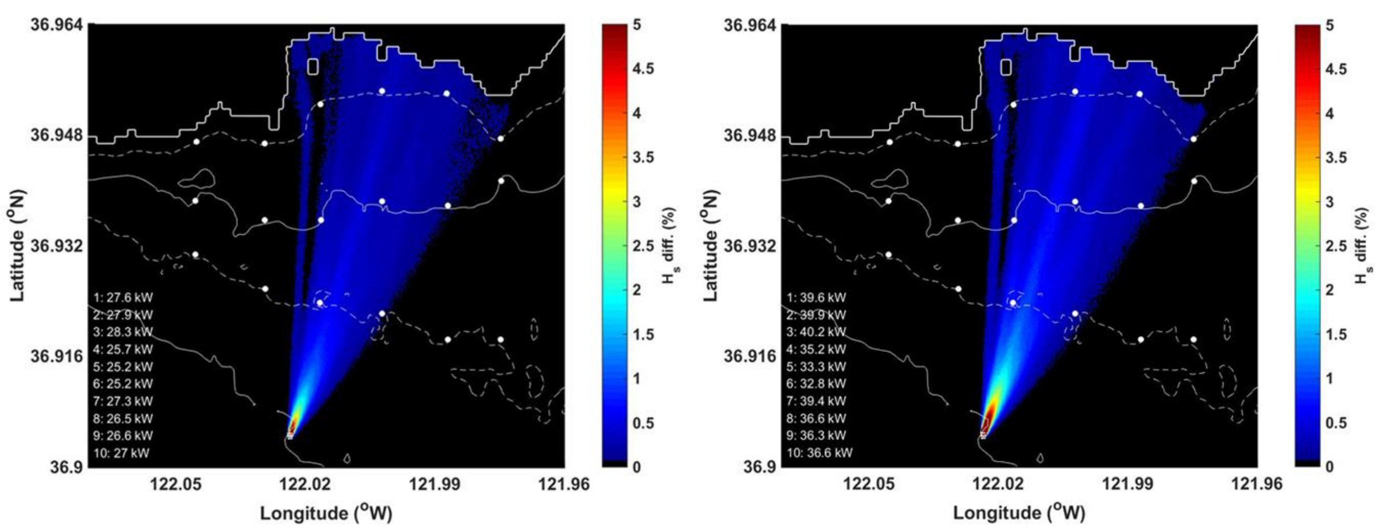

FIGURE 3. PERCENT CHANGE IN WAVE HEIGHT FOR AN EXAMPLE WAVE FARM USING OBCASE 1 (LEFT PANEL) AND OBCASE 3 (RIGHT PANEL).

model WEC-WEC interaction. Finally, code modifications were made to an earlier version of SNL-SWAN to better represent power take off for input power matrices. The release of SNL-SWAN v1.1 is planned for Fall 2015, v1.0 source code and executables can be downloaded from the SNL-SWAN GitHub site at https://github.com/SNL-WaterPower/SNL-SWAN/releases.

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