Development of SNL-SWAN, a Validated Wave Energy Converter Array Modeling Tool

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Abstract— **Commercialization of wave energy will lead to the necessary deployment of Wave Energy Converters (WECs) in arrays, or wave farms. 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 a result, the environmental impacts of wave farms are largely determined by numerical wave models, however spectral wave models are currently limited in their ability to model WECs. Sandia National Laboratories is developing SNL-SWAN, a modified version of Simulation WAves Nearshore (SWAN) that includes a validated WEC Module to more realistically model the frequency and sea state dependent wave energy conversion of WECs.**

Keywords— **wave energy, wave farm, WEC array, SWAN, spectral modeling**

I. INTRODUCTION

Wave Energy Converter (WEC) developers are in various stages of development, commonly referred to as Technology Readiness Level (TRL), where those furthest along have tested their devices in the open ocean, and some are even pursuing full-scale grid connected deployments. Even so, while the wave energy industry has made significant progress, utility scale commercialization has yet to be achieved. There are many barriers to the commercialization of wave energy, a few examples of which include: cost of energy, survivability, fatigue, environmental impact and public opinion. Each of these factors play an important role in shaping the future of wave energy. In order to overcome some of the existing environmental barriers, the work presented in this paper is an effort to address some of the environmental concerns related to the development of wave energy, specifically to better understand the environment impact of deploying arrays of WECs, or wave farms, by modifying the spectral wave model SWAN [1]. This is important because in the United States all WEC projects are required to get an environmental assessment, which results in either a finding of no significant impact or an environmental impact statement by the federal government. Since there are no commercial wave farms, and therefore environmental impact is an unknown, numerical models play a pivotal role in the success or failure of WEC projects, especially with respect to potentially harmful environmental impacts.

II. BACKGROUND

Initial studies on the environmental impact of wave farms used spectral wave models to model WEC arrays. An example of which is the Wave Hub site evaluation that used SWAN to model a wave farm [2]. As a first step towards understanding the near and farfield effects of WEC arrays, spectral models were used to model WECs with constant energy absorption, by extracting a fixed percentage of the incident wave energy. In SWAN, this is achieved by modeling WECs as obstacles with a constant transmission coefficient. However, this approach brought to light a lot of unanswered questions, like what is a reasonable percentage of WEC energy absorption? What if more energy is taken out of some wave periods than others (which is typically the case with WECs)? Will tuned devices transform uni-modal wave spectra to bi-modal spectra by extracting a disproportionate amount of energy out of the near peak power absorption periods? How does array spacing and configuration impact the near and farfield? What effect will a change in spectral shape have on waves at the shore? As a result, the approach of modeling WECs as obstacles with a constant transmission coefficient has been deemed insufficient, largely because it does not capture the frequency dependent energy extraction that is fundamental to all WECs.

More recently, several researchers have implemented frequency dependent methods to model WECs in order to better understand the near and farfield effects of WEC arrays. Beels modelled the Wave Dragon and a farm of Wave Dragons using the wave propagation model MILDwave [3]. Both Nørgaard & Lykke Andersen and Angelelli & Zanuttigh

calibrated the MIKE21 Boussinesq model against experimental data to model WEC arrays [4], [5]. Alexandre and Porter independently modelled WEC arrays in SWAN by propagating waves to the line of WECs, modifying the wave spectra based on a measured WEC power curve, and propagating the waves the rest of the way to shore [6], [7]. Both saw changes in the lee wave energy spectra magnitude and shape as a result of this approach, and performed numerical comparisons to experimental data. Silverthorne modified the TOMAWAC source code by adding a frequency and directional dependent WEC term and modelled WECs with representative power curves [8]. Smith furthered the initial Wave Hub site evaluation by modifying the SWAN source code to include both a frequency and directional dependent WEC source term, the modified SWAN code was then used to model the Wave Hub site for WEC arrays with varying power transfer functions [9]. However Silverthorne's and Smith's work are both without experimental comparison, meaning to date there is yet to be a spectral code modified to better model WECs that includes validation. A more extensive review of WEC array modeling approaches is given by Folley, this paper includes spectral wave farm modeling approaches in addition to many others [10].

The work described in this paper is in regards to Sandia National Laboratories' (SNL) development of SNL-SWAN, a version of the spectral wave model SWAN developed by TU Delft, modified to include a WEC Module that accounts for the frequency and sea state dependent nature of wave energy extraction. Additionally, SNL-SWAN development includes verification of the code's functionality, and validation of the code through comparison to experimental wave tank testing, the details of which will be described in the following sections.

III. SNL-SWAN DEVELOPMENT

Through the development of SNL-SWAN, SNL is furthering previous WEC array modeling work by creating a WEC Module in SWAN and validating it by comparison to the experimental array tests of the Columbia Power Technologies' "Manta 3.1" WEC performed at Oregon State University's Hinsdale Tsunami Wave Basin [11]. In SNL-SWAN, the WEC Module is capable of modeling the frequency dependent energy extraction of WECs via three methods: baseline SWAN's obstacle formulation, a WEC's relative capture width (RCW) curve, and a WEC's power matrix. By more accurately modeling the energy extraction of

WECs, greater confidence can be given to the numerically observed environmental effects due to the presence of wave farms. Results from SNL-SWAN can also be incorporated into circulation models, such as SNL-EFDC, to study a wave farm's potential impact on coastal circulation patterns and sediment transport [12]. Findings from these numerical studies are used by environmental regulatory agencies to assess the potential environmental impact of wave farms. Currently, numerical methods are the only available avenue to assess environmental impact because there has yet to be a commercial wave farm deployment. As such, the accuracy of these numerical models is very important because they can directly affect permitting, and hence the success or failure of a particular project.

A. Code Modifications

The addition of the WEC Module to SWAN allows the user to model the frequency and sea state energy extraction of WECs. SNL-SWAN's WEC Module is a modification of baseline SWAN's obstacle function, that has three options (or switches):

0 = Baseline SWAN (constant transmission coeff, Kt)
1 = WEC Power Matrix
2 = WEC Relative Capture Width (RCW) Curve

Similar to baseline SWAN's obstacle formulation, each of the switches requires the user to specify the location and number of WECs in the model domain. Additionally, the desired switch (0, 1, or 2) must be specified in a text file (Width.txt), located in the same directory as the SNL-SWAN executable, along with the device width. This tells SNL-SWAN with which method to model the WECs defined within the model domain (the same switch must be used for each WEC in the model domain). Also defined in the Width.txt file is the WEC width, which is used to calculate incident power available to the WEC based on incident power flux. When option 0 is selected, the code is run like baseline SWAN, as an obstacle with a constant transmission coefficient. However, if either option 1 or 2 are selected, SNL-SWAN requires the user to define a power matrix or a RCW curve, samples of which are shown below in Table I and Fig. 1 respectively. The power matrix and RCW curve values shown here are based on the NumWEC project since developer specific power performance data is proprietary [13].

TABLE I
SAMPLE WEC POWER MATRIX

| Mean Power Flux [kW/m]	T_p [s]														
H_s [m]	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	0.0001	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
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
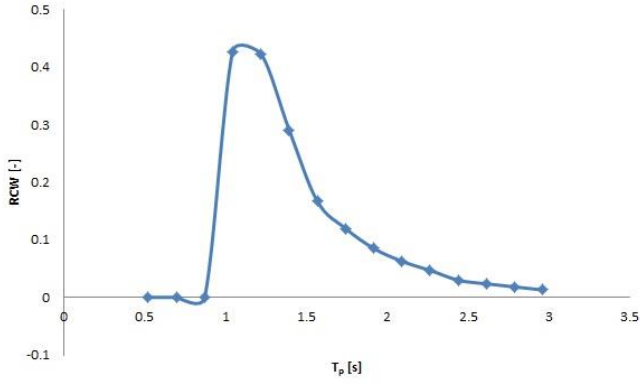
Fig. 1 Sample RCW Curve

Option 1, the WEC power matrix, requires the user to define three additional text files in the SNL-SWAN executable directory (Period.txt, WaveHeight.txt and Power.txt), where these files specify the x- and y-axes of the power matrix, as well as the device's power performance at each of the sea states. The power matrix must be defined in terms of significant wave height (H_s) and peak wave period (T_p). The WEC Module calculates the incident wave power available to the WEC based on the incident power flux and the device width. Then the ratio of the absorbed power to the incident power is determined based on the WEC's specific power matrix. This power ratio is then returned to SNL-SWAN as the power transmission coefficient (K_{tp}) for the obstacle, and printed to the SWAN output file. The discretised action balance equation (Eq. 1) in curvilinear coordinates solves for the action density (N), defined as the energy density per a particular frequency, which is conserved. In the presence of obstacles, the action balance equation includes the time derivative ($1/\Delta t$), diffusion coefficients (D), source terms such as depth induced breaking (S), and the obstacle transmission coefficient (K_t). Baseline SWAN's obstacle transmission coefficient (K_t) is squared in the spectral action balance equation, due to the fact that this coefficient represents the ratio of lee to incident wave heights at the obstacle, as shown below in Equation 1. By contrast, K_{tp} represents a power ratio, and is therefore not squared in the spectral action balance equation.

Option 2, the WEC RCW curve, requires the user to define two additional text files in the SNL-SWAN executable directory (Period.txt and Power.txt), where these files specify the x- and y-axes of the RCW curve. The RCW curve must be defined in terms of peak wave period (T_p). The WEC Module then reads the RCW curve, and returns it to SNL-SWAN as the power transmission coefficient (K_{tp}) for the obstacle.

Equation 1 Spectral Action Balance Equation in Curvi-Linear Coordinates with Kt, from SWAN Manual [1]

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

Currently, SNL-SWAN allows the user to model WECs three different ways, with the baseline SWAN obstacle formulation, with the WEC power matrix (Option 1) which allows the user to specify a WEC's period and wave height dependent energy absorption, and with a WEC RCW curve (Option 2) which is purely wave period dependent. All of the modifications to the SWAN source code were made to SWAN4072abcde due to its compatibility with DELFT3D, which is commonly used for assessing water quality and sediment transport, especially for artificial environments like harbours and locks. Also, more recent releases of SWAN do not have additional features that are thought to impact wave farm modeling.

B. Verification and Application

Once the source code modifications were made to SWAN4072abcde, the compiled code's functionality was verified in order to assure that SNL-SWAN is fully operational and captures the appropriate physics. SWAN provides a series of test cases to run for this purpose, these correspond to the refraction, diffraction and slanting current tests. MATLAB scripts were written to quickly run each test case, import the model results, and compare the compiled code to the baseline SWAN executable. Review of the test cases showed no significant difference between the test case results for SNL-SWAN when compare to the baseline SWAN executable.

In addition to verifying SNL-SWAN's functionality in comparison to baseline SWAN for the provided test cases, a comparison of SNL-SWAN to baseline SWAN was performed for a previously developed model domain in Monterey Bay, CA [14]. The purpose of this direct comparison was to verify that the WEC Module was indeed functioning, and that it produced different near and farfield effects than baseline SWAN. Additionally, this exercise provided feedback from several SNL-SWAN users on suggestions for improvements and helped catch bugs in the code.

Prior to beginning development of SNL-SWAN, SNL performed a SWAN sensitivity analysis using the Monterey Bay model domain to better understand SWAN's baseline functionality and its sensitivity to different model parameters. The Monterey Bay SWAN model domain, along with the model output locations are shown in Fig. 2 below. The sensitivity analysis varied the following parameters:

transmission coefficient, reflection coefficient, directional spreading, WEC array spacing, orientation, location, and farm size. An expected finding from this analysis was that the obstacle transmission coefficient has the most significant impact on wave energy distribution in the near and farfield, which directly lead to the development of SNL-SWAN. While direct comparison between baseline SWAN with constant transmission and SNL-SWAN were completed to verify its functionality, they are not presented in this paper.

As a realistic application of the model, SNL-SWAN was used to model the Monterey Bay domain with 10 WECs arranged in an equidistant honeycomb pattern along the 40m depth contour, with 6x center-to-center spacing, orientated in the dominant wave direction. Figs. 3 and 4 below show the comparison of baseline SWAN (without obstacles) to SNL-SWAN using three different WECs (B-OF, F-2HB and F-OWC) which were characterized by the NumWEC project, descriptions of which can be found in Table 2. The percentages refer to differences between SWAN and SNL-SWAN at each of the output locations.

The model was then run for two different regular wave cases, once for H_s of 1.7m and T_p of 12.5s, and again for H_s of 3.5m and T_p of 12.5s, with the incident waves propagating from the southwest. Fig. 3 shows the significant wave height percent difference between the two versions of SWAN using the WEC power matrix (switch 1), where black corresponds to no difference. Fig. 4 shows the significant wave percent difference using the WEC RCW curve (switch 2). These results show that SNL-SWAN yields a significant difference in the significant wave height in both the near and farfield for both switches. Both the near and farfield produce the expected trends, with significant wave height reduction most pronounced in the nearfield, and with H_s reduction in the farfield, but to a lesser extent. The regions of wave scattering shown in the model results are thought to be a result of diffraction being turned off and the chosen directional spreading parameter (dd). This is a topic of future interest. Additionally, while these simulations were based on numerically determined power performance data, they demonstrate that different WEC technologies will likely have different environmental impacts both in the immediate lee of the array, and in the nearshore region. This comparison provides both a realistic application of SNL-SWAN, and further verification that the WEC Module is functioning properly.
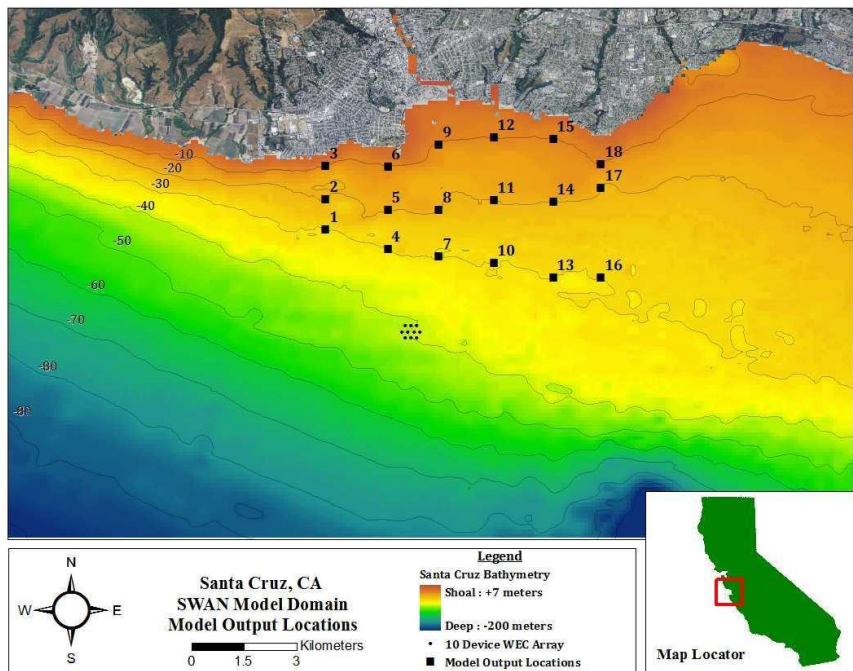

Fig. 2 Monterey Bay SWAN Model Domain, WEC array located on the 40m contour and model outputs labelled 1 to 18.

TABLE 2
WEC Type and Dimensions

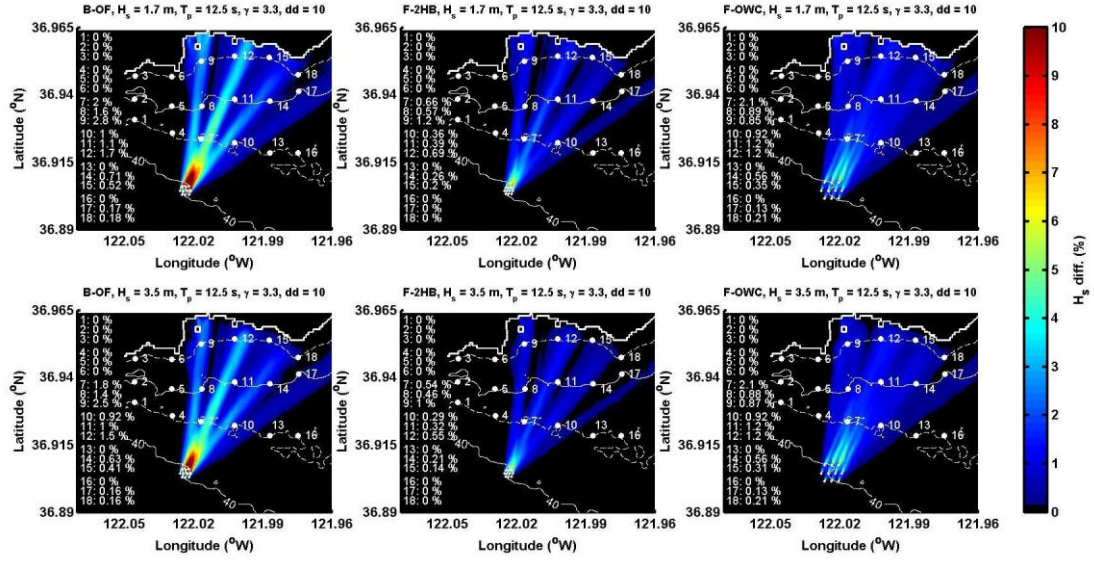| WEC Type	Abbr.	Diam (m)
Floating two-body heaving converter	F-2HB	20
Bottom-fixed oscillating flap	B-OF	26
Floating oscillating water column	F-OWC	50

Fig. 3 SNL-SWAN switch 1 H_s comparison to baseline SWAN for frequency distribution spread (γ) = 3.3 and directional distribution spread (dd) = 10
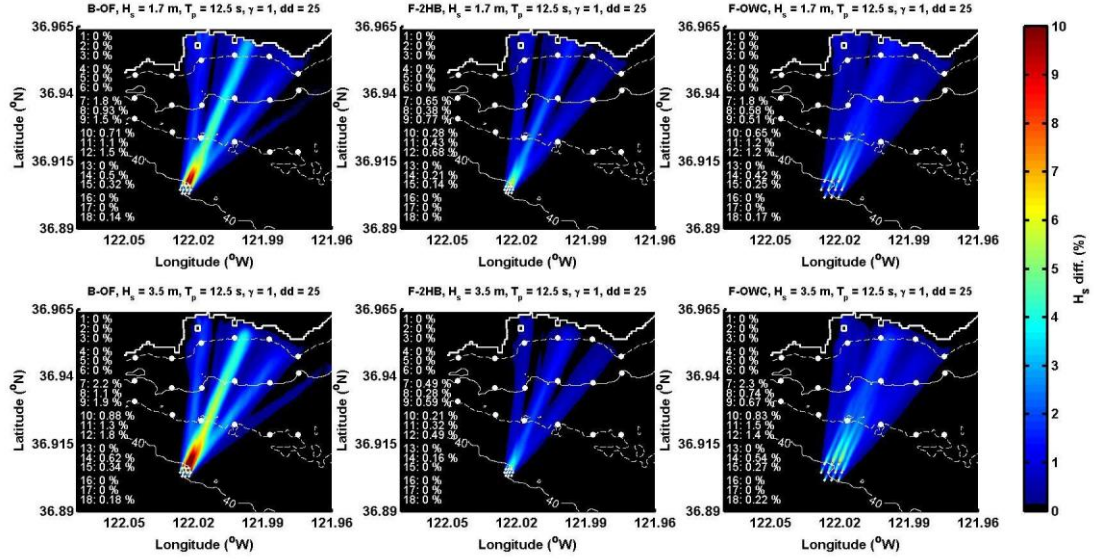

Fig. 4 SNL-SWAN switch 2 H_s comparison to baseline SWAN for frequency distribution spread (γ) =1 and directional distribution spread (dd) = 25

C. Validation

The next stage in the development of SNL-SWAN is validation of SNL-SWAN through comparison to the experimental array tests of the Columbia Power Technologies' (CPT) Manta 3.1 WEC performed at Oregon State University's Hinsdale Tsunami Wave Basin. SNL is working with OSU to obtain details about the experimental setup, and with CPT for performance data. The WEC array experiments consisted of trials with up to five, 1:33 scale "Manta 3.1" WECs moored in the in the Tsunami Wave Basin. Arrays of 1, 3 and 5 WECs were tested with a variety of wave conditions, in both regular waves and with representative wave climates. Information on these experiments is available in greater detail in Haller 2011 and Porter 2012 [7], [11]. Fig. 5 shows a picture from the WEC array tests at Hinsdale with 5 devices in the basin.
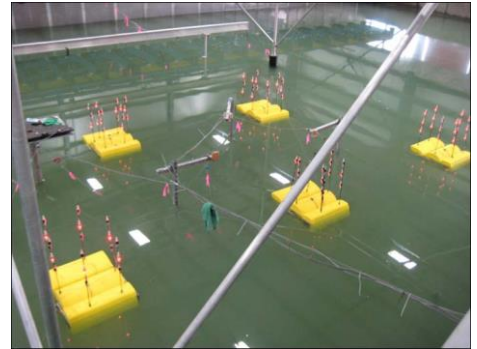

Fig. 5 CPT Manta 5 WEC Array Testing at OSU Hinsdale

In order to compare the numerical results from SNL-SWAN model directly to experiments, a Tsunami Wave Basin model domain was developed from measured bathymetry and basin dimensions. Data output from the numerical model trials can be compared to data points at the locations of the wave gauges used in the experiments, see Fig. 6.
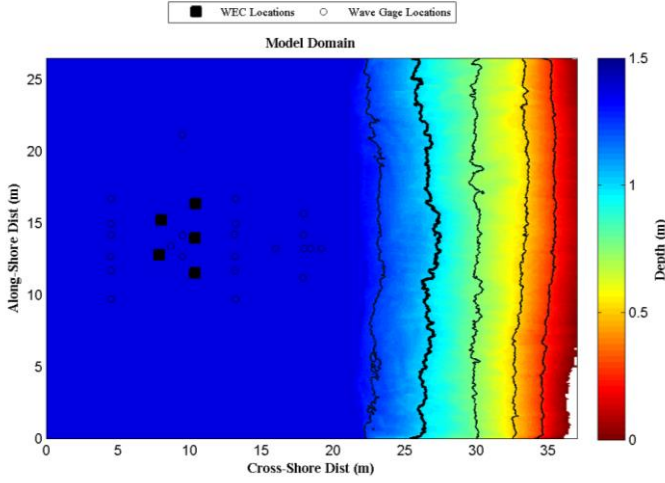

Fig. 6 Tsunami Wave Basin SWAN Model Domain with 5 WEC Array and Wave Gauges

An initial sensitivity analysis using baseline SWAN (similar to the one in the Monterey domain) was performed in the Tsunami Wave Basin to test the model domain, and provided an additional mode of comparison between baseline SWAN, SNL-SWAN and the WEC array experiments. Building on the sensitivity analysis, conceptual comparisons between the observational data set and the present version of SNL-SWAN numerical model results have been performed, an example of an idealized WEC is shown in Fig. 7 (at field scale). The WEC in this case was parameterized by an RCW curve called out in the text files, Period.txt and Power.txt. Other model-data comparisons for such data as power deficits and wave spectra shapes and other are performed, but not shown here.
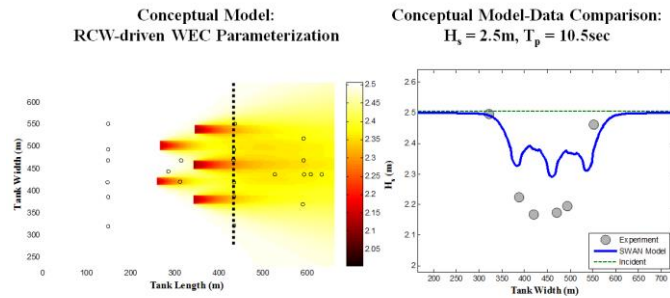

Fig. 7 Conceptual Comparison of Numerical Model results (left panel) to the observational data set (right panel, grey dots).

IV. CONCLUSIONS AND FUTURE WORK

An initial version of SNL-SWAN has been compiled, and used to model both a realistic domain in Monterey Bay, and the WEC array tank experiments in the Tsunami Wave Basin. SNL-SWAN is a modified version of SWAN4072abcde, with the addition of a WEC Module to more realistically model the frequency and sea state dependent wave energy absorptions of WECs. The WEC Module currently has three switches, or methods to model WECs. Switch 0 implements the baseline SWAN obstacle formulation with a constant transmission coefficient. Switch 1 calls on a user defined WEC power matrix to account for both wave period and wave height dependent WEC power conversion. Switch 2 calls on a user defined RCW curve that accounts for wave period dependent WEC power conversion. WEC power matrices and RCW curves are common ways to characterize WEC power performance in industry, IEC standards, and academia. As such, they were chosen as the method for implementation of the WEC Module to account for non-uniform power conversion across wave periods and sea states. This allows for easy integration of WEC power performance data into SNL-SWAN for wave farm environmental impact studies. Once development of SNL-SWAN is complete with validation, the executable and source code will be publicly available for use by the wave energy industry.

Currently, the WEC Module in SNL-SWAN calculates an effective transmission coefficient based on the power matrix or RCW curve's value at the dominant wave period using a linear interpolation schedule, and applies this coefficient at each WEC in the array. SNL plans to refine this algorithm so that instead of applying a constant effective transmission coefficient, SNL-SWAN will directly apply a transmission coefficient based on the WEC power matrix or RCW curve for each binned wave frequency. This has not been implemented thus far because it requires digging further into the code, and modifying the source formulation in the spectral action balance equation (Equation 1). These refinements will be made to the next iteration of SNL-SWAN. Validation will parameterize WECs based on measured performance data from the wave tank experiments, and the numerical wave field results will be compared to the observational wave tank data set.

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