Extreme Conditions at Wave Energy Sites

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ABSTRACT

Wave measurements and models are applied to quantify the extreme conditions that Wave Energy Converters (WECs) must withstand for prolonged deployments in the ocean. A deficiency in existing wave models, in which forecasts underestimate the extreme conditions relative to observations, is confirmed. New SWIFT buoy data has been collected to aid in calibrating the models, and to examine the conventional metrics for characterization of extreme conditions. Data analysis is focused on short-term temporal variability and the breaking of steep waves, which may not conform to the statistical distributions developed under more moderate conditions.

1. INTRODUCTION

Extreme conditions are a risk to wave energy converters (WECs). Large, breaking waves may impart forces that are several orders of magnitude greater than the forces expected by present WEC designs. Designing for survivability in these conditions is challenging, because these conditions are, by definition, rare. For any given WEC deployment site, there is limited data on the extremes for that site. Even for the multi-decade buoy records that exist at some US sites, there may only be a few occurrences of extreme conditions (often less than one per year). Buoy data can be supplemented with wave model hindcasts, however there is a known deficiency in which most models under-estimate peak conditions [1].

The problem of extreme conditions is further complicated by the statistical approach of describing wave conditions (i.e., the sea state) using bulk parameters. The significant wave height, H_s, is the average of the highest one-third of all the waves in a given sea state, which is assumed to have a Rayleigh distribution of wave heights and have stationary statistics. However, high sea states and focal zones are known to have sufficient non-linear dynamics that the Rayleigh distribution is inadequate [2, 3]. Large, or 'rogue' waves, relative to a given theoretical distribution, are more probable in such conditions. Furthermore, the conditions may have non-stationary statistics, in which the sea state varies more rapidly than the 30-minute window common in the averaging of buoy data, or the 3-hour window common for wave modeling.

Finally, wave breaking is more common in these conditions, because breaking probabilities are linked to wave steepness and wave non-linearity [4]. Wave breaking may present the greatest hazard to WECs during extreme conditions, because the impact forces of a breaking crest will greatly exceed the forces of a non-breaking wave. In non-breaking wave motion, the fluid particle velocities and accelerations are much smaller than the wave phase speed. When wave breaking occurs, the fluid particle velocities increase sufficiently to outrun the wave crest, with a commensurate increase in the dynamic and inertial forces.

Here, we examine these concerns for the South Energy Test Site (SETS) offshore of Newport, OR (USA). An existing implementation of the WAVEWATCH3 model is compared with data from a nearby NDBC buoy at Stonewall Bank (#46050). Figure 1 shows that model-data agreement is excellent for most conditions. However, for significant wave heights exceeding 8 m, the model is biased low relative to the data. The 15 year buoy record has over 20 events with $H_s > 8$ m, including events up to $H_s = 12$ m, but the model hindcast for the same time has no results above $H_s = 8.5$ m. Furthermore, the use of the significant wave height parameter itself may be insufficient to describe peak forces during

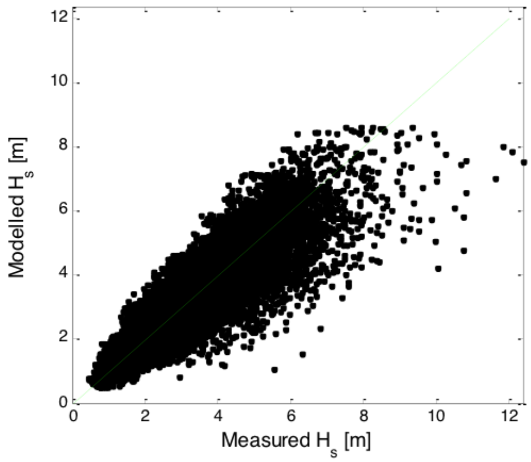

Figure 1: HINDCAST VERSUS MEASURED WAVE HEIGHTS AT STONEWALL BANK, OFFSHORE OF NEWPORT, OR, USA.

extreme conditions. Recognizing this issue as common to many wave energy sites, we have begun collecting and analyzing high-fidelity wave data during extreme conditions at SETS. For this site, we define extreme conditions as events with $H_s > 8$ m, which exceeds the 99^{th} percentile of the conditions historically observed at NDBC buoy #46050.

2. METHODS

The data collection approach is a rapid response to forecasts of extreme conditions, in which wave measurement buoys are deployed from the air a few hours prior to forecast extremes. The wave buoys are Surface Wave Instrument Floats with Tracking (SWIFT), which are designed and built at the University of Washington's Applied Physics Laboratory and described in [5]. In addition to measuring the typical wave parameters, the SWIFTs are designed to measure the wave breaking process, by sampling buoy motion at high rates (25 Hz instead of the typical 2 Hz), by collecting images of the sea surface, and by using Doppler sonars to measure the turbulent fluid velocities within the crests.

The rapid-response SWIFT deployments are performed by dropping pairs of buoys from a helicopter hovering at approximately 30 m altitude over the site. Figure 2 shows the helicopter, owned and operated by Brimm Aviation in Astoria, OR, and one of the SWIFTs. Once the SWIFTs are deployed, the helicopter leaves the site and the buoys are left to drift freely. The buoys report positions and processed wave results (bulk parameters, directional frequency spectra, and motion histograms) every hour using an Iridium satellite modem with global coverage. The buoys can also be tracked locally using radio collars (10 km range).

To date, two deployments have been conducted. A pair of SWIFTs were deployed on 6 Dec 2016 as a live test in $H_s = 4$ to 6 m conditions. This test was successful, and the buoys were recovered in fine condition when they eventually washed ashore. Another pair of SWIFTs were subsequently deployed on 11 Dec 2016 as

Figure 2: SWIFT BUOYS AND HELICOPTER USED FOR DEPLOYMENTS.

Figure 3: SWIFT BUOY DEPLOYMENT AND DRIFT TRACKS ON 11 DEC 2016.

a full extreme condition mission in $H_s = 5$ to 8 m. These SWIFTs also washed ashore and were recovered in fine condition. The drift track from 11 Dec 2016 is shown in Figure 3. If the SWIFTs drift offshore, rather than onshore, in future missions, they have sufficient battery life to be tracked for 6 months, during which time they can be recovered using a vessel.

3. RESULTS

The significant wave heights and dominant wave periods from the 11 Dec 2016 mission are shown in Figure 4. These statistical parameters are calculated using 10-minute windows, and this shows temporal variability in the parameters that might be obscured using 1-hour NDBC buoy records or 3-hour model results. The elevated temporal variability is caused by sampling variability, due to the fact that only fifty 12-second waves are sampled in a 10-min window, as well as the natural variability of the wind and waves.

Figure 5 evaluates dependence on record length, or window, used to calculate wave parameters. Assuming stationarity in the wave statistics, the figure shows the significant wave heights obtained by parsing the raw wave data from the whole 10-hr deployment in various window lengths. This demonstrates an important consideration in quantifying conditions for WEC sites: the

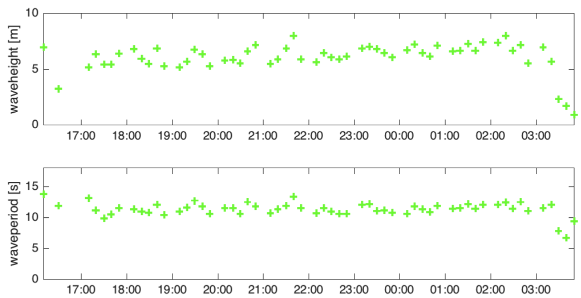

Figure 4: SIGNIFICANT WAVE HEIGHTS AND DOMINANT WAVE PERIODS ESTIMATED EVERY 10 MINUTES DURING DEPLOYMENT ON 11 DEC 2016.

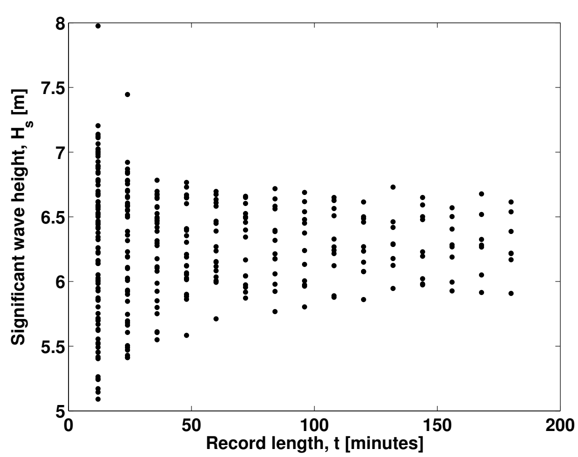

Figure 5: VARIATIONS IN SIGNIFICANT WAVE HEIGHTS AS A FUNCTION OF THE RECORD LENGTH OF THE RAW TIME SERIES USED.

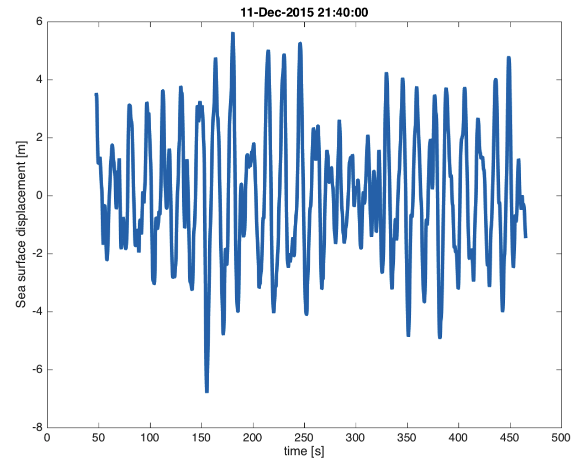

Figure 6: EXAMPLE TIME SERIES OF RAW SEA SURFACE ELEVATIONS ON 11 DEC 2016.

natural/statistical variability of the waves can be substantial, such that, for this case study, only a signal 10-minute window has waves that meet the site-specific definition of extreme ($H_s \geq 8$ m). Although the underlying raw data is the same, the occurrence of this extreme condition would be obscured when using hourly, or even 30-minute, wave parameters, as is commonly done in wave forecasting and in NDBC archiving.

Figure 6 shows the raw time series of sea surface elevation during the 10-minute window with $H_s \approx 8$ m. There is a large wave, with a crest to trough amplitude of approximately 11 m, that occurs 150 seconds into the record. Surface images collected onboard the buoy suggest that this wave was breaking, and thus the forces associated with this wave would greatly exceed those calculated with linear wave theory. This individual wave of 11 m is 1.4 times greater than the significant wave height $H_s = 8.1$ m calculated for that 10-minute window. Although large, this wave is still within the Rayliegh distribution of wave heights associated with $H_s = 8.1$ m. Although it does not meet the criteria for rogue wave, a wave such as this may still be of significant concern for WEC survivability.

Figure 7 expands on this statistical description by showing the Gaussian probability distribution functions obtained by fitting to the raw data of 10-minute windows and by fitting to all 20-hrs of raw buoy data (10 hrs deployment times two buoys). Note that linear theory predicts wave heights are Rayleigh distributed, but that the sea surface elevation should be a Gaussian distribution [6]. For the large excursions of ± 5 m that may affect the survivability of a WEC on a wave-by-wave basis, the probability is always small (< 0.01). However, this small probability can double from one 10-minute window to the next (i.e., 0.005 to 0.01), commensurate with changes in the significant wave height calculated from that collection of waves. This presents a significant challenge to WEC design, as it may be a single wave at very low probability that is critical for survival of a given device.

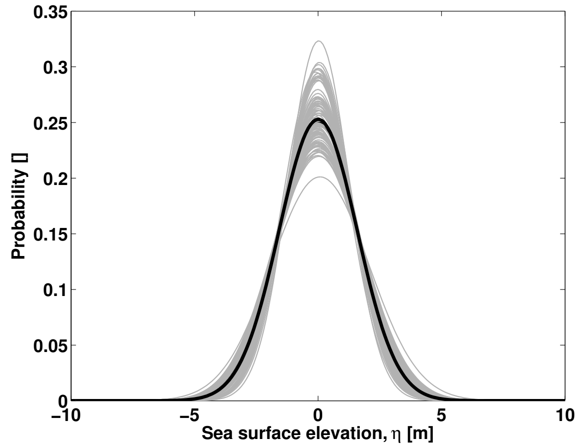

Figure 7: Fitted Gaussian probability distribution functions of the raw sea surface elevation data for all 10-minute windows (gray curves) and the entire 10-hr dataset (black curve).

4. CONCLUSIONS AND FUTURE WORK

The data for this project has just been collected, and there is much work left to be done. Existing wave models and bulk statistical metrics appear to be insufficient to quantify extreme conditions for wave energy sites, and analysis of the newly collected data will seek to advance both issues. To improve the wave model results, use of higher resolution (space and time) wind inputs is being tested. To address wave metrics, statistical models of wave breaking are being developed based on measured wave steepness and measured deviations from expected Gaussian distributions of the sea surface elevation and Rayleigh distributions of individual wave heights. The final step will be to connect these metrics back to the wave models, such that models can be better used to infer the site-specific probabilities of extreme conditions.

5. ACKNOWLEDGEMENTS

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