PROBABILISTIC DISTRIBUTIONS OF EXTREME WAVE HEIGHTS AT THE WAVE ENERGY TEST SITE, HAWAII

Ning Li[1]
Hawaii Natural Energy Institute
University of Hawaii at Manoa
Honolulu, HI, USA

Kwok Fai Cheung
Department of Ocean & Resources Engineering
University of Hawaii at Manoa
Honolulu, HI, USA

Patrick Cross
Hawaii Natural Energy Institute
University of Hawaii at Manoa
Honolulu, HI, USA

[1]Corresponding author: ningli@hawaii.com

INTRODUCTION

Hawaii has a complex wave climate due to its mid-Pacific location and massive archipelago. Figure 1 illustrates the main wave regimes around the Hawaiian Islands. Extratropical storms near the Kuril and Aleutian Islands generate swells toward Hawaii from the northwest to north during the boreal winter. The year-round Southern Hemisphere Westerlies augmented by mid-latitude cyclones in the summer bring modest swells to south-facing shores. Persistent trade winds generate waves from the northeast to east throughout the year, while subtropical cyclones during the winter and passing cold fronts can generate wind swells from all directions. The steep volcanic islands modulate the wind fields to create regional wave patterns with large spatial variation. WETS, strategically located off the east shore of Oahu, is subject to persistent trade wind waves and intermittent north swells with wave power reaching 160 kW/m, but is sheltered from the most energetic northwest swells and the year round south swells by headlands. Despite the favorable wave conditions for testing of WECs, the site is also subject to tropical and subtropical cyclones, and passing cold fronts, which may generate severe seas, requiring survival analysis for the devices.

Two waverider buoys, NDBC #51207 and #51210 deployed in 2012 and 2016 respectively, have recorded the seasonal variations of wave conditions at WETS, albeit with occasional downtime. However, the 5-year duration of records is insufficient for quantification of extreme events. Other buoys have provided long-term in-situ wave measurements at strategic offshore and nearshore locations along the Hawaiian Islands, but they are limited to discrete locations and their records might not be representative of the semi-sheltered WETS. A detailed description of the complex wave climate and extreme events in support of operations and survivability analysis at WETS is, therefore, best accomplished by numerical modeling.

We assembled a spectral wave model system to produce a global and Hawaii regional hindcast dataset from February 1979 to May 2013 that was validated with buoy and satellite observations [1]. The hindcast, which captures extreme wave events albeit with slight underestimations at their peaks, provides a baseline for probabilistic analysis of waves generated by extra-tropical and subtropical cyclones, trade winds, and cold fronts. The waves generated by tropical cyclones can also be hazardous. However, their historical records are limited over the vast expanse of Hawaii waters, despite their more frequent occurrences in the recent years. Probabilistic studies, which require a large sample of hurricane events,

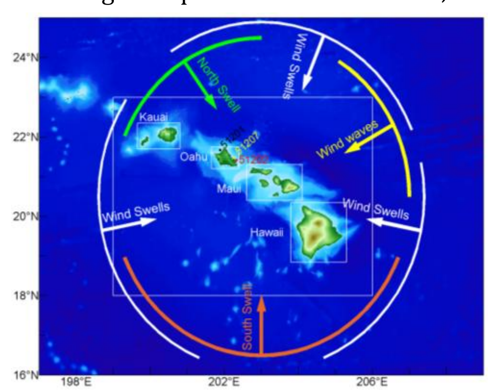

FIGURE 1. HAWAII WAVE CLIMATE, LOCATIONS FOR BUOYS AROUND OAHU. RECTANGLES DELINEATE MODEL COVERAGES.

typically rely on synthetic tracks and intensity from historical records [2]. Climate model downscaling provides an effective approach to develop a scenario dataset representative of the location and frequency of hurricane activities. We utilize the simulated events in the wave model system to produce a set of hurricane wave events to complement the probabilistic analysis for WEC design.

WAVE MODEL SYSTEM AND HINDCAST DATASET

We have built a wave hindcast system from the 3rd generation spectral models, WAVEWATCH III [3] and SWAN [4], on a hierarchy of nested grids with increased spatial and temporal resolution from the globe to the island shores. Figure 1 shows the coupled Hawaii WAVEWATCH III grid within the global grid and the nested SWAN grids for the major islands or island groups. High quality global and regional wind data is crucial for modeling the multi-modal seas in Hawaii. The NOAA NCEP Climate Forecast System Reanalysis (CFSR) produces assimilated surface winds at 0.5° resolution around globe from 1979 to 2011 and 0.205° afterward that provides the boundary conditions for downscaling of Hawaii regional winds by the Weather Research and Forecasting (WRF) model [1]. Both the global CFSR and the high-resolution WRF winds are concatenated to provide input for the coupled global and Hawaii WAVEWATCH III hindcast. The model output includes significant wave height, peak wave period, and peak direction at each grid point and wave spectra at buoy locations and along boundaries of the SWAN grids for subsequent analysis. The nesting of SWAN in WAVEWATCH III produces higher resolution wave conditions over the shallow insular shelves and reefs of Hawaii.

With thorough validation by measurements from offshore and nearshore buoys as well as satellite altimeters, the hindcast allows characterization of interannual and long-term wave climate as well as spatial variation of the wave conditions across the Hawaiian islands [1]. The dataset provides a good description of the prevailing wave conditions, but tends to underestimate the peak of extreme conditions due to limited resolution of the wind forcing in the atmospheric model and the lack of a diffraction scheme in the wave models to physically propagate wave energy into sheltered regions [1]. For instance, the maximum wave height at the Mukapu buoy (NDBC 51207) immediately to the east of WETS is 5.9 m from the hindcast over a 13-year period from 2000 to 2013, which is 0.6 m (10%) less than the measurement. The underestimation could increase in more sheltered regions to the west, where WETS is located. Therefore, a safety factor is needed when considering extreme wave heights in the design of WECs to be deployed at WETS.

PROBABILISTIC DISTRIBUTIONS OF WIND WAVES, WIND SWELLS, AND SWELLS

The long-term hindcast covers wave events of various sources for probabilistic analysis of extreme wave events to define design conditions based on risk levels accepted by WEC developers. The various ocean conditions at WETS, from wind waves to swells, have unique ranges of wave heights and peak periods, as well as recurrence probabilities. This requires separate probabilistic analyses for the respective extreme value (EV) distributions. We could retrieve the wave heights for the components by partitioning the 2D spectra. However, the sea state in Hawaii is always multi-modal. The more effective approach is to sort the hindcasted significant wave height based on the peak period into the groups of wind waves (<10 s), wind swells (10-14 s), and swells (>14 s) to identify the dominant component while retaining the total energy level of the mixed sea state. We selected the annual maximum significant wave height for each group rather than the peaks over a threshold for the EV distribution to minimize the bias introduced by inter-annual climate cycles. The annual maxima of each group provide the input to populate the EV distribution through the Weibull function in the MATLAB stats toolbox.

This analysis considers the innermost and outermost berths at WETS, which are located at 30- and 80-m depth with varying exposure to ocean waves. Figures 2(a) and (b) show the probabilistic distributions of the significant wave height. Despite the outliers for the swell and wind swell events, the EV distributions fit the occurrence frequencies of the annual maximum

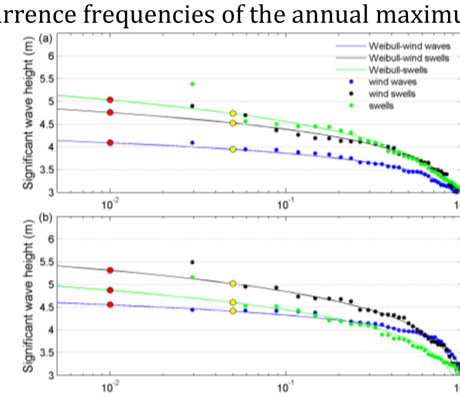

FIGURE 2. EXTREMAL DISTRIBUTIONS FOR WIND WAVES (BLUE), WIND SWELLS (BLACK), AND SWELLS (GREEN) AT (A) THE 30-M BERTH AND (B) THE 80-M BERTH. DOTS DENOTE RANKED ANNUAL MAXIMA FROM THE WAVE HINDCAST, LINES ARE THE WEIBULL DISTRIBUTIONS, AND YELLOW AND RED CIRCLES ARE 20- AND 100-YEAR EVENTS.

wave height reasonably well. At the 30-m berth, the swell events are most energetic with significant wave heights reaching 4.8 and 5.1 m for annual exceedance probabilities of 0.05 and 0.01, equivalent to 20- and 100-year return periods. The wind waves have the lowest energy level with wave heights of 4.0 and 4.1 m for the 20- and 100-year events. The wind swells, which are usually associated with mesoscale weathers such as cold fronts and subtropical cyclones, have wave heights of 4.5 and 4.8 for the 20- and 100-year events. Such waves, generated by strong winds under extreme local weathers, can surpass the energy level of swells reaching 5.0 and 5.3 m over 20- and 100- year periods at the 80-m berth. The heights of wind waves and swells are about 0.5 m larger and 0.2 m lower than those at the 30-m berth for both 20- and 100-year events. This illustrates the local variation of wave conditions over a small region within WETS due to the complex bathymetry and coastlines.

PROBABILISTIC DISTRIBUTION OF HURRICANE WAVES

Besides extreme waves from distant extratropical and local subtropical cyclones, WETS is also subject to severe seas generated by tropical cyclones approaching from the east and south. The waverider buoy at 80 m water depth recorded a maximum significant wave height of 4.4 m when Hurricane Lester passed within 180 km of the site in 2016. A direct landfall or a closer approach would produce much more severe wave conditions, putting the WECs at risk. This points to the need for survivability analysis associated with hurricane waves during the design of WECs to be deployed at WETS.

There is an insufficient number of recorded tropical cyclones in the past 50 years for probabilistic analysis, despite more frequent occurrences in recent years. Numerical simulations can provide synthetic hurricane events that represents regional weather conditions. Global climate models, when forced by historical greenhouse gas concentrations, can describe synoptic weather patterns for downscaling of hurricanes using a stochastic-deterministic approach [5]. We utilize 50 downscaling simulations from the NCAR-CCSM4 model over the North Central Pacific for the 1980-1999 period. This quasi 1000-year dataset includes 2436 simulated hurricane events [6]. The pattern follows the historical records with general migration from east to west and severe landfalls from north-tracking hurricanes. Among the simulated hurricanes, there are 252 events with category-1 strength or above when passing within 200 km of WETS that might produce hazardous wave conditions at the site. These events, as shown in Figure 3, have radius of maximum winds, central pressure, and maximum wind speed from 19 to 70 km, 945 to 999 hPa, and 29 to to 69 m/s respectively at the nearest approach to WETS. The 252 events provide an adequate coverage of hurricane scenarios for detailed modeling of storm waves at WETS [6].

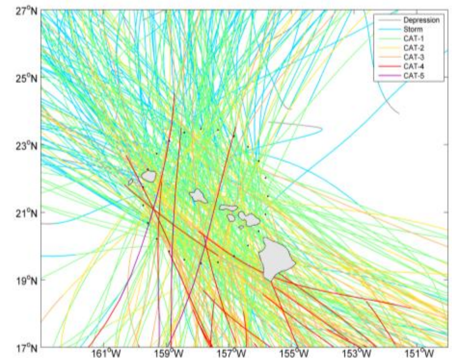

FIGURE 3. SIMULATED HURRICANE EVENTS PASSING WITHIN 200 KM OF WETS (INSIDE THE DOTTED CIRCLE).

A parametric hurricane model defines the wind forcing from the track, the maximum sustained wind speed, and the radius of maximum winds for the 252 selected hurricane events. Implementation of WAVEWATCH III with nested Hawaii and Oahu grids provided the corresponding wave conditions [6]. The modeled results cover severe hurricane wave conditions at

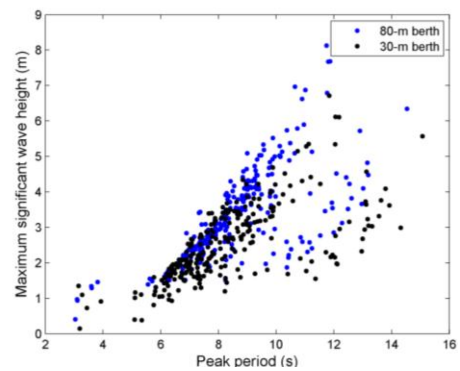

FIGURE 4. MAXIMUM SIGNIFICANT WAVE HEIGHT VERSUS THE PEAK PERIOD AT WETS FOR THE 252 SELECTED HURRICANE EVENTS.

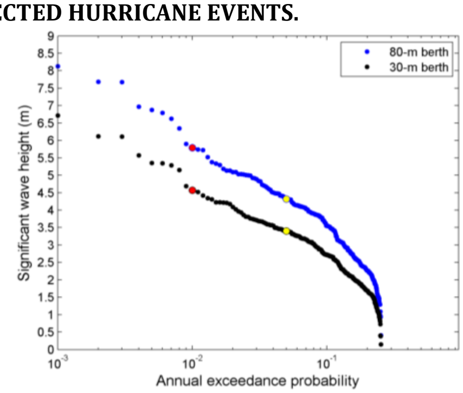

FIGURE 5. PROBABILISTIC DISTRIBUTIONS OF HURRICANE WAVE HEIGHT AT THE 30- AND 80-M BERTHS.

WETS over a quasi-1000-year period and provide a dataset for probabilistic analysis. Figure 4 plots the maximum significant wave height versus the peak period for each event at the 30- and 80-m berths. The scatter plot shows a clear breaking limit at both sites associated with wave steepness. The spreading alludes to the competing influence of factors such as hurricane intensity, size, and approach as well as their relative distance from the site. Figure 5 plots the significant wave height as a function of the annual exceedance probability. The 20- and 100-year wave heights are 4.4 and 5.8 m at the 80-m berth and decrease to 3.4 and 4.6 m at the 30-m berth due to sheltering by a small island to the east. Fortuitously, the 4.4 m wave height for the 20-year return period at 80-m berth is the same as that recorded at the 80-m waverider buoy from Hurricane Lester in 2016. The wave height is lower than that of the wind swells for the same 20-year return period obtained from the hindcast. However, the 100-year hurricane wave height is much larger than those in other sources. This indicates the high risk level posed by hurricanes on infrastructure over a long return period.

DISCUSSION AND CONCLUSIONS

The wave hindcast from 1979 to 2013 provides a basis for extreme-value analyses of commonly occurring wave conditions at WETS. Those include wind waves, wind swells, and distant swells with unique peak period ranges. Infrequent tropical cyclones can also produce hazardous seas posing a risk to the WECs at WETS. We utilized 50 downscaling simulations from the global climate model NCAR-CCSM4 for the 1980-1999 period to assemble a quasi 1000-year hurricane dataset. Hurricanes of Category 1 or above, passing within 200 km of the site, are selected for detailed wave modeling to define a probabilistic distribution of wave height.

The probabilistic analyses of hindcast and simulated wave data at the 30- and 80-m berths provide full coverage of the extreme wave conditions at WETS. Table 1 summarizes the design wave conditions at both sites. Swells are the most energetic at the 30-m berth for both 20- and 100-year return periods. The respective heights are smaller at the 80-m berth due to the more sheltered location by the headlands to the north. The same berth, however, is more exposed to local weather conditions. Wind swells associated with subtropical cyclones and cold fronts become the strongest for the 20-year return period, while hurricane waves are the most severe at the longer 100-year return period due to their low occurrence and yet strong localized impact. The extreme wave conditions for each component in the multi-modal sea state provide a baseline for WEC design and berth selection at WETS. A safety factor is still needed in their design due to potential underestimation of the input wind forcing during extreme weather events and the lack of diffraction in the numerical wave models. This potential underestimation during specific events and the joint probability of various wave components are areas of future WETS research.

TABLE 1. THE EXTREME WAVE HEIGHTS (M) AT 30- AND 80-M BERTHS.

	30-m berth		80-m berth	
	20yr	100yr	20yr	100yr
Wind waves	4.0	4.1	4.4	4.6
wind swells	4.5	4.8	5.0	5.3
Swells	4.8	5.1	4.6	4.9
Hurricane waves	3.4	4.6	4.3	5.8

ACKNOWLEDGEMENTS

NAVFAC provided support through contract no. N00024-08-D-6323 via the Applied Research Laboratory at the University of Hawaii. Kerry Emanuel provided the 50 downscaling simulations of the NCAR-CCSM model. We also thank Luis Vega for his comments on the paper.

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