WAVE TRANSFORMATION, PREDICTION, AND ANALYSIS AT KAUMALAPAU HARBOR, LANAI, HAWAII

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1. INTRODUCTION[1]

Assessing the wave climate at a project site is imperative to both design and post-construction monitoring of a navigation project, particularly when coastal structures are being employed to attenuate wave impact on calling vessels and navigation project features. At Kaumalapau Harbor, wave data was collected prior to breakwater repair to aid in design, as well as part of the monitoring program to aid in assessment of wave impact on the completed structure and post-construction wave conditions at the barge pier.

Kaumalapau Harbor is a small barge harbor located on the southwest coast of the Island of Lanai, Hawaii (Figures 1a and 1b). The harbor is located in a small embayment providing a 10-acre berthing area with water depths of 20 to 60 feet (ft). Kaumalapau Harbor is Lanai's only commercial harbor and provides the only deep-water access point to the island. A breakwater was constructed in the 1920s extending toward the south from the northwest headland of the embayment. Shore side facilities on the north side of the embayment in the lee of the breakwater include a 400-ft-long pier, operations buildings, and barge loading and unloading equipment. In 1992, Hurricane Iniki damaged the breakwater badly; the deteriorated condition of the breakwater permitted significant wave energy to reach the pier, resulting in berthed vessel motion that rendered cargo handling and fuel offloading difficult, and at times hazardous or impossible.

Repair of the breakwater was completed by the US Army Corps of Engineers (USACE) Honolulu District in July 2007. The design of the new breakwater incorporated 1-layer of 35-ton CORE-LOC® concrete armor units to be placed in deep water (up to 70 ft deep near the structure toe), using the existing structure's approximate footprint and stone material as the foundation and core of the new breakwater (Figure 2). The breakwater was designed to withstand hurricane waves up to 35 ft in height. The intent of the repaired structure was to reduce wave action in the harbor, and increase harbor safety and usability.

Post-construction monitoring of the breakwater was completed between 2007 – 2010 as part of the USACE Monitoring of Completed Navigation Projects (MCNP) Program, administered by

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[1] Contents of this paper are largely extracted from Podoski and Smith (2011), in publication.

the Engineering Research and Development Center. The monitoring program collected data intended to further knowledge on concrete armor unit strength, movement and potential damage to the armor layer and concrete cap in the initial years following construction, breakwater toe stability, and the post-construction wave climate at the navigation project.

This paper focuses on the data collection and analysis completed in order to quantify the post-construction wave climate at the harbor. Specifically, the intent of this portion of the monitoring was to determine the wave environment incident to the repaired breakwater and any correlation with observed structure movement/damage as well as the wave conditions at the barge pier, and the relative improvement in mooring conditions compared to pre-project conditions.

Discussion of wave data collection methods, wave transformation models, offshore to nearshore correlation methods, and calculated wave conditions within and around the harbor will be discussed, as well as the insights this has provided to the post-construction monitoring program.

2. WAVE DATA COLLECTION

Four general wave types typically characterize the wave climate in Hawaii. These are easterly trade wind waves, South Pacific (southern) swell, North Pacific swell, and Kona wind waves. The direction of approach of trade wind waves normally varies between NNE clockwise to ESE in accord with the winds that generate them. Very little, if any, trade wind wave energy reaches Kaumalapau Harbor due to its location on the west central coast of Lanai. Strong storms in the southern hemisphere generate waves that propagate into the central Pacific, regularly reaching exposed Hawaiian Island shores as long-period swell during summer months in the northern hemisphere. Depending on the position and track of southern hemisphere storms, south swells approach the Hawaiian Islands from the southeast (SE) through the southwest (SW). Kaumalapau Harbor is directly exposed to wave energy from the south through southwest.

The project site is partially sheltered from North Pacific swell primarily by the Island of Molokai and to some extent by Maui, Oahu, Kauai and Lanai itself. The degree of sheltering is heavily dependent upon the direction of approach. During a due North swell, Kaumalapau Harbor is almost completely shadowed by Molokai, while during a W-NW swell, a significant amount of energy can refract around Oahu and Kauai resulting in an almost direct approach toward the harbor. Upper level subtropical cyclones that form near the islands and cause high winds and waves to approach from the southeast through southwest are known as Kona storm waves. These events are relatively infrequent, typically occurring every few years. The project site is directly exposed to Kona storm waves.

Waves from tropical storms and hurricanes are less frequent, as these storms typically pass to the south or dissipate before reaching the island chain. However, the occurrence of a handful of very damaging hurricanes over the past several decades (including Hurricane Iniki as previously mentioned) require that they be considered as part of the wave climate.

A Datawell Waverider buoy, located approximately 1 mile west of the harbor in 650 feet depth was deployed in May 2007 as part of the monitoring program by the Coastal Data Information Program (CDIP), see Figure 3. The wave data recorded since deployment of the buoy includes waves from the northwest (315 True North (TN)) counter-clockwise through south-southeast (158 TN), with the majority of waves arriving from south-southwest (32%) and south (30%). Typical wave periods range from 8 to 20 seconds, with the majority of long period swell energy coming from the southwest, and some to some extent from the northwest. A wave height rose and wave period rose for the buoy are shown in Figures 4a and 4b. Figure 5 is a time-series plot of significant wave height (reported as H_{m0}, the spectral estimate of significant wave height) over the entire period of record, with some data gaps due to periodic instrumentation failure. The largest wave event recorded at the buoy occurred in December 2007 with a maximum significant wave height of 14 ft, a typical wave period of 8.3 seconds, and wave directions from southwest. This event was a Kona storm. The time-series plot also shows that during the period of record, several Kona storms, south swell events and west-northwest swell events were recorded at the buoy. No hurricanes or tropical storms have occurred near the islands during the post-construction period.

Also in support of the MCNP Program, the University of Hawaii's Department of Oceanography deployed two bottom-mounted, non-directional pressure sensor wave gages in and near the harbor in the months immediately following construction completion (Figure 6). The interior wave gage was located in the lee of the breakwater adjacent to the barge pier (in a water depth of approximately 27 feet), to determine typical mooring conditions and obtain a "lower bound" of incident wave energy since this is the most sheltered location within the harbor. This gage was active between July 2007 and September 2008, with a 6 week data gap in September through October 2007. The exterior wave gage was located near the entrance to the harbor at a depth of roughly 49 feet. The exterior gage was active from October 2007 through early November 2008.

Comparison of this nearshore wave gage data with the offshore wave buoy data during the same time periods shows the correlation between the amount of wave energy that is observed at the buoy versus that which reaches the entrance of the harbor and that which diffracts around the breakwater toward the barge pier. This comparison is completed through use of the amplification factor, A', defined as ratio of the local wave height (H_i) to the incident wave height measured at the offshore wave buoy (H_o).

$$A' = \frac{H_i}{H_o} \tag{1}$$

This calculation of wave height amplification factor between both the interior and exterior gages and the offshore buoy was completed for the peak of four selected wave events, a Kona storm, a south swell, and two back to back W-NW swells (Table 1). Though this value of A' represents only the amplification factor at the peak of the storms, a calculation of A' at various times over the duration of each event showed that these values are representative of the average amplification factor during the storm. Comparison of the amplification factors illustrates both the dependence of wave conditions at the harbor on deepwater wave period and direction. At the entrance of the harbor, the wave events that approach the harbor from the most direct angle (the Kona storm and W-NW Swells) are most efficient at maintaining wave height, as evidenced by the larger values of A'. At the interior gage adjacent to the barge pier, the long-period wave events (south swell and W-NW events to a lesser degree) diffract most efficiently around the breakwater and into the harbor.

Finally, a portable, directional wave buoy was deployed at various locations around the harbor entrance and barge pier on December 5, 2008 by Sea Engineering, Inc. (Sea Engineering, Inc. and Group 70 International 2009). The free-floating buoy (a Datawell DWR-G4) is designed for short-term data collection and it is required that the buoy be observed during deployment by a trailing watercraft since there is no mooring. This instrument was chosen for the additional wave measurements because of its ability to measure multiple incident wave directions and frequencies as well as reflected wave energy, making it ideal for measurements of complicated wave conditions in the nearshore and within a harbor. The wave conditions in the islands during the deployment were dominated by a relatively mild northwest swell, with wave conditions at CDIP 146 ranging from 3.7 ft to 4.3 ft with periods of 13 sec - 15 sec and direction between 270° and 290°. Deployment locations included areas coinciding with wave gage locations, as well as other areas of interest along the barge pier and oceanward of the breakwater. This buoy deployment captured the complex wave spectrum at each of the measurement locations resulting from incident wave energy, as well as the effects of diffraction and reflected wave energy from the breakwater, barge pier, and the steep and rocky interior harbor shoreline.

3. WIS HINDCAST DATA

USACE maintains a wave database generated from a 24-year Pacific Basin hindcasting effort associated with the Wave Information Studies (WIS) initiated in 1976. Parametric wave information such as significant wave height (H_{m0}), peak period (T_p), and peak direction (D_p) are provided for predetermined save points beginning January 1981 and ending December 2004. WIS hindcast save points near Kaumalapau (WIS113, WIS114, WIS115, and WIS116) are shown in Figure 7, along with the National Oceanographic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) buoy 51027.

Selection of a single WIS location dataset for use was necessary to accurately quantify frequency of occurrence of a particular wave condition. WIS116 was selected based on an analysis of agreement with historical buoy data in the nearby area.

A threshold frequency of occurrence of 0.2 percent was established as criteria for selection of a particular wave condition for higher resolution modeling. Any wave condition within a pre-defined wave window with a frequency of occurrence exceeding this value became an incident condition or ”case” to be evaluated in higher resolution modeling, and anything below this was filtered out. This resulted in 122 unique wave cases being selected for wave transformation modeling. Fifteen additional cases were included in the model runs to augment those determined during WIS116 analysis with cases of particular interest and those known to occur frequently. These cases included smaller long-period south swell (8 cases), hurricane conditions (4 cases), and Kona wind waves (3 cases).

4. WAVE TRANSFORMATION MODELING AND VALIDATION

Simulating Waves Nearshore (SWAN) is a third generation wind wave model developed at the Delft University of Technology (2011). SWAN was used to transform incident wave cases at the deepwater model boundaries to intermediate/shallow water near Kaumalapau Harbor. The model was set up to run in stationary mode, meaning that the incident wave conditions are not time dependent. Computational resolution was set at 18 seconds, or approximately 500 m. Bathymetric resolution was set higher (1 sec) to ensure that the interpolated depth at the computational grid point was as accurate as possible. Bathymetry for the domain was compiled from the 1-minute General Bathymetric Charts of the Oceans, Scanning Hydrographic Operational Airborne LiDAR Survey (SHOALS), USGS 5-sec, EROS Data Center, and the National Elevation 10-m topographic grid datasets.

Validation of the SWAN model results was performed using forecast wave model data as the model boundary condition during the period from 18 August 2007 to 28 October 2007, since WIS hindcasts are not available for this time period. This forecast model includes a global wave model, Hawaii wave model, and separate nearshore domains for Kauai, Oahu, Maui, and the Big Island (The Maui domain including Kaumalapau Harbor is also shown in Figure 7.). The global wave model is a duplicate of NOAA's Wavewatch3 (NWW3) operational forecast model. The Hawaii model is a nested regional implementation of NWW3. The individual nearshore domains utilize SWAN, and are nested within the Hawaii Domain. For this period, output data from the forecast model was compared to the existing CDIP 146 buoy data in order to obtain performance indices. The VBL01 H_{m0} performance indices include a Mean Error of -0.13m, Root Mean Square Error of 0.2m and Scatter Index of 0.24.

Parametric output wave data from the SWAN model was obtained at three locations, VBL01, VBL02, and VBL03 (Figure 8). VBL01 is co-located with the CDIP 146 buoy (also known as NDBC 51203) in order to facilitate performance analysis and lookup table development. VBL02 is located directly in the entrance of the harbor, and VBL03 is located approximately 0.1 nautical miles (nm) west of the harbor entrance, and was used to provide boundary conditions to subsequent Refraction/Diffraction (REF/DIF) modeling. Incident wave conditions from each case derived from the WIS116 analysis (and supplementary wave cases added) were applied uniformly across each boundary of the SWAN model. Based on the results of the tradewind swell cases, it was determined that it is highly unlikely that tradewinds can produce swell that will impact the harbor. Very small wave heights occur at VBL01 from ~310 deg. The combination of small wave height, short wave period, and oblique approach direction limits incident tradewind wave energy at harbor. Tradewind cases were not brought forward for further analysis.

REF/DIF1 version 2.5, developed by Kirby and Dalrymple (1994), was used to transform SWAN wave output to points in and near the harbor, utilizing a smaller, higher resolution domain focused on the harbor area. This nonlinear model includes processes of wave refraction, diffraction, shoaling, and energy dissipation. The boundary wave conditions for the model were obtained from SWAN output at VBL03, in a water depth of 107 ft. A mean sea level tide (0.9 ft MLLW) was used for model analyses. The model output was analyzed at eight wave stations (Figure 8): Station W1 was collocated at the SWAN boundary input point VBL03, W2 at the harbor entrance (location of SWAN-VBL02), one station each was located at ocean and harbor sides of the breakwater (W3 and W4, respectively), three were along the barge pier (K01-location of interior wave gage, K02, and K03), and one was at the location where the exterior wave gauge was deployed in May 2007 (W5) as shown in Figure 9.

Validation of the REF/DIF model results was performed by comparing model output to data from a 1998 three-dimensional physical model study performed at ERDC as part of the design phase of the project (Smith, 1998), as well as to wave data from the year-long interior wave gage deployment completed as part of the monitoring program. Data from the exterior wave gage was determined to have some potentially erroneous data, and was not used for model validation. The roving buoy data collection was not yet complete as of the initial validation process, but was subsequently used for additional comparison.

The as-built breakwater most closely resembles the "dogleg breakwater" alternative of the 1998 physical model study. *A'* was calculated for various directions and periods at various "gauge" locations along the barge pier in the study. In a similar manner, amplification factors were developed from the REF/DIF results with H_o at Station W1, and H_i as REF/DIF output points K01, K02, and K03 which are analogous to the study's gauge points 3, 1, and 4 respectively. For periods of 12 seconds, REF/DIF *A'* varies from 0.45 to 0.55 along the pier length, while physical model *A′* varies from 0.60 to 0.75. For periods of 14 seconds, REF/DIF *A′* varies from 0.55 to 0.70 along the pier length, while physical model *A′* varies from 0.65 to 0.80. For periods of 16 seconds, REF/DIF *A′* varies from 0.55 to 0.82 along the pier length, while physical model *A′* varies from 0.60 to 0.82. While REF/DIF seems to predict amplification factors (roughly within 25% of measurements) corresponding to greater wave reduction than that of the model study, this broad comparison is indicative of general agreement between the two modeling methods.

In order to conduct more detailed comparisons of model output to the interior wave gage data, *A'* values at the model output Station K01, were calculated and plotted as a function of T_p (peak wave period) and D_p (peak wave direction), and fitted with a three-dimensional surface as shown in Figure 10. A three-dimensional surface plot of *A'* was also generated for wave data collected at the interior wave gage during the period of 3 Jul 07 – 29 Aug 07. The advantage of this method is that this "predictive surface" allows for interpolative, and to some extent, extrapolative estimates of *A′*.

The difference between predicted and measured *A′* values varied between +0.49 (over predicted) for wave periods between 15 to 20 seconds coming from the south through south-southwest direction (180 – 215 TN) to -0.21 (under predicted) for shorter wave periods (~5-10s) coming from the south (190 TN). The overall difference between the two surfaces is indicative of a general over prediction of *A′* values by the numerical modeling at this location, in contrast with the comparison to the 1998 physical model data presented above. The comparison of modeled to predicted wave height is explored in further detail later in this paper. Due to the phasing of monitoring program funds and the timing of wave data availability, it was not possible to use these results to recalibrate and rerun the model. Rather, the two datasets for station K01 (predicted and partial measured *A′* values) were combined, and a new surface was developed using the combined dataset. The resultant combined surface represents the best estimate of *A′* values at this location. Similarly, predictive surfaces (without augmentation from wave data) were developed for other points in and near the harbor (K02, K03, W2, W3, W4, and W5). These surfaces were used to develop lookup tables that correlate 119 unique wave conditions at the CDIP 146 buoy to predicted conditions at eight locations in and around Kaumalapau Harbor.

Finally, a comparison was made between predicted wave heights and amplification factors based on numerical modeling results with measured wave heights and amplification factors obtained with the roving wave buoy. Results of this comparison are shown in Table 2. The results of this comparison show that the modeled data is capable of providing satisfactory estimates of H_{m0} in and near the harbor, though there is again a consistent positive bias (over prediction of measured data) in the resulting wave heights. In most cases, the prediction was within 0.5ft of the measured H_{m0}. Inclusive of the outlier difference of 1.1ft at K03, errors in predicted wave heights ranged from 0% to 69%, with a mean value of 25%. This comparison also demonstrates that the interior wave conditions exhibit sensitivity to changing input peak period (T_p) conditions and peak direction (D_p). The physical explanation for the directional sensitivity lies in the orientation of the harbor entrance, which faces almost due west. As the deepwater wave direction turns more northerly but wave period remains constant, the pier locations are less exposed to wave energy.

5. KPWAVE PROGRAM

The previously presented wave data from both measured and modeled sources and the resulting predictive surfaces were used to develop a FORTRAN-based program, KPWAVE (Sea Engineering, Inc., 2009), which calculates predicted wave height values at the seven designated locations in and around the harbor (W2, W3, W4, W5, K01, K02 and K03) when given the offshore wave conditions (H_{m0}, T_p, D_p) at the Kaumalapau Buoy (CDIP 146/NDBC 51203). The program also has the capability to read a time series input file of wave parameters produced directly from the CDIP buoy data server website, and create an output file of the corresponding time series at the output locations. The maximum input file size for KPWAVE is one year at 30 minute intervals or 17,520 records.

The three-dimensional predictive surfaces of *A'* (example shown in Figure 10) were developed with a resolution of 0.25 degrees by 0.025 seconds which resulted in a grid with 680 bins for wave period ranging from 3 to 20 seconds and 480 bins for direction ranging from 180 to 300 degrees. The program will filter out any input records that contain a parameter which falls outside these stated limits. A text output file was generated for each of these predictive surface grids and used as a database for the predictive algorithm described in the separate report "KPWAVE: Program Modification and User Manual" (Sea Engineering, Inc., 2009).

The database parameters are transformed into corresponding matrix indices, which identify the coupled A' values for the seven reporting stations listed above. If indices return a value which lies too far outside of the limits of real data used to generate the predictive surface, the resulting A' value will be flagged with the qualified text, "EXTRAPOLATED" to indicate to the user that the value may be less accurate due to extrapolation over sparse data. If input parameters in an input text file exceed range limits, then the flag column will report the string, "OUTOFBOUNDS" and the wave height reporting stations will all be set to '0' for that time step. The output file for the time series implementation of the program consists of a simple text file listing the input date and time, output wave heights at each of the seven reporting stations, and the flag comment (if any) as described above.

6. TIME SERIES ANALYSIS AND RESULTS

As an additional validation, a direct comparison of the wave height time-series between the measured 2007-2008 wave gage data at K01 and the predicted wave height (developed using the CDIP buoy data as input to the KPWAVE program) is shown in Figure 11. This time-series comparison includes the events selected for further analysis in Section 2 and shown in Table 1 as points of reference, namely the Kona storm, the south swell, and W-NW "Swell 1" and "Swell 2" as indicated in the figure.

Figure 11 shows that the KPWAVE-predicted wave height is in good agreement with measured data for the south swell and W-NW Swell 2, however, it is significantly over predicting wave height for the Kona storm condition and W-NW Swell 1. Possible explanations for this over prediction during certain wave conditions are: these specific offshore wave conditions were not adequately represented in the model runs completed to create the lookup table (requiring extrapolation by KPWAVE), the wave transformation model (REF/DIF) does not accurately represent the diffraction occurring in the lee of the breakwater under these conditions, and/or the partial wave gage measurements from K01 that were incorporated into this predictive surface for improvement did not include these conditions. A combination of two or more of these elements is also likely.

Further improvement of the KPWAVE program could be completed with additional measurements, model calibration, and model runs, but for the purposes of the monitoring study, the program is considered an adequate estimation of wave height at the barge pier (K01, K02, and K03) for the south swell condition and the W-NW swell condition with wave directions from approximately 290 degrees or less. These conditions represent the most extreme cases at which the harbor would still be considered operational (i.e. – barges would not be attempting to enter or tie up to the pier during Kona storms or hurricanes). The program is also considered a reasonable estimation of wave height at the location seaward of the breakwater (W3) during all conditions. Though no validation data has been collected at this location, it is assumed that because there are virtually no effects due to diffraction and waves propagate directly from the buoy to this location experiencing only refraction and bottom friction, that the numerical model should be able to predict the wave height at this location reasonably well.

Prediction of the full time-series of wave heights at all seven KPWAVE output locations (W2, W3, W4, W5, K01, K02, and K03 – located as shown in Figure 10) was completed using the 3.75-year CDIP buoy data from May 2007 through December 2010. Examination of the results in the following will focus on the locations adjacent to the barge pier (K01, K02, and K03), in order to evaluate post-construction mooring conditions, as well as the location seaward of the breakwater (W3), in order to evaluate incident wave conditions affecting the repaired breakwater.

Comparison of the wave height time-series derived by the KPWAVE program at the three barge pier locations K01, K02, and K03 shows interesting results. First, it appears that a sizeable wave event (offshore wave height of approximately 6.0 ft or greater) of any type or direction is likely to cause a noticeable response at all locations along the pier. This is evident in the predicted wave heights during the November 2007 South swell, the January 2009 W-NW swell, and the December 2007 Kona storm (even considering positive bias), all of which show a marked increase in wave heights at the barge pier locations. However, during non-swell conditions (approximately 95% of this data sample), the wave heights along the barge pier were less than 3 feet.

Second, the K02 output station shows a greater response to south swell events, while the K03 output station exhibits greater energy during W-NW swell events. This result is likely due to both the sheltering of the breakwater and the overall geometry of the harbor. Since moored barges typically occupy the locations adjacent to both K02 and K03, they can anticipate experiencing waves as high the 3 to 5+ foot range at the pier during long-period W-NW and south swell conditions. Without directional pre-construction wave data at either offshore or harbor locations, it is not possible to make a definitive determination on the possible post-project reduction in wave heights for specific wave conditions; however, based on discussions with harbor users and field observations it is reasonable to conclude that conditions along the barge pier have improved significantly during typical operational conditions (where short-period wave energy was transmitted through the pre-construction breakwater) and moderately during longer period swell events.

The time-series of wave height predicted by KPWAVE at the location W3 represents the incident conditions at the breakwater structure. Typical predicted waves are in the 1.0 to 5.0 foot range, with several occurrences of 6 feet and over each year. The median wave height value is 2.2 ft. The three most extreme predicted wave heights occur in November 2007 (previously identified south swell), December 2007 (previously identified Kona storm), and January 2009 (a W-NW swell) with peak significant wave heights of 9.6 ft, 10.0 ft, and 8.2 ft, respectively.

These extremes are much lower than the breakwater design wave height of approximately 35 feet, due to the fact that the design is based on a hurricane wave, which is not part of the data collected in the May 2007 to December 2010 timeframe. Running KPWAVE with test wave parameters indicates that a deep water wave of 35 feet must occur at the buoy location (with T_p = 12 or 16 sec and θ = 240 deg TN) in order to generate a 35 ft incident wave height at location W3.

7. CONCLUSIONS

The availability of 24 years of hindcast wave data, long-term deep water buoy data for the islands, and medium- as well as short-term wave data sets collected as part of this monitoring program has enabled implementation of three validated wave transformation models (WW3 forecast model, SWAN, and REF/DIF) and development of a wave lookup table in order to correlate offshore buoy data to nearshore wave conditions at Kaumalapau Harbor. Lookup table output has been compared to physical model results conducted during the design phase of the breakwater project as well as compared to short-term wave gage and buoy data in the areas of interest in and around the harbor. Finally, an easy to use computer program has been created which includes a predictive algorithm for relating buoy data to wave heights at the harbor, based on these lookup table results. This program has enabled the calculation of several multi-year time series of estimated incident wave height at the breakwater as well as estimation of wave conditions at locations along the barge pier.

The analysis of calculated wave height time series indicates that the wave response along the barge pier varies in magnitude with location, the type of offshore conditions (swell direction, wave period) as well as the magnitude of particular wave events in terms of wave height. The sheltered location adjacent to the western end of the pier (location K01) remains relatively calm except in the largest wave events where wave heights approach 2.0 to 2.5 feet (according to measured data). This area may be experiencing a significant amount of reflected wave energy from the breakwater, pier and nearby steep and rocky shoreline.

The areas adjacent to the middle and eastern ends of the barge pier experience larger wave heights because they are less sheltered by the breakwater. The location at the middle of the barge pier (K02) appears to respond more often to wave events with a southerly direction, with wave heights in the 3.0 to 4.0-foot range (according to modeled data and excluding events such as the December 2007 Kona storm). In contrast, the location at the eastern end of the barge pier (K03) appears to respond most often to wave events with a west-northwest direction, and is likely also experiencing reflected wave energy during these events. The maximum wave heights at this location are in the 3.5 to 5.5–foot range (according to modeled data and excluding events such as the December 2007 Kona storm). These results at the locations along the barge pier, now protected by the repaired breakwater, indicate that safe mooring and offloading should be possible during all but the most extreme events such as hurricanes, large Kona storms and extreme W-NW or south swells.

The time series of calculated wave heights at the location incident to the breakwater (W3) shows that waves impacting the structure are typically in the 1.0 to 5.0-foot range, with some wind-wave and swell events generating incident waves of almost 10-foot in height. This dataset (developed from available wave observations) indicates that only the most extreme events (hurricanes passing south of the island chain or approaching the islands directly) are likely to generate incident waves approaching the design wave height of 35 feet and thereby threaten armor stability.

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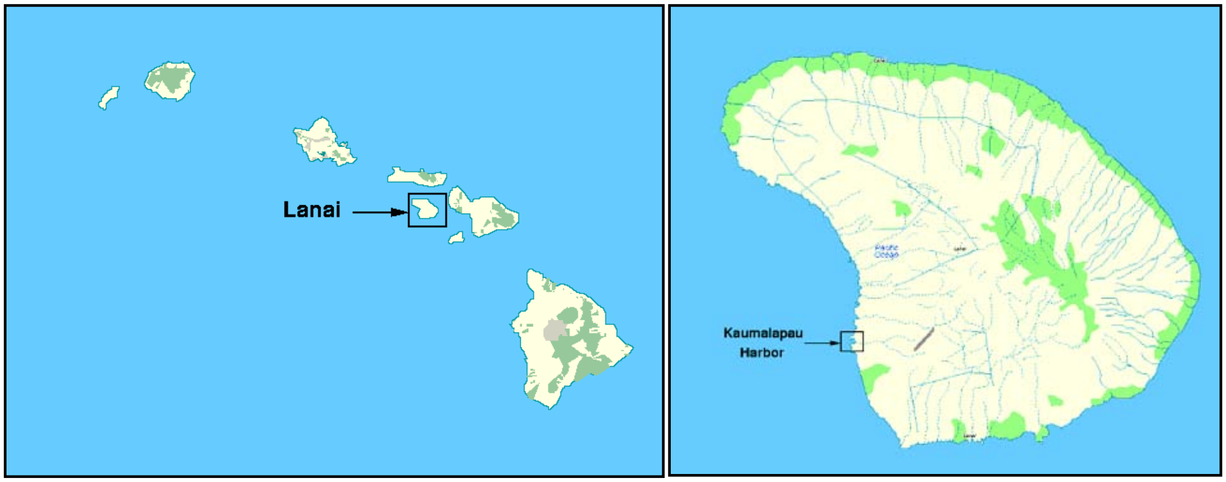


Figurea 1. Location Map of (a) Island of Lanai and (b) Kaumalapau Harbor

Figure 2. Breakwater under Repair at Kaumalapau Harbor.

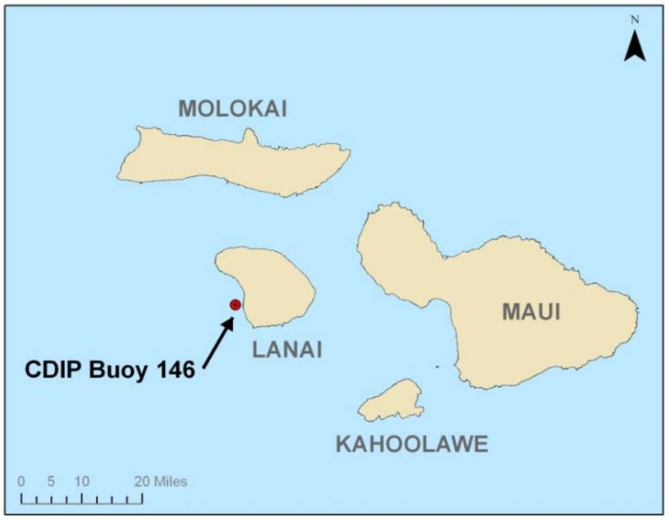


Figure 3. Location of CDIP Buoy 146 1nm West of Harbor.

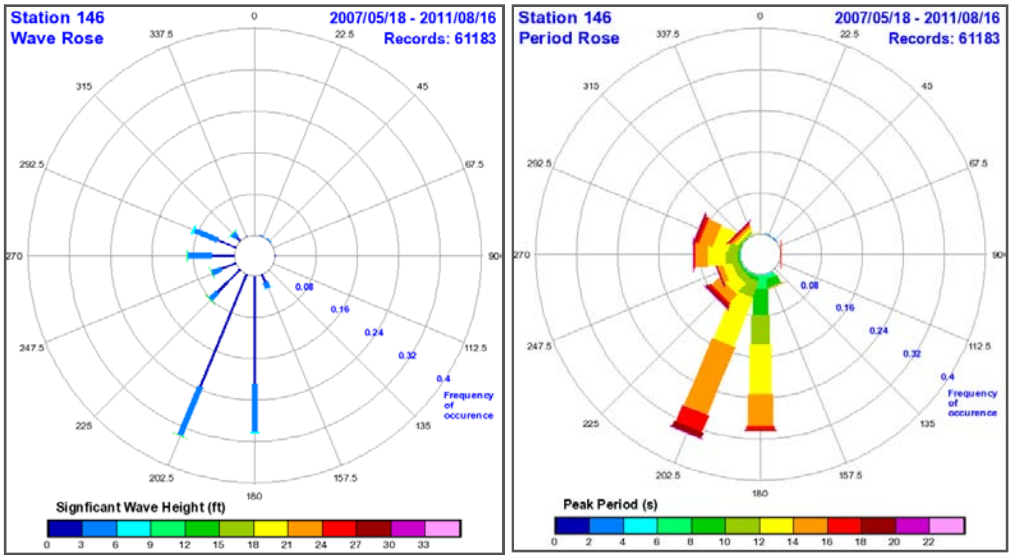


Figure 4. CDIP Buoy 146: (a) Wave Height Rose, (b) Wave Period Rose

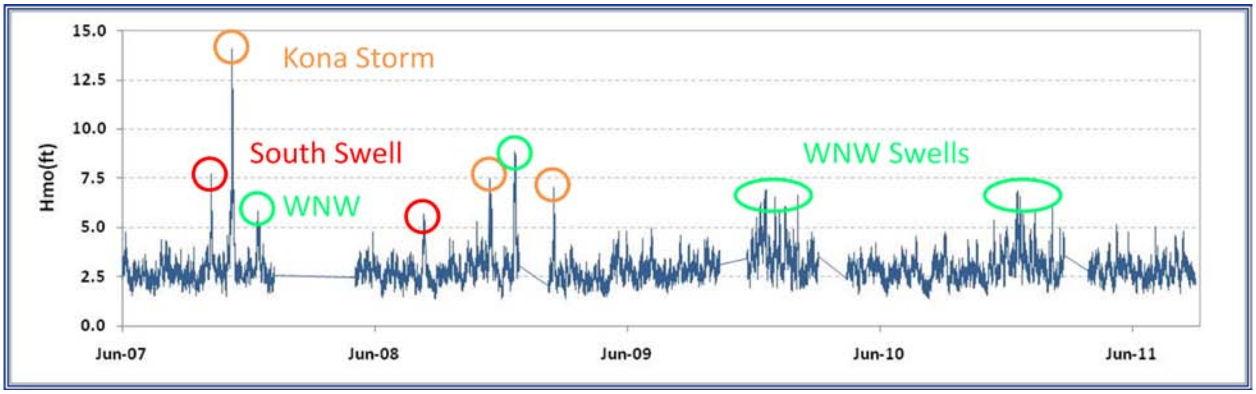


Figure 5. Time-Series of H_{m0} at CDIP Buoy 146 from June 2007 – August 2011

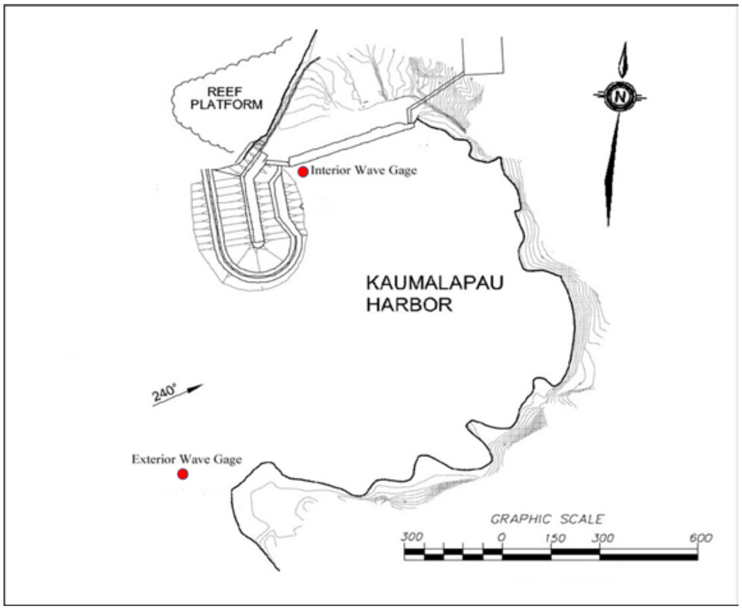


Figure 6. Location of Interior and Exterior Wave Gages at Kaumalapau Harbor.

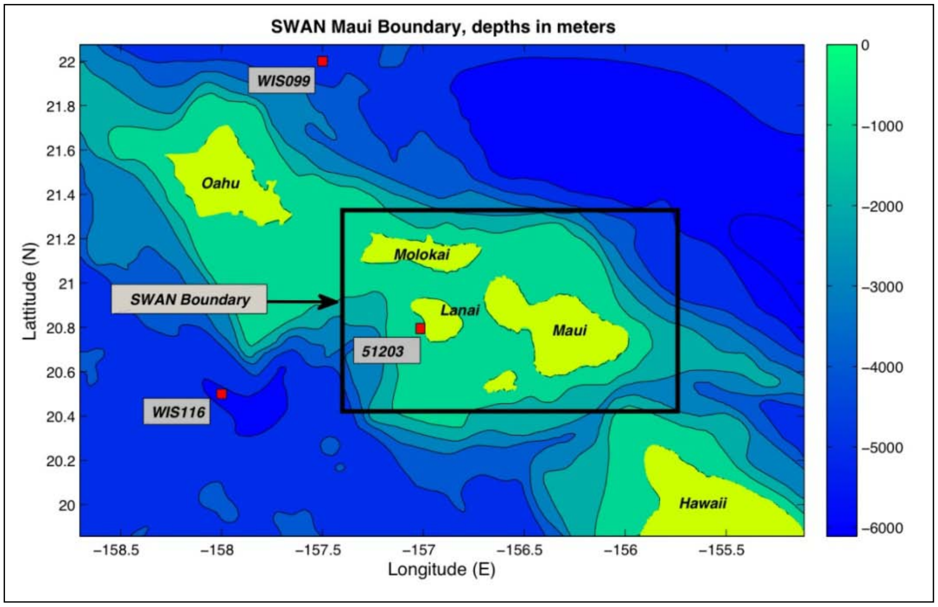


Figure 7. Location of Pacific WIS Station 116 and SWAN Model Domain

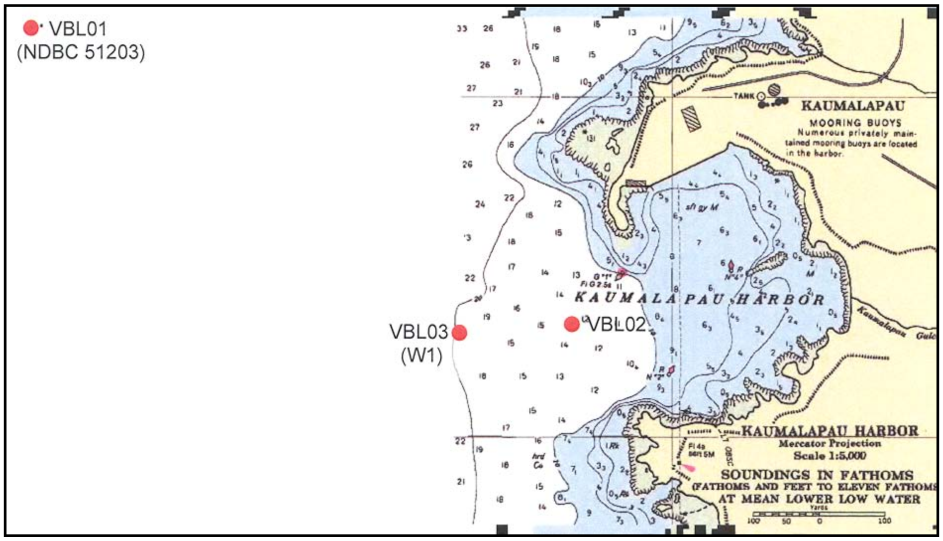


Figure 8. SWAN model output locations.

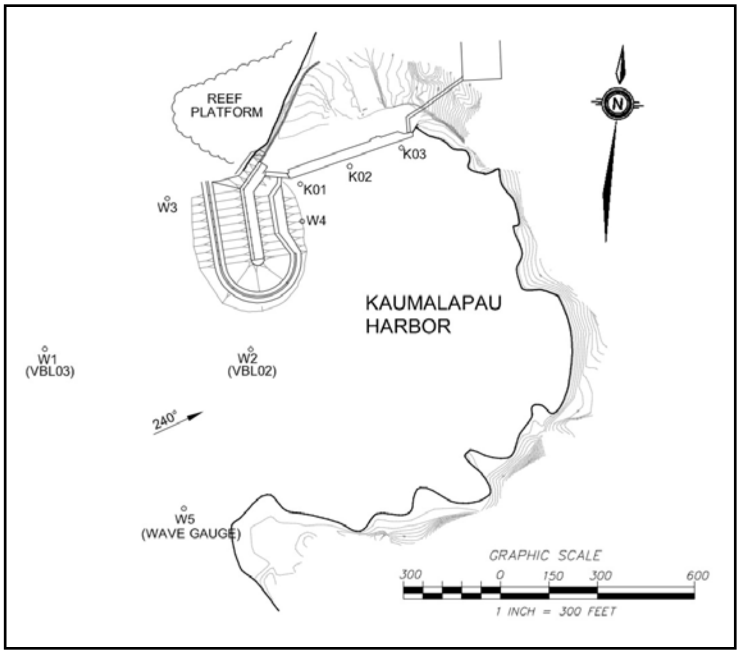


Figure 9. REF/DIF Wave Output Stations

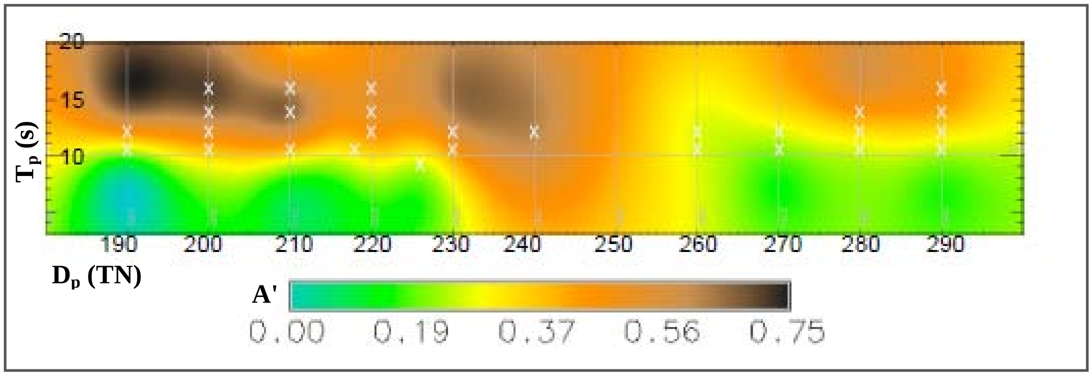


Figure 10. Three-dimensional surface plot of A' at Location K01

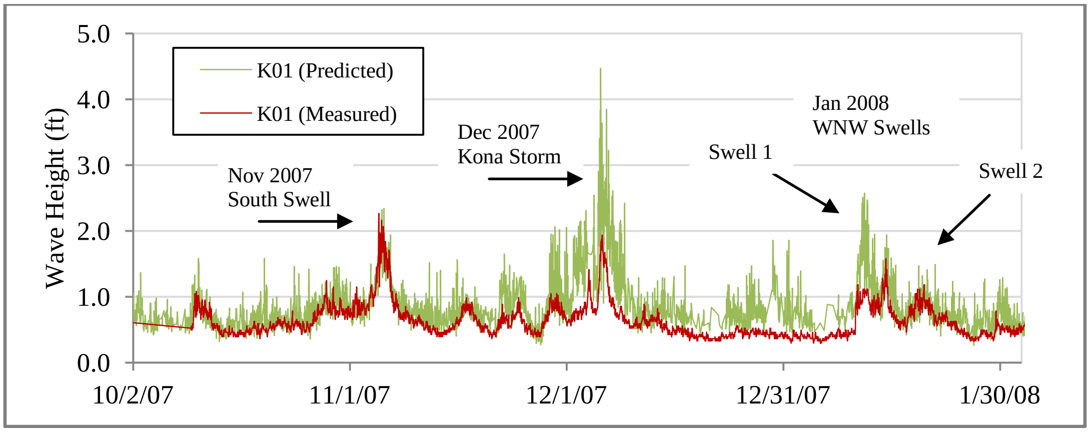
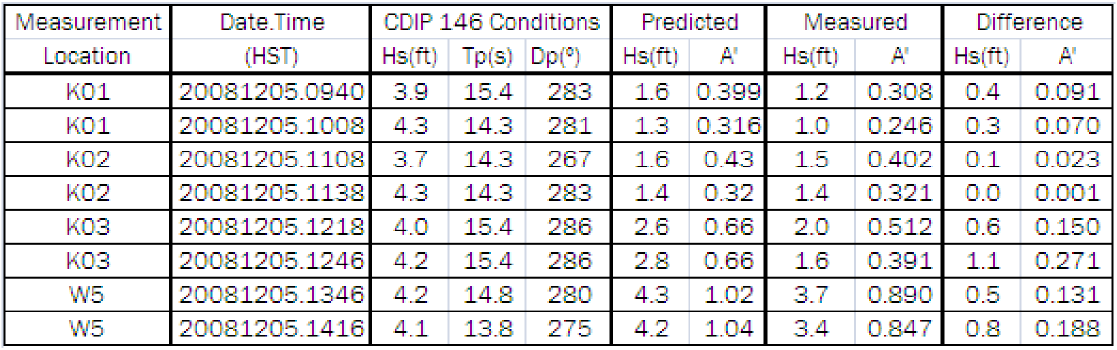


Figure 11. Time-series comparison of Wave Height at K01: Measured gage data (red) and Predicted Wave Heigh from KPWAVE (green)

Storm Event	Buoy H_{m0} (ft)	Buoy T_p (s)	Buoy Dir	Ext. H_{m0} (ft)	Ext. A'	Int. H_{m0} (ft)	Int. A'
Kona Storm (12/07)	14.1	8.3	224 (SW)	9.4	0.67	1.8	0.13
South Swell (11/07)	7.7	16.7	190 (S)	4.3	0.56	2.0	0.26
W-NW Swell 1 (01/08)	5.6	15.4	298 (W-NW)	3.7	0.66	1.1	0.20
W-NW Swell 2 (01/08)	5.0	15.4	281 (W-NW)	5.0	1.00	1.1	0.23

Table 1. Comparison of Peak Wave Height Amplification Factor (A’) at Wave Gages During Selected Wave Events



Measurement	Date.Time	CDIP 146 Conditions			Predicted		Measured		Difference	
Location	(HST)	Hs(ft)	Tp(s)	Dp(°)	Hs(ft)	A'	Hs(ft)	A'	Hs(ft)	A'
K01	20081205.0940	3.9	15.4	283	1.6	0.399	1.2	0.308	0.4	0.091
K01	20081205.1008	4.3	14.3	281	1.3	0.316	1.0	0.246	0.3	0.070
K02	20081205.1108	3.7	14.3	267	1.6	0.43	1.5	0.402	0.1	0.023
K02	20081205.1138	4.3	14.3	283	1.4	0.32	1.4	0.321	0.0	0.001
K03	20081205.1218	4.0	15.4	286	2.6	0.66	2.0	0.512	0.6	0.150
K03	20081205.1246	4.2	15.4	286	2.8	0.66	1.6	0.391	1.1	0.271
W5	20081205.1346	4.2	14.8	280	4.3	1.02	3.7	0.890	0.5	0.131
W5	20081205.1416	4.1	13.8	275	4.2	1.04	3.4	0.847	0.8	0.188

Table 2. Comparison of Measured vs. Predicted Wave Heights and Amplification Factor (A’) for 5 Dec 2008 at Specified Locations