Paper ID #25805

Wave and Circulation Modeling of Infrastructure Installations at Rota Harbor in the Northern Marianna Islands

Dr. Lihwa Lin, U.S. Army Corps of Engineers

Dr. Lin is a Senior Research Civil Engineer in the Coastal and Hydraulics Laboratory at the U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. Dr. Lin earned his master's degree in Ocean Engineering from Oregon State University, and Ph.D. in Civil Engineering from the University of Florida. Dr. Lin is also appointed as adjunct professor at Civil and Environmental Engineering Department, Jackson State University, MS. He offers one of two courses, 'Linear Wave Mechanics and Theory' and 'Ocean Wave Spectral Analysis and Applications' in the fall semester.

Dr. Lin's research interests include field studies, physical and numerical modeling of coastal processes; inlet and navigation channel risk analysis; morphodynamics and sediment transport; coastal engineering project assessment and coastal climate information. Recent works include Dana Point Harbor, Pillar Point Harbor, and Noyo Harbor, CA, Grays Harbor, WA, Matagorda Bay, Corpus Christi Bay, and Galveston Bay, TX, Point Judith Harbor, RI, Cleveland Harbor, OH, Buffalo Harbor, NY, and Hilo Harbor, HI.

Wave and circulation modeling of infrastructure installation at Rota Harbor in Northern Marianna Islands

INTRODUCTION

Rota Harbor is located on the northwest coast of the Rota Island in the US Commonwealth of the Northern Mariana Islands (CNMI), approximately 6,100 km west of Hawaii. Rota Island is small, around 85.5 km^2 above the mean sea level (MSL), 17 km long and 8 km wide with a highest elevation of 500 m on Mt. Manira. Rota harbor was constructed by the US Army Corps of Engineers (USACE) between 1978 and 1985. It lies 60 km northeast of Guam and 110 km southwest of Saipan at 14^o 10' N, 145^o 14' E (Fig. 1). The study area is located on a sandy peninsula, partially surrounded by fringing coral reef. Adjacent to Rota Harbor, the natural reef extends seawards approximately 300 m from the shoreline with depths ranging from 0.5 to 1.5 m. The Harbor consists of an entrance channel of 210 m long, 91 m wide, and 6 m deep; a turning basin of 135 m long, 55 to 122 m wide, and 5 m deep; a revetted mole of 165 m long and 3 m high; a basin extension of 85 m long, 46 m wide and 5 m deep (Fig. 2).

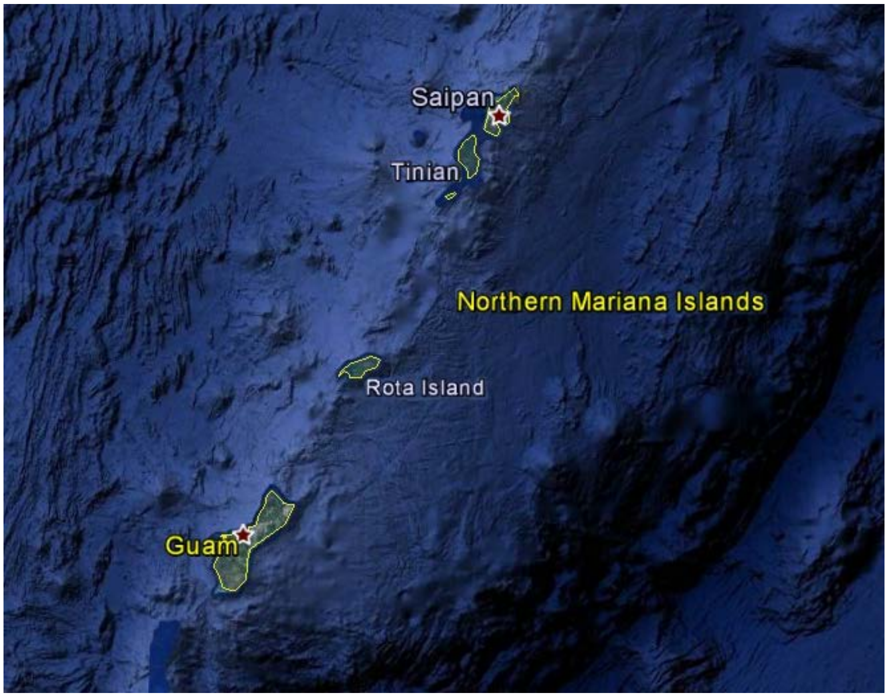

Figure 1. Location map of Rota, Tinian, Guam, and Saipan Islands

A harbor feasibility study for navigation improvements has been underway aiming at efficient and safe passage of waterborne commerce among major islands in the region, including Rota, Saipan, Tinian, and Guam. Because local strong wind wave and current conditions can disrupt navigation and delay port operations, proposed improvements to harbor require a comprehensive analysis of wind waves, water levels, and circulation to determine safety of vessels entering and passing through the channel to access mooring and docking inside the harbor.

The USACE Engineer Research and Development Center (ERDC) and Honolulu District were presently assisting CNMI Government Commonwealth Ports Authority to investigate structural alternatives to improve navigation and provide better protection of Rota Harbor. The numerical modeling effort was conducted to evaluate access, usability and impacts of infrastructure installations for improving future capacity and safer navigation at the harbor.

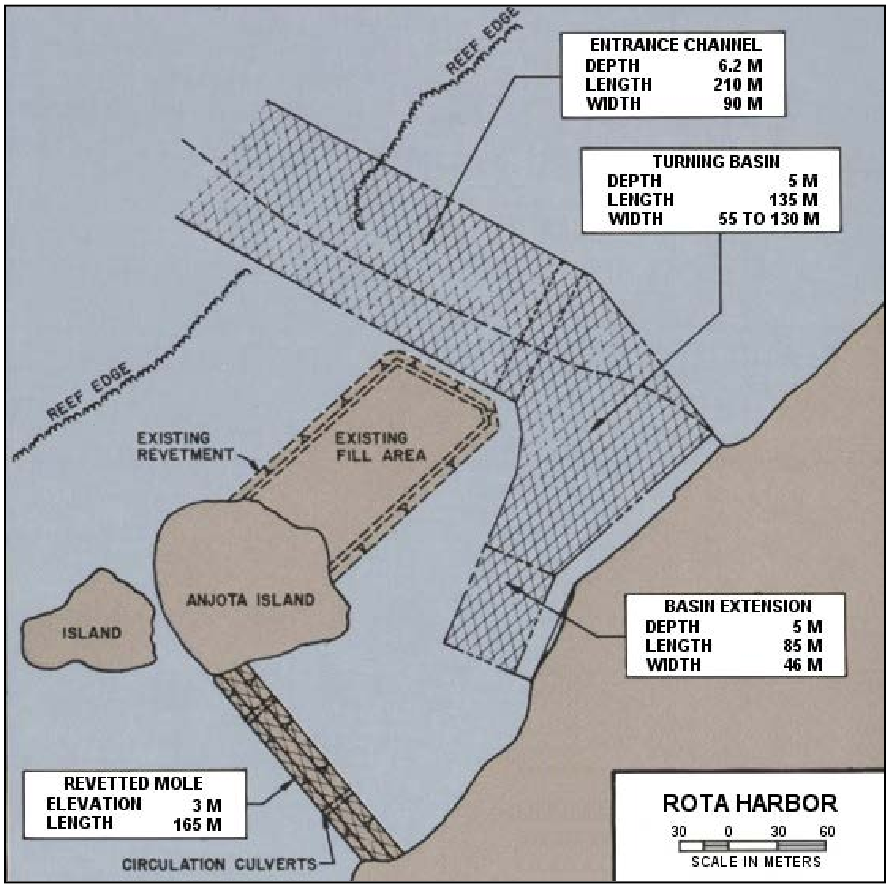

Figure 2. Rota Harbor entrance channel and basin map

INFRASTRUCTURE MODIFICATIONS

Three structural alternatives were proposed for modeling: (1) Alt 1 – a detached shore-parallel breakwater, approximately 75 m long with the crest of 3.25 m above the MSL, just offshore of the existing entrance channel, (2) Alt 2 – an attached north breakwater, approximately 340 m long with the crest of 2 m, MSL, lies primarily on the existing reef adjacent to channel and extend beyond the edge of the reef flat, and (3) Alt 3 – a dogleg breakwater, approximately 445 m, extends Alt 2 seaward and connects to Alt 1. The existing configuration is denoted as Alt 0. Table 1 presents the description of these alternatives. Figure 3 shows the footprint of Alts 0 to 3.

Table 1. A list of four structural alternatives Alts to 3

Alt	Configuration	Features
0	Existing Condition	The present harbor infrastructures
1	A detached breakwater*	A detached shore-parallel breakwater ~ 75 m long, offshore the harbor entrance channel
2	An attached north breakwater*	A north breakwater ~ 340 m long, along the north side of entrance channel
3	Extend Alt 2 breakwater to Alt 1 breakwater	A dogleg breakwater ~ 445 m long, extends Alt 2 seaward and connects to Alt 1
* The crest elevation of breakwater is 3.25 m in Alt 1 and 2 m in Alt 2 above MSL.		

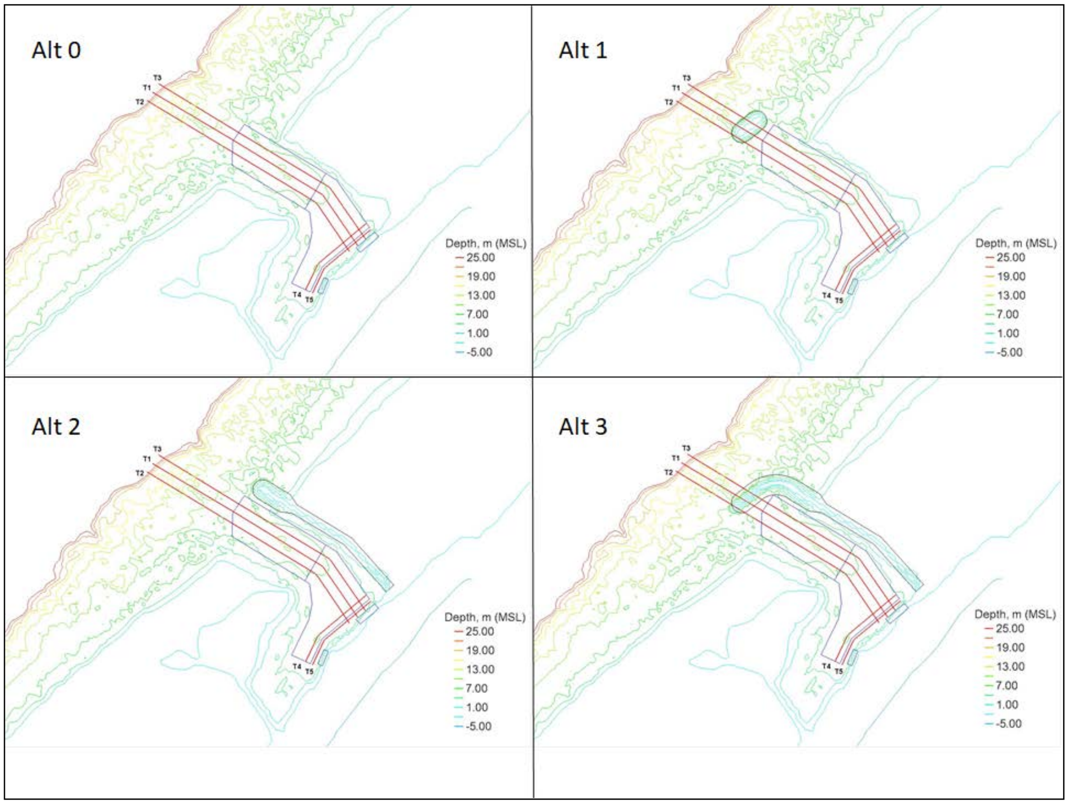

Figure 3. Rota Harbor existing Alt0 and alternatives Alts 1 to 3

BATHYMETRY AND METOCEAN DATA

The harbor interior, navigation channel, and structure data were based on the Honolulu District surveys completed in March 2013 and November 2016. The offshore bathymetry was based on the 5-m (16-ft) grid map from the Pacific Islands Benthic Habitat Mapping Center (www.soest.hawaii.edu/pibhmc/cms/). Coastal and shoreline digital data were extracted from the NGDC database (www.ngdc.noaa.gov/mgg/shorelines/shorelines.html).

Water level and wind measurements are available from NOAA Coastal Stations 1630000 (13o 26’ 30” N, 144o 39’ 12” E) at Apra Harbor and 1631428 (13o 25’ 42” N, 144o 47’ 48” E) at Pago Bay, Guam (Figure 4). The local tide is mixed semi-diurnal, with a mean range of 0.5 m and a great diurnal range of 0.72 m at Apra Harbor. In this region of the western Pacific, trade winds from east or northeast are strong from November to April and moderate in other months. The cyclonic typhoon season is during late summer and fall months. On average, severe tropical storms have caused coastal damage every 2 to 5 years. Higher storm water in CNMI may reach 1 to 2.5 m above the MSL as result of strong wind and large waves, combined with low atmospheric pressure, around the islands.

Waves around Rota include wind seas generated by the northeasterly trade winds and ocean swells from south or west. Wave measurements are available from Coastal Data Information Program (CDIP; https://cdip.ucsd.edu/) Buoys 196 (13^o 41’ 01” N, 144^o 48’ 44” E, near Ritidian Point, Guam) and 197 (15^o 16’ 05” N, 145^o 39’ 44” E, near Tanapag, Saipan). Wave hindcasting data around CNMI are available from the USACE Wave Information Studies (WIS; http://wis.usace.army.mil/) and NOAA Wave Watch III (WW3, http://polar.ncep.noaa.gov/waves).

Figure 4 shows the location map of CDIP Buoys 196 and 197, and WIS Stations 81101, 81102, and 81104 around the study area. In the present study, WIS Station 81102 (14.5^o N, 144.5^o E) provides the long-term wave climate condition (1980-2011) for the numerical modeling of Rota Harbor. Figure 5 shows the wind and wave rose diagrams at WIS 81102 for 1980-2011. The wind rose indicates the dominance of trade winds in the region. The annual average wind speed is 7.2 m/sec. Waves around the CNMI are the result of combined northwest, southern, and trade wind waves, as well as the sheltering effect of islands. The majority of waves coming from the east-northeast sector are caused by the trade winds. Annual mean significant wave height (Hs) and dominated wave period at WIS 81102 are equal to 1.9 m and 9.6 sec, respectively. Figure 6 shows wave roses at CDIP Buoys 196 and 197 for 2013 and 2014. The island sheltering effect is strong at these two CDIP buoys as islands block waves from the east, southeast, and south directions. For Rota Harbor, only waves coming from the northwest sector are affecting the navigation as waves from other sectors are sheltered by the island.

NUMERICAL MODELS

The USACE Coastal Modeling System (CMS) numerical models (Demirbilek and Rosati, 2011) were implemented in the present modeling study. The CMS is a suite of numerical wave, current, salinity, and sediment transport models consisting of CMS-Wave and CMS-Flow. CMS-Wave is a finite-difference, two-dimensional steady-state wave spectral transformation model that calculates wave propagation, generation, refraction, diffraction, reflection, transmission, run-up, and wave-current interaction (Lin et al. 2008, 2011). CMS-Flow is a finite-difference, time-dependent three-dimensional circulation model which also calculates sediment transport, morphology change, salinity, and temperature fields (Buttolph et al. 2006).

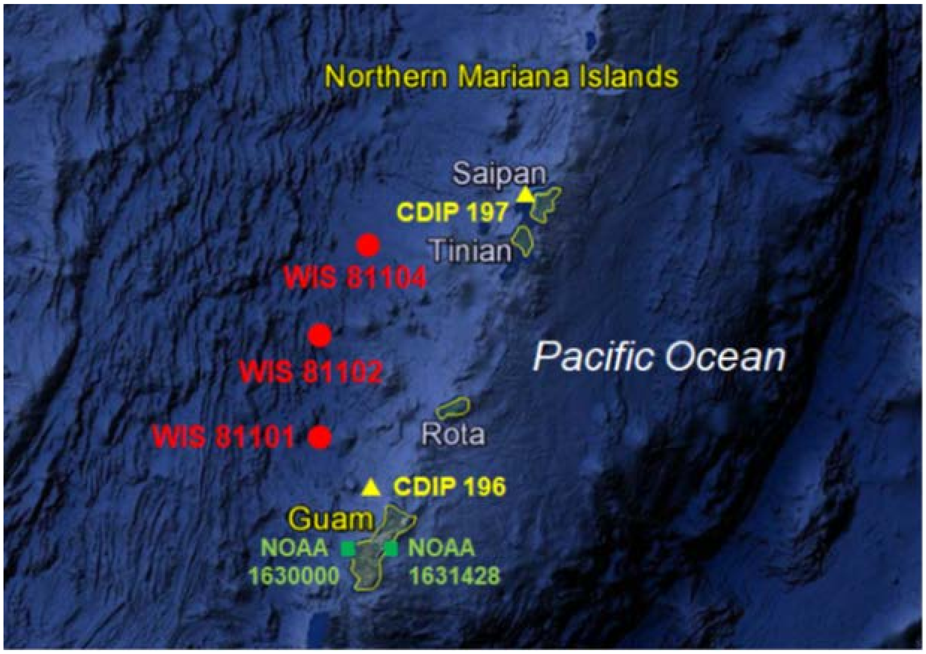

Figure 4. Location map of NOAA, CDIP and WIS Stations near study area

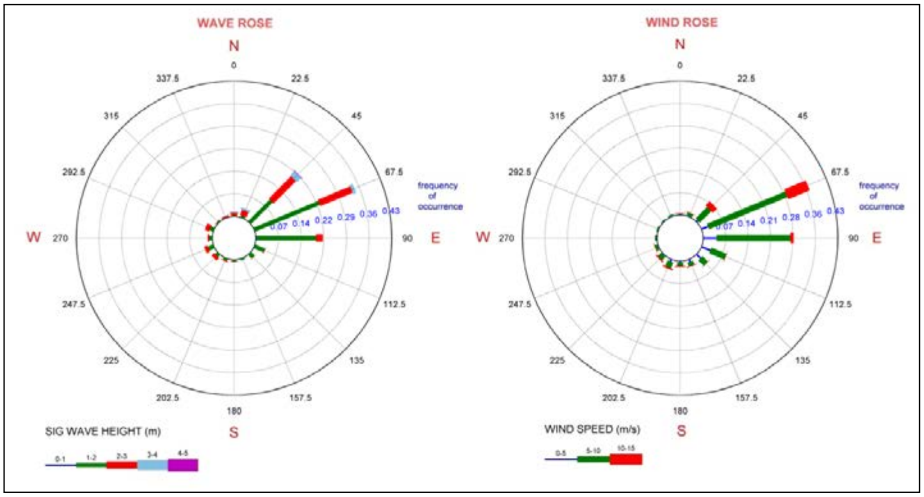

Figure 5: Wind and wave rose diagrams at WIS 81102 for 1980-2011

CMS-Wave and CMS-Flow can be run separately or coupled on a non-uniform Cartesian grid. In the coupling mode, the variables passed from CMS-Wave to CMS-Flow are the significant wave height, peak wave period, wave direction, wave breaking dissipation, and radiation stress gradients. CMS-Wave uses the update bathymetry, water levels, and currents from CMS-Flow. The coupling can be operated through the Surface-water Modeling System (SMS, Zundel, 2006) by providing the total simulation period of CMS-Flow with the constant interval of running CMS-Wave. Coupling CMS-Wave and CMS-Flow can simulate important coastal processes like wave-current interaction, longshore current, channel infilling, beach erosion, coastal flooding, and storm damage to nearshore structures. Both models have the nested grid capability as an alternative for circulation, sediment transport, and wave transformation in the local high resolution area.

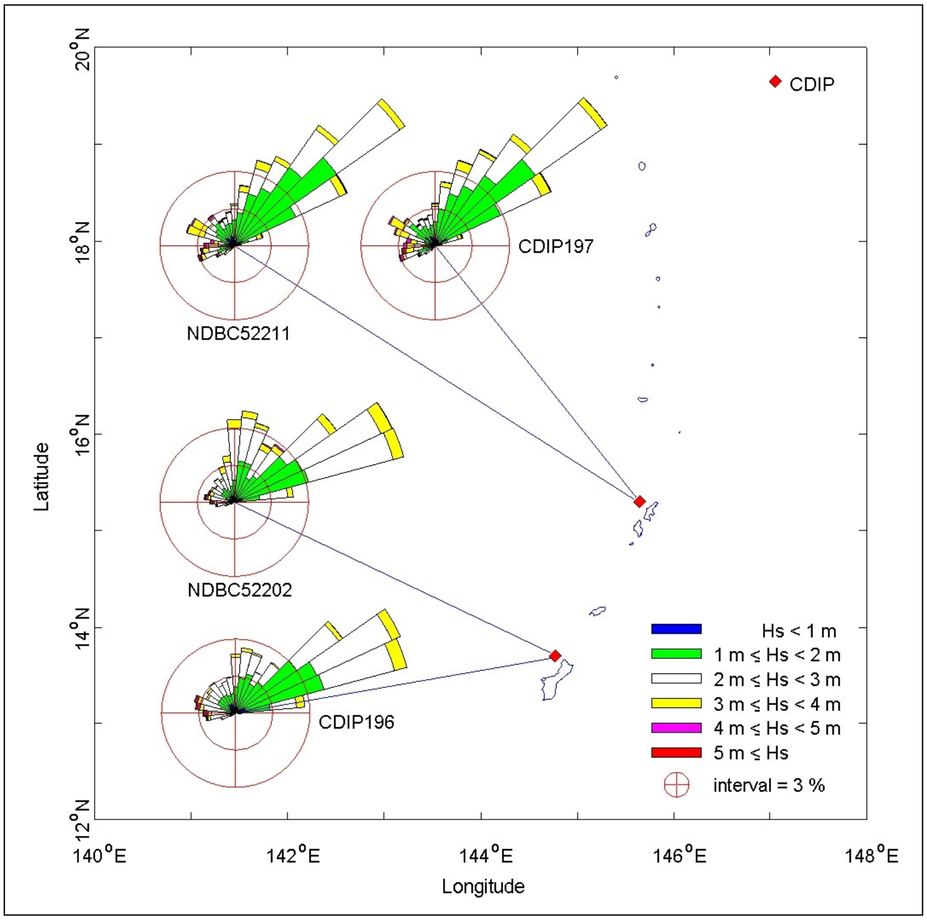

Figure 6: Wave roses at CDIP Buoys 196 and 197 for 2013 and 2014

MODEL CALIBRATION

The CMS model domain is a rectangular area that extends approximately 2 km across shore and 4.4 km alongshore (Figure 7). It covers Rota Harbor and coastal reefs with the offshore boundary reaching to the 300-m isobath. The grid consists of 241 x 487 cells with finer grid resolution to 4 m x 4 m in the harbor and coarser resolution to 60 m x 60 m at the ocean boundary away from the harbor. In the present modeling, CMS-Wave and CMS-Flow are run using the same rectangular grid.

The CMS calibration was performed for December 2016 when three ADCPs were deployed for 3-month field data collection (Figure 8). Incident wave spectra were transformed from CDIP 196 to the CMS grid offshore boundary using the linear wave theory with a simple assumption of shore-parallel depth contours. The wind input data were obtained from a solar powered anemometer (Met Station) installed at the harbor marina during the field data collection. The water level data from NOAA Station 1630000 at Apra Harbor, Guam, were used as input to the CMS grid sea boundary. The default CMS setting was applied and CMS-Wave was coupled with CMS-Flow at 2-hr interval. Figure 9 shows the CDIP 196 data used for incident waves. Figure 10 shows the water level and wind data used as input for the model calibration.

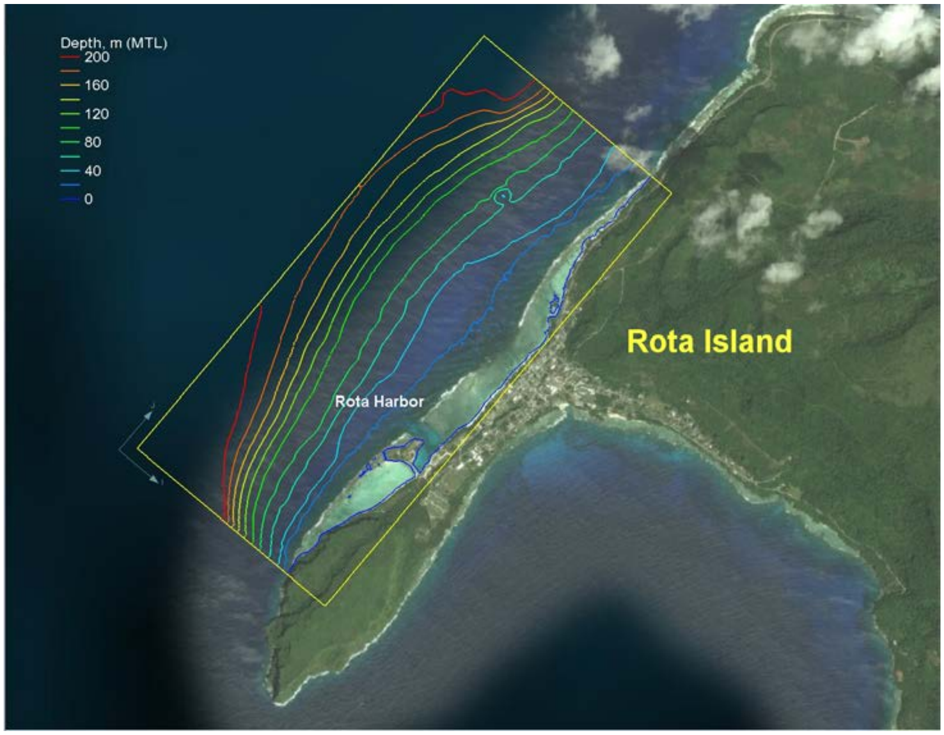

Figure 7: The CMS model domain and bathymetry contours

Figure 8: Field data collection stations, December 2016 – February 2017

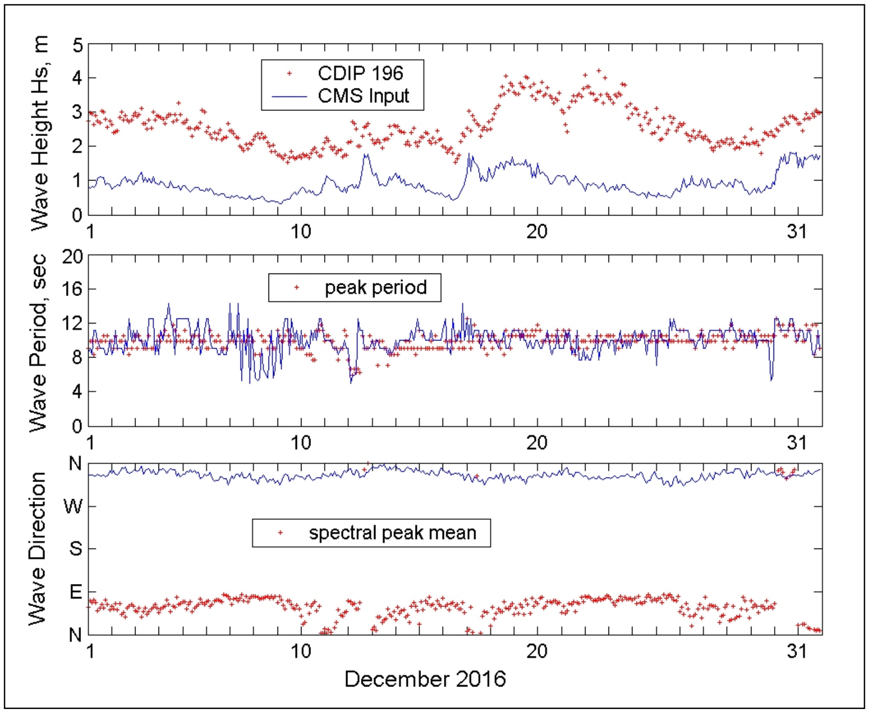

Figure 9: CDIP 196 data and incident waves for CMS input, December 2016

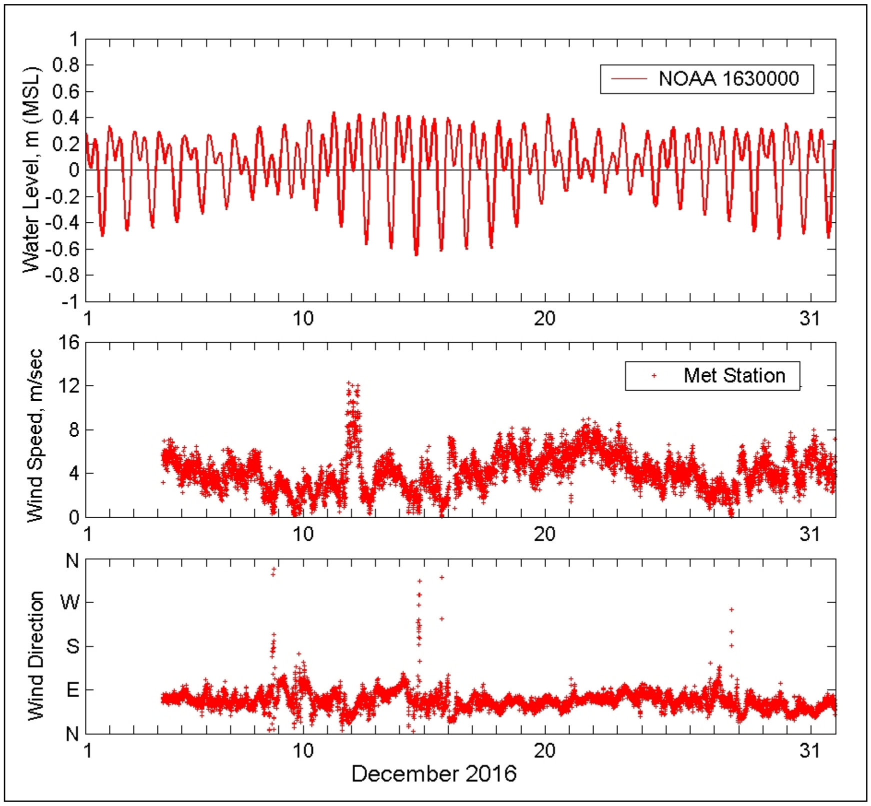

Figure 10: Water level and wind data for CMS input, December 2016

Figure 11 shows comparison of model water levels versus data at three ADCP locations (Offshore, Inshore, and Basin gages) for December 2016. Model water levels and data are well correlated, with correlation coefficients greater than 0.95 at three gage locations. The water levels are similar among three gages at Rota Harbor and they are not much difference from NOAA Station 1630000 at Apra Harbor, Guam, indicating the overall water level change is quite homogeneous in the NCMI region.

Figures 12 to 14 compare model waves versus data at three ADCP locations for December 2016. Model results show wave heights decrease consistently from Offshore to Inshore, and to Basin gage locations. Model wave heights generally agree with data at three gages. The correlation coefficients between model wave heights and data are greater than 0.9 at three gages. Model wave periods also agree well with data at three gages. The corresponding correlation coefficients between model wave periods and data are greater than 0.8. Wave direction data are available only from Offshore and Inshore gages. Model wave directions correlate well with data at Offshore and Inshore gages. The root-mean-square differences between model wave directions and data are smaller than 6 deg at these two gage locations.

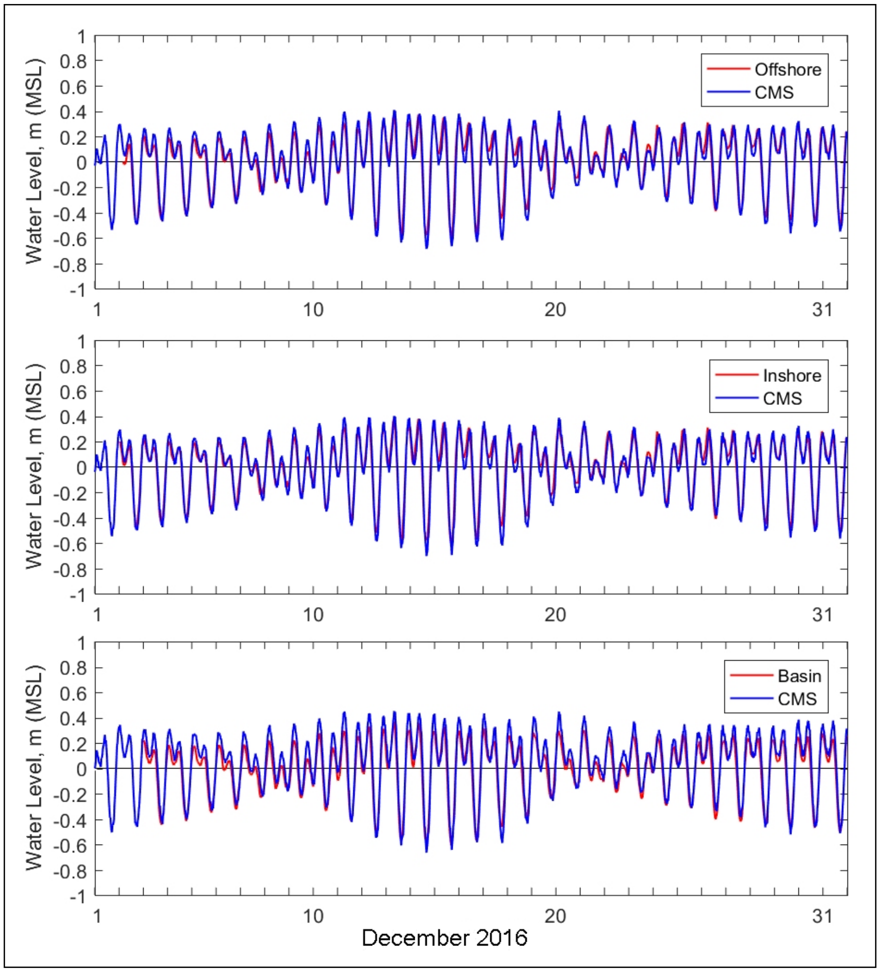

Figure 11: comparison of model water levels versus data at three ADCP locations

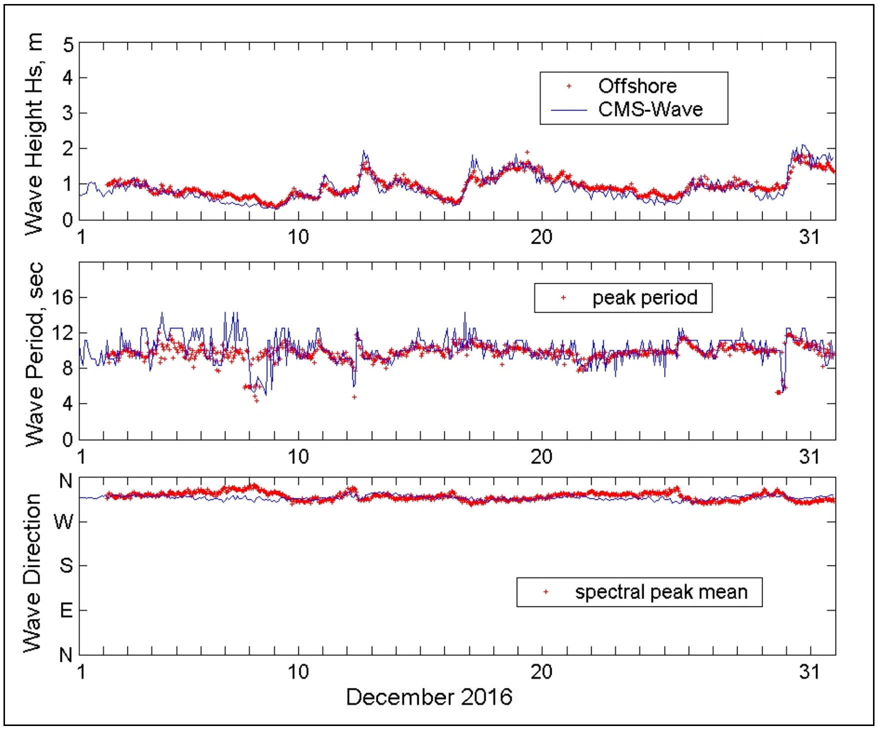

Figure 12: comparison of model waves versus data at Offshore ADCP location

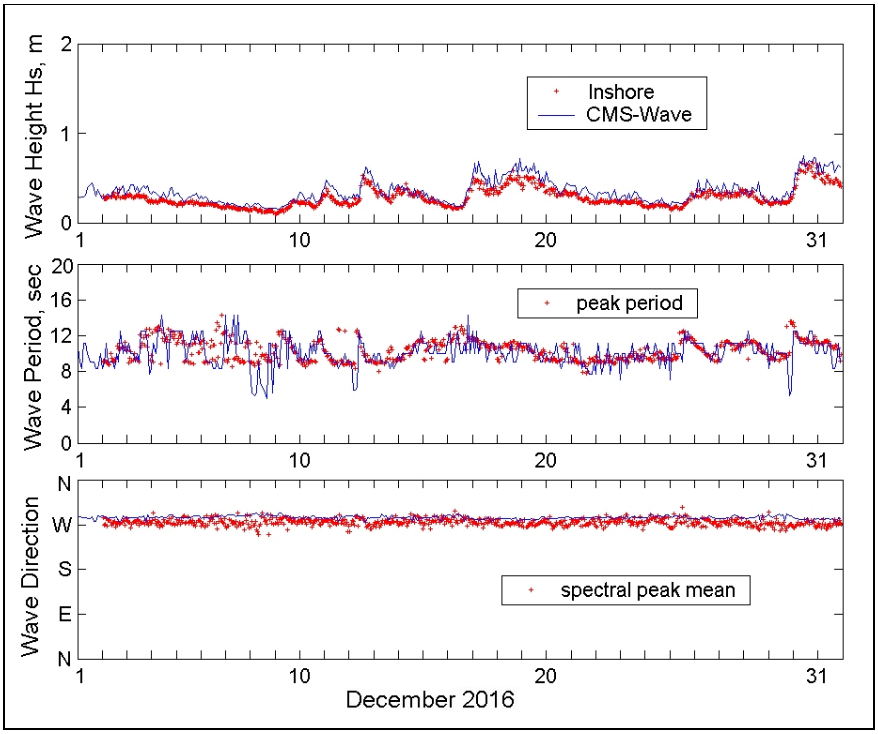

Figure 13: comparison of model waves versus data at Inshore ADCP location

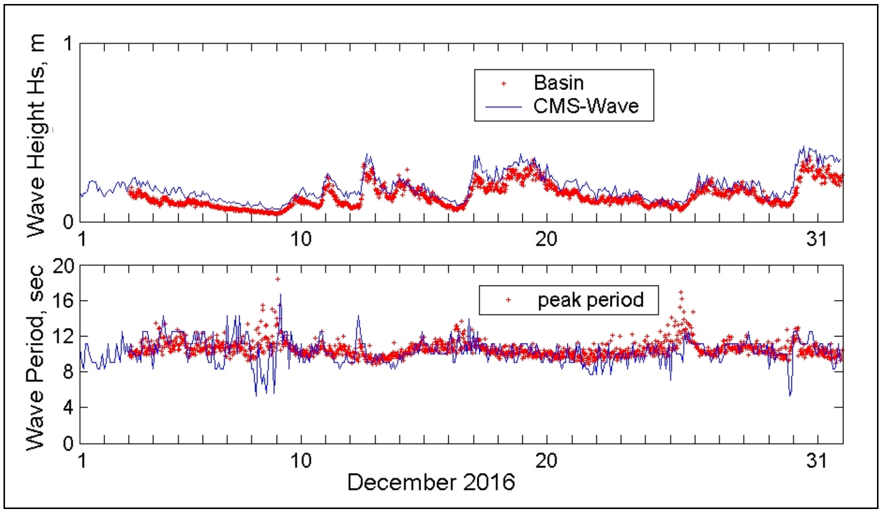

Figure 14: comparison of model waves versus data at Basin ADCP location

MODELING AND EVALUATION OF ALTERNATIVES

The CMS grid applied in the model calibration is used for the existing configuration, Alt 0. This same grid was modified with proposed structures in Table 1 for each alternative of Alts 1, 2, and 3. Based on the wave hindcasting data from WIS 81102 offshore Rota Harbor and water level measurements from NOAA Station 1630000 at Apra Harbor, Guam, a combination of five (5) incident wave height/period condition, and three (3) mean wave directions with two (2) water levels was used as offshore boundary conditions. Table 2 presents the combination of incident wave forcing parameters for the CMS boundary conditions. The smallest wave height for offshore wave forcing is 0.61 m which is the design input wave for safe harbor access and operation. The largest wave height for offshore wave forcing is 1.83 m which is more specific for the structure design under severe typhoon conditions. Among three primary wave directions selected for model simulation, the 320° wave direction is aligned with the harbor entrance channel. Two water levels of 0 and 0.3 m selected for the modeling represent the MSL and MHHW (Mean Higher High Water), respectively. For each incident wave and water level combination, the model simulation is conducted for a total of 18-hr duration to reach the steady-state condition with coupling of CMS-Wave and CMS-Flow at 1-hr interval.

Table 2. Incident wave and water level combination

Offshore Wave Forcing Parameters	Increments
Significant Height (m)	0.61, 0.91, 1.22, 1.52, 1.83
Corresponding Peak Period (sec)	11, 13, 14, 14, 14
Mean Direction (deg, meteorological)	300, 320*, 330
Water Level, MSL (m)	0, 0.3
* 320° wave direction is aligned with harbor entrance channel centerline.	

Model results were evaluated along five transects T1 to T5 (Figure 3), where T1 corresponds to the entrance channel centerline, T2 and T3 delineate the entrance channel south and north sidelines, respectively; T4 and T5 corresponding to docking and anchor areas along the south shoreline of the turning basin. Figures 15 and 16, for example, show model wave and current fields, respectively, for Alts 0 to 3 and 0 water level input with the annual mean significant wave height of 1.22 m and mean period of 14 sec from 320 deg (meteorological convention) arriving the navigation channel. The model wave field displays stronger wave refraction, diffraction, and breaking on the shallow reef and around the breakwater. Waves arriving and breaking on shallow reef can create strong current over reef. In Alts 0 and 1, wave-induced currents over the shallow reef tend to converge and exit to the harbor channel, resulting return flow in the entrance channel. The magnitude of return flow is approximately proportional to the breaking wave height. This return flow is insignificant in Alts 2 and 3 as the proposed long breakwater along the north side of entrance channel will block wave-induced currents from the adjacent fringing reef area to the entrance channel.

Figures 17 and 18 show model wave heights along T1 and T5, respectively, for Alts 0 to 3 under an operational threshold wave height of 0.61 m (2 ft) associated with 11 sec and incident 320 deg at the entrance channel. Note the threshold wave heights allowed in the harbor operational hours (a 12-hr period during the daytime from 6 am to 6 pm) are 0.61 m (2 ft) in the navigation channel and 0.3 m (1 ft) near harbor docks and marina along the backside of the turning basin. For Alts 0 and 2, incident waves are more easily coming into the entrance channel than Alts 1 and 3. Because Alt 0 has stronger return flow in the entrance channel than Alt 2, model wave heights along T1 are greater in Alt 0 than in Alt 2 as a result of more wave-current interactions.

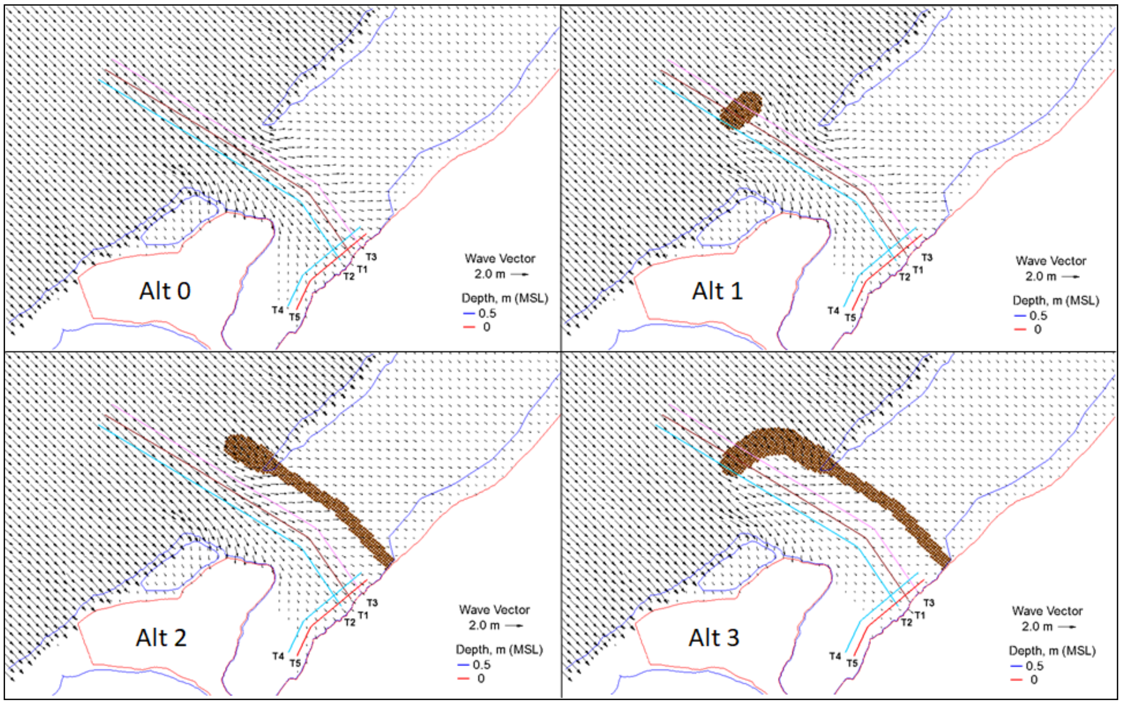

Figure 15: Model wave fields for Alts 0 to 3 with incident waves of 1.22 m, 14 sec, from 320 deg

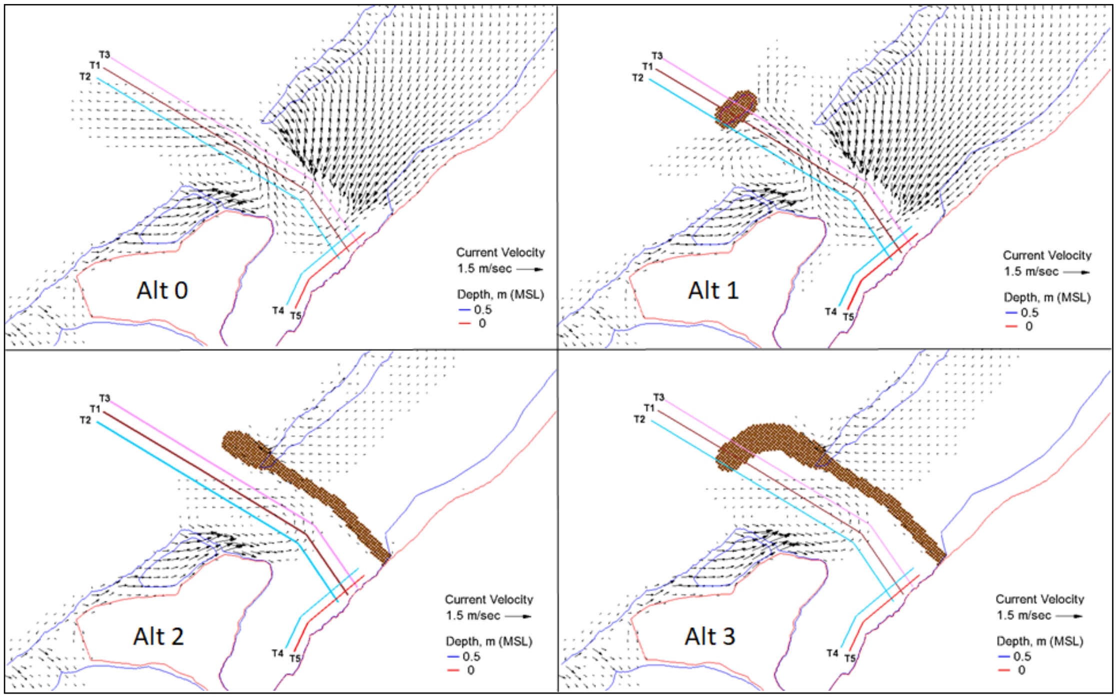

Figure 16: Current fields for Alts 0 to 3 with incident waves of 1.22 m, 14 sec, from 320 deg

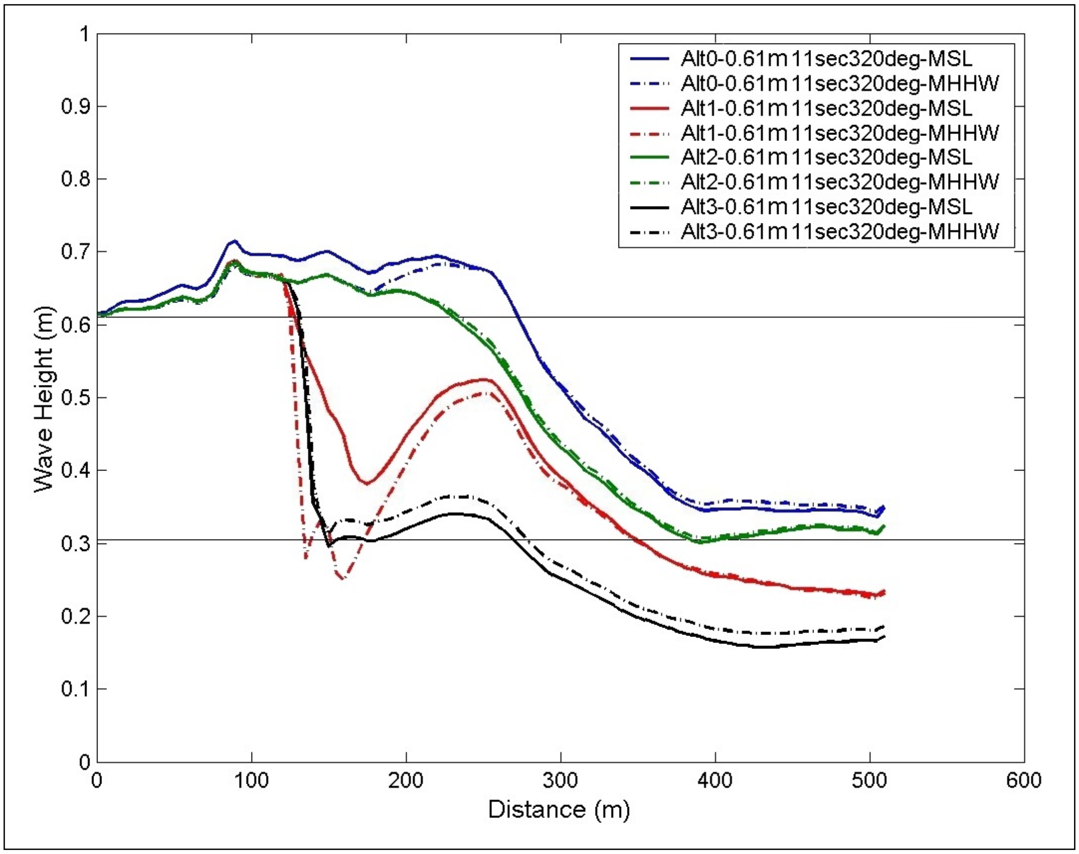

Figure 17: Wave heights along T1 for Alts 0 to 3, incident wave of 0.61 m, 11 sec, from 320 deg

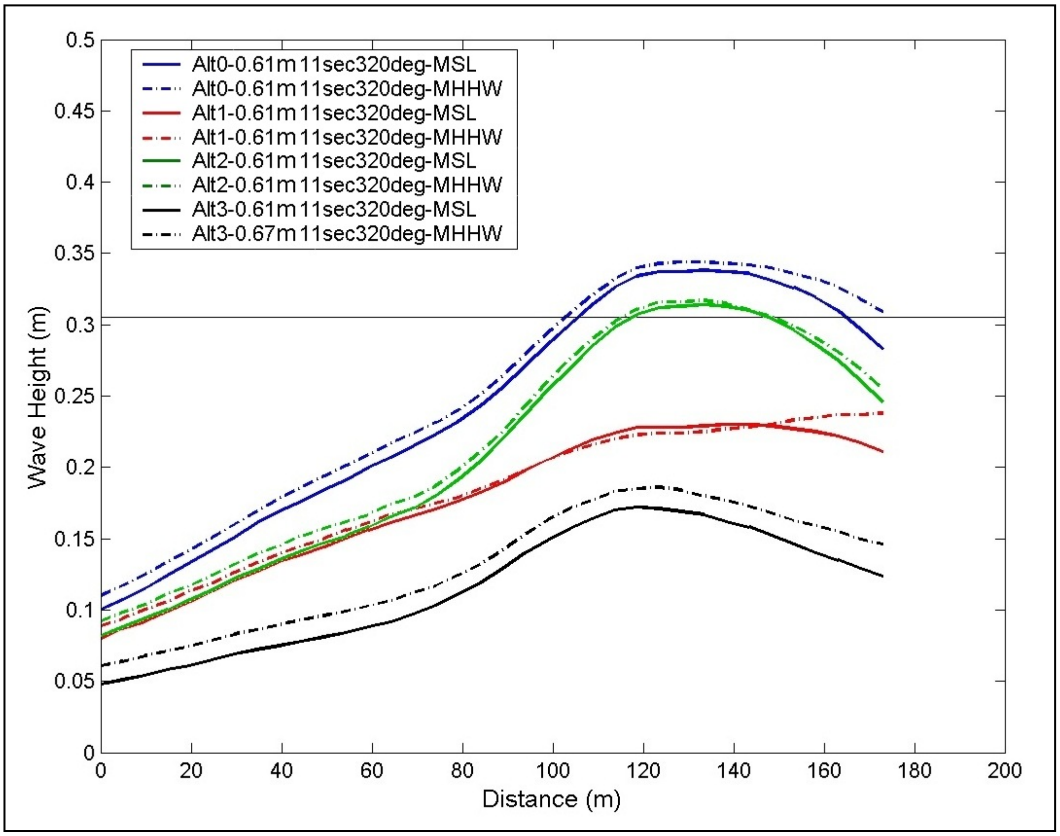

Figure 18: Wave heights along T5 for Alts 0 to 3, incident wave of 0.61 m, 11 sec, from 320 deg

For Alts 1 and 3, having the proposed breakwater partially sheltered the harbor entrance, waves along T1 are generally much smaller than Alts 0 and 2 in the lee of the breakwater. Because Alt 1 consists of only a detached breakwater, more waves can come into the entrance channel than Alt 3. Wave-current interactions are also stronger in Alt 1 due to more return flow presence in the entrance channel. Accordingly, waves getting to the back side of turning basin along T5 show higher waves for Alts 0 and 2, and lower waves for Alts 1 and 3. In general, Alt 3 presents the best navigable and operational condition and Alt 0 shows the worst condition for Rota Harbor.

Based on long-term wave hindcasting data (1980-2011) from WIS Station 81102 and modeling of selected incident wave and water level combination, the harbor usability and operability time table can be established. For example, Tables 3 presents harbor daytime (6 am to 6 pm) operability estimates for Alts 0 to 3 with the threshold wave height Hs < 0.61 m (2 ft) in the entrance channel and Hs < 0.3 m (1 ft) at harbor docks and marina. The harbor usability percent estimate is based on 2-hr exceedance of the threshold wave heights in a 32-year duration of 1980-2011 and in a worst year of either 1997 or 2004. These estimates, including 0 and 0.3 m water level input, indicate Alts 0 and 2 have smaller percentage than Alts 1 and 2 on average of harbor daytime usability. Alt 3 provides the best percentage of usability among four alternatives. For the worst and stormier year of 1997 or 2004, Alt 3 also provides highest usability percentage than other alternatives while Alt 1 shows the lowest usability percentage.

Table 3. Harbor daytime usability estimate for Alts 0 to 3 with $H_S < 0.61$ m in entrance channel and $H_S < 0.3$ m at harbor docks and marina

Alt	Percent usable (1980-2011)*	Percent usable (worst year)*
0	82.8 %	71.8 % (1997)
1	86.5 %	76.8 % (2004)
2	83.6 %	73.6 % (1997)
3	91.4 %	83.8 % (2004)
* Include 0 and 0.3 m water level input, and all incoming wave directions between 230 and 360 deg, and between 0 and 50 deg.		

SUMMARY AND CONCLUSIONS

Numerical modeling was conducted to investigate proposed breakwater installation to protect navigation and operations at Rota Harbor, a commercial port facility located at the northwest coast of Rota of CNMI in the western Pacific. The harbor was constructed by the US Army Corps of Engineers between 1978 and 1985. The typical wind and wave activity in the region can cause rough conditions in the harbor for extended periods of time to be challenging or unmanageable for both vessel transit through the entrance channel and operations at offloading docks. These conditions often result in cancelled or delayed deliveries of commodities to the harbor, creating economic hardship for the island.

The CNMI is situated some 1,000 km east of a breeding area of cyclonic disturbances in the western Pacific. This puts Rota in the middle of the infamous typhoon alley and subject to at least one typhoon passing by or through each year during July to January. Strong winds greater than 120 mph with storm wave heights up to 10 m offshore is common during a super typhoon. Besides frequent tropical storms, the Harbor is always exposed to consistent wind sea and distant swell generated in the western Pacific Ocean. The daily tide is mixed semi-diurnal and moderate with a mean range of 0.5 m and a great range of 0.75 m. The storm surge may rise up locally to 2.5 m above MSL during a super typhoon.

Wave and hydrodynamics numerical models of the CMS, developed and maintained at ERDC, were applied with field measurements and hindcasting data. Field data including current and wave measurement at three ADCPs installed outside harbor, by the entrance channel, and in the turning basin were collected from 2 December 2016 to 3 March 2017. The field data were used to calibrate the CMS models. Model simulations of the existing harbor and three proposed structural alternatives were conducted for typical sea states and storm conditions. Operational wave model runs were based on the most frequently occurring conditions including three incident wave heights (0.61 m, 0.91 m, and 1.22 m) associated with respective wave periods (11 sec, 13 sec, and 14 sec), three wave directions (300 deg, 320 deg, and 330 deg, meteorological), and two representative water levels (0 m, MSL, and 0.3 m corresponding to MHHW). Additional runs were conducted to include two larger wave heights (1.52 and 1.83 m) for storm conditions.

The CMS modeling was conducted for the existing configuration (Alt 0), the offshore detached breakwater (Alt 1), the north breakwater (Alt 2), and the dogleg breakwater (Alt 3) as listed in Table 1. Model results were evaluated along five transects T1 to T5 (Figure 3), where T1 corresponds to the entrance channel centerline, T2 and T3 align with the entrance channel south and north sidelines, respectively; T4 and T5 corresponding to docking and mooring areas along the south shoreline of turning basin.

Model results show wave breaking on adjacent reef flat causing return flow in the harbor entrance channel. The magnitude of return flow is approximately proportional to the breaking wave height. This return flow is insignificant in Alts 2 and 3 as the proposed long breakwater along the north side of entrance channel blocks wave-induced currents from the north fringing reef area to the entrance channel. Alts 2 and 3 also outperform Alts 0 and 1 in terms of wave height reduction in the entrance channel and along the backside of turning basin.

The Rota Harbor entrance channel is considered as an access channel for year around usage of barge delivery of cargo. For safe transit into harbor and safely stay within the mooring area, typical criteria adopted for threshold wave heights, as noted in the Coastal Engineering Manual (CEM), V-5-2 (https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1100_Part-05.pdf), are 0.61 m in the channel and 0.3 m at harbor docks. Based on long-term hindcasting waves (1980-2011) from WIS Station 81102, the local wave climate outside harbor entrance was developed and linearly interpolated to entrance channel and harbor basin for estimate of harbor usability which includes harbor accessibility and operability.

The harbor operability is considered for daytime operational hours from 6 am to 6 pm local time. The criterion for harbor accessibility and usage is based on 2-hr exceedance of the threshold wave heights, i.e., 0.6 m in the entrance channel and 0.3 m at harbor docks. These estimates, including 0 and 0.3 m water level input, indicate Alts 0 and 2 have smaller percentage than Alts 1 and 2 on average of harbor daytime usability, based on 1980-2011 wave hindcasting data. Among all four alternatives tested in modeling, Alt 3 provides the best percentage of usability. For the worst and stormier year of 1997 or 2004, Alt 3 also provides highest usability percentage than other alternatives while Alt 1 shows the lowest usability percentage.

Alt 3, though it would substantially reduce wave height in the entrance channel and turning basin, the breakwater built along the north side of entrance channel and extended eastward to partially shelter the entrance would impact vessel transit in and out of the harbor. There are also issues of constructability and high cost of construction and maintenance with the dogleg breakwater in Alt 3 as the proposed alignment quickly ventures into deeper water.

Alternatively, a shorter structure in Alt 3 may be considered for the modeling as it is economically and constructively more feasible to build. The future studies should include the condition of harbor interior expansion, an eligible project being requested and considered by the Government Commonwealth Ports Authority. Additional numerical modeling investigation is recommended for representative super typhoons with high wind and water conditions in structure design and safe harboring estimate.

The present study provides concepts and numerical modeling approach for engineering education communities to investigate structural modification for safer navigation and ship maneuvering in coastal harbors. The study site of Rota Harbor presents a typical island harbor affected by the combination of moderate waves, winds, tides, and occasional severe storms. The use of numerical models could potentially change the traditional practice of design and construction of marine infrastructures (jetties, seawalls, breakwaters, etc.) by engineering manuals and handbooks.

This paper is also intended to inspire both critical thinking and creativity to enhance educational engineering outcomes. The objective includes the introduction of numerical modeling strategy and practical approach in education and researches. The challenging of using the numerical modeling for prototype harbor applications should be reflected in the academic curriculum to prepare the future workforce with advanced technology and standards in coastal engineering.

ACKNOWLEDGMENT

The authors are grateful to Dr. Julie D. Rosati and Ms. Tanya Becky for their continual support and encouragement towards development and improvement of Coastal Modeling System capabilities to increase the reliability of numerical modeling for regional and local coastal management, operation and maintenance of the navigation channel, planning and guidance for future O&M activities. Permission was granted by the Chief, US Army Corps of Engineers to publish this information.

REFERENCES

Buttolph, A.M., C.W. Reed, N.C. Kraus, N. Ono, M. Larson, B. Camenen, H. Hanson, T. Wamsley, and A.K. Zundel. 2006. Two-dimensional depth-averaged circulation model CMS-M2D: Version 3.0, Report 2: Sediment transport and morphology change. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL TR-06-7. Vicksburg, MS: US Army Engineer Research and Development Center.

Demirbilek, Z. and J.D. Rosati. 2011. Verification and Validation of the Coastal Modeling System: Report I, Executive Summary. Technical Report ERDC/CHL-TR-11-10. Vicksburg, MS: US Army Engineer Research and Development Center.

Lin, L., Z. Demirbilek, and H. Mase. 2011. Recent capabilities of CMS-Wave: A coastal wave model for inlets and navigation projects. Proceedings, Symposium to honor Dr. Nicholas Kraus. Journal of Coastal Research, Special Issue 59, 7-14.

Lin, L., Z. Demirbilek, H. Mase, J. Zheng, and F. Yamada. 2008. CMS-Wave: A near-shore spectral wave processes model for coastal inlets and navigation projects. Coastal and Hydraulics Laboratory Technical Report ERDC/CHL-TR-08-13. Vicksburg, MS: US Army Engineer Research and Development Center.

Zundel, A.K. 2006. Surface-water Modeling System reference manual: Version 9.2. Provo, UT: Brigham Young University Environmental Modeling Research Laboratory.