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Wave Modeling of Infrastructure Modifications at Faleasao Harbor in American Samoa

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ABSTRACT

A numerical wave modeling study using B2D and CMS-Wave models was conducted to evaluate impacts of infrastructure modifications for improving navigation at Faleasao Harbor in the American Samoa. The harbor, sitting on a coral rocky bottom with the northward entrance exposing to Pacific Ocean, is sheltered on the west by a rocky natural headland and partially protected by a detached west breakwater. Three infrastructure modifications including breakwater addition, widening and deepening entrance channel were proposed and modeled. Modeling results indicated that with addition of a new west breakwater provides more efficient protection to the harbor.

KEY WORDS: Faleasao Harbor; wave modeling; breakwater; alternative.

INTRODUCTION

Faleasao Harbor in the American Samoa (territory of the U.S.) is a small federally constructed shallow-draft harbor located on the northwest coast of Tau Island, approximately 17 square miles in conical shape and the largest of the Samoa Islands in the south-central Pacific Ocean. Navigation in the harbor is affected by large waves passing over reef bottom at and outside the harbor entrance. Swells from the north and northwest breaking on the reefs create unfavorable conditions to boats entering, berthing, and exiting the harbor. The harbor entrance is sheltered on the west by a rocky headland and flanked by an unraveling west breakwater now more like a detached spur (Fig. 1). A jetty along the east side of navigation channel extends a short distance northeast from the boat launching ramp. Both existing west breakwater and east jetty have been deteriorating in recent years that they no longer provide effective protection to harbor interior from large sea swells and waves.

The U.S. Army Corps of Engineers (USACE), Honolulu District, and USACE Research and Development Center are presently conducting a joint study to conduct numerical wave modeling for proposed infrastructure modifications to improve the navigation and docking condition at Faleasao Harbor. The main goal is to determine how the proposed modifications can accommodate larger vessels for safer navigation in the entrance and better maneuvering inside harbor. The modeling effort investigates potential alternatives include deepening the navigation channel and turning basin, and reconstructing the west breakwater for more effective shield of incoming waves.

Fig. 1 Faleasao Harbor study area.

INFRASTRUCTURE MODIFICATIONS

The wave modeling includes the existing harbor geometry and three infrastructure modifications. The existing harbor is denoted as Alternative 0 (Alt 0) while three modifications are referred to as Alternative 1 (Alt 1), Alternative 2 (Alt 2), and Alternative 3 (Alt 3).

Alt 0 Depths in the present navigation channel vary from 10 to 13 ft (3 to 4 m), Mean Sea Level (MSL). Channel widths at the south and north ends are approximately 135 and 150 ft (41 and 46 m), respectively.

Alt 1 This alternative involves deepening the channel from 13 to 19 ft (4 to 6 m), and turning basin from 11 to 19 ft (3.3 to 6 m), MSL. The channel widths at the north and south ends remain the same as in Alt 0.

Alt 2 This alternative involves reconstructing a 230-ft (70-m) long west breakwater to the tip of west peninsula that extends eastward toward the channel entrance. It is a rubble-mound breakwater with the crest elevation of 6.6 ft (2 m), MSL, and side slopes of 2 on 3 (2V:3H).

Alt 3 This alternative involved reconstructing a 280-ft (85-m) long west breakwater to the tip of west peninsula that extends eastward toward the channel entrance. It is a rubble-mound breakwater with the same cross section as in Alt 2.

Table 1 presents a brief description of four alternatives (Alts 0 to 3) and Fig. 2 shows the footprint of these alternatives.

Table 1 Four harbor configurations evaluated

Case	Configuration	Features
Alt 0	Existing Harbor	Existing harbor geometry
Alt 1	Deepen channel and turning basin	Deepen navigation channel and turning basin from 10.5 ft (3.2 m) to 19 ft (5.8 m) MSL
Alt 2	Alt-1 with 230-ft west breakwater	A 230-ft (70-m) long breakwater from the tip of peninsula eastward toward the channel, is added to Alt 1
Alt 3	Alt-1 with 280-ft west breakwater	A 280-ft (85-m) long breakwater from the tip of peninsula eastward toward the channel, is added to Alt 1

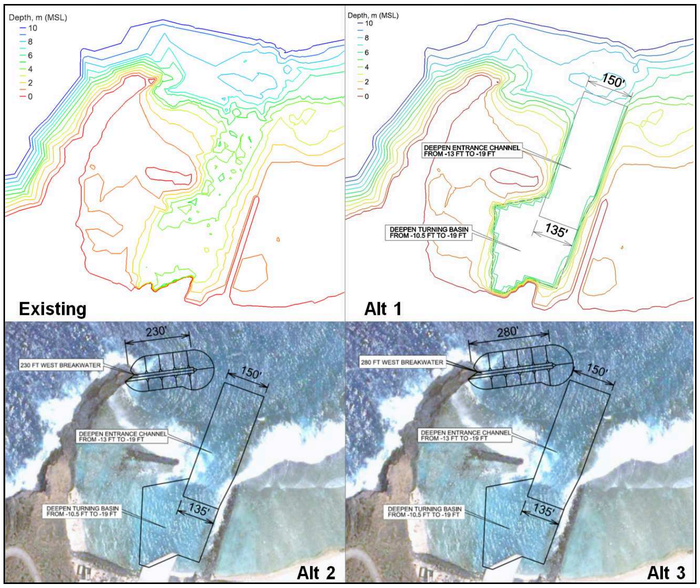

Fig. 2 Faleasao Harbor study area.

BATHYMETRYAND METOCEAN DATA

The harbor interior, channel, and structure data were based on the Honolulu District surveys. The offshore bathymetry was based on the 5-m grid map from the Pacific Islands Benthic Habitat Mapping Center (www.soest.hawaii.edu/pibhmc/pibhmc_amsamoa_tau_bathy) and on the National Geophysical Data Center (NGDC) 3-arc-sec bathymetry and topography of coastal digital elevation models (DEMs) (www.ngdc.noaa.gov/dem/squareCellGrid/download/647). Coastal and shoreline digital data were extracted from the NGDC database (www.ngdc.noaa.gov/mgg/shorelines/shorelines.html). Geo-referenced image files were downloaded from Google Earth (earth.google.com).

Water level data were available from the NOAA Coastal Station 1770000 (14° 16' 48" S, 170° 41' 24" W) at Pago Pago, Tutuila Island, approximately 70 miles west of Tau Island. The local tide was mixed semi-diurnal, with a mean range of 0.77 m, a spring range of 0.83 m, and a neap range of 0.4 m.

Coastal wind data are available from NOAA Pago Pago Station (1770000). In this region of the southern hemisphere, trade winds from the east are strong during May to November and moderate in other months. The cyclonic typhoon season is during the winter months. On average, tropical storms have caused coastal damage every 3 to 5 years.

Waves at American Samoa and vicinity include wind seas generated by the easterly trade winds and the ocean swells from south or north. There are no wave measurements at Tau and nearby Ofu Island (Fig. 3). Offshore wave hindcasting data are available from the Wave Information Studies (WIS; http://wis.usace.army.mil/hindcasts.html). Fig. 3 shows the nearest WIS stations north and west of Tau. In the present study, WIS Sta 81137 (13.5° S, 169.5° W) provides incident wave conditions. Fig. 4 shows the wind and wave rose diagrams for 1980-2012 at Sta 81137. WIS data at Sta 81137 indicated seasonality in wave height and wind speed. Annual mean significant wave height and wave period are equal to 1.6 m and 10.5 sec, respectively. The corresponding annual average wind speed is 6 m/sec. The majority of waves coming from the east sector are caused by the trade winds.

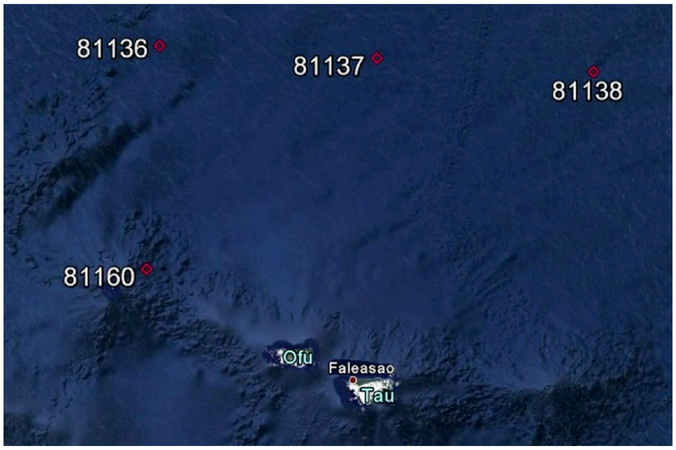

Fig. 3 WIS Stations near Faleasao Harbor.

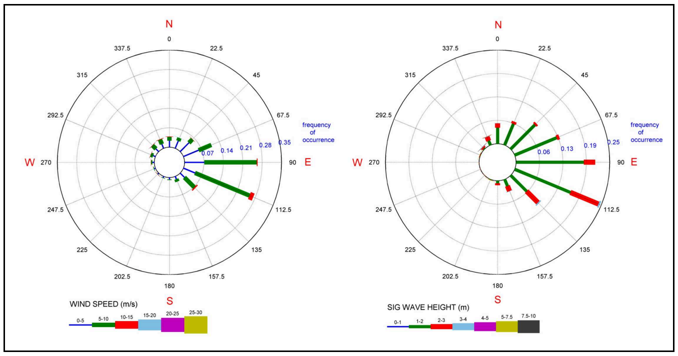

Fig. 4 Wind and wave rose diagrams for 1980-2012 at WIS Sta 81137.

WAVE MODELS AND SIMULATION CONDITION

Two classes of wave models, BOUSS-2D (B2D) and CMS-Wave, were used to investigate improvement of navigation at Faleasao Harbor. B2D is a Boussinesq type two-dimensional (2D) wave model (Demirbilek and Nwogu 2007; Demirbilek et al. 2005a, 2005b; Nwogu and Demirbilek 2001). This model is used in this study to investigate proposed alternatives at Faleasao Harbor to represent different infrastructure changes. CMS-Wave is a steady-state 2D spectral wave model (Lin and Demirbilek 2012; Lin et al. 2011; Lin et al. 2008; Demirbilek et al. 2008) to transform WIS waves to nearshore for input conditions to B2D. CMS-Wave is part of an integrated Coastal Modeling System (CMS) for coastal inlet navigation and regional sediment modeling applications (Demirbilek and Rosati 2011).

Model Domains

CMS-Wave model domain covers a large coastal region while the B2D model domain covers the local harbor channel and basin area. Figs. 5 and 6 show the CMS-Wave and B2D model domains with depth contours for Alt 0. The CMS-wave grid covered a rectangular area approximately 21 mi x 24 mi (13 km x 15 km). It included the eastern coast of Olosega and northwest coast of Tau. The grid cell size in the model varied from 20 to 1,640 ft (6 to 500 m), and water depths 0 to 7,550 ft (0 to 2,300 m). Four B2D grids, each extends from Harbor to approximately 160-ft (50-m) depth offshore, were generated for simulation of incident waves from N, NNE, NNW, and NW directions. A constant 5-m size was used in all B2D grids.

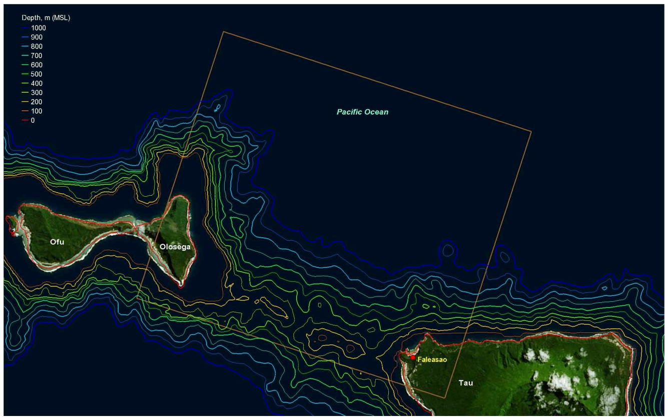

Fig. 5 CMS-Wave model domain.

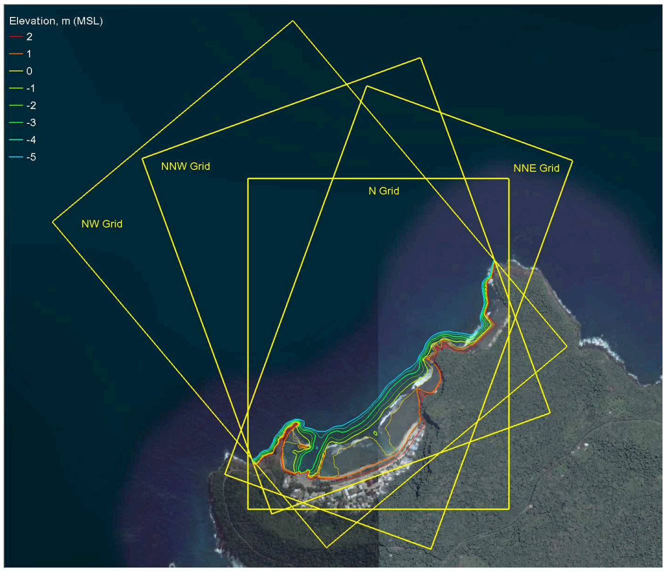

Fig. 6 B2D model domains.

Incident Wave Conditions

Storm and average waves affecting Faleasao Harbor were selected as incident waves for wave modeling. Based on the WIS Sta 81137 hindcast, storm events were selected from the top 10 events ranked by maximum wave height. Three wave conditions representing storms from N and NW directions were selected. Two of these conditions corresponded to recent Category-5 cyclones Heta in January 2004 and Olaf in February 2005. The third corresponded to Category-1 Hurricane Tusi, which made a direct hit on Tau in January 1987. Table 2 presents wind and wave conditions for three storms modeled with CMS-Wave at two different water levels of 0 and 0.5 m, related to the Mean Sea Level (MSL), representing the mean and high water levels, respectively.

Table 2 Storm wave heights (H_s), peak periods (T_p), and directions.

Date/Time (UTC)	Wind and Wave Condition*	Water Level (MSL)	Label
2005/02/16 14:00	H_s=9.83 m, T_p=13 sec, θ_m=320 deg, U_w=30 m/sec, θ_w=315 deg	0 m	H9.8T13D320W0
		0.5 m	H9.8T13D320W0.5
2004/01/06 00:00	H_s=9.09 m, T_p=14 sec, θ_m=330 deg, U_w=23 m/sec, θ_w=350 deg	0 m	H9.1T14D330W0
		0.5 m	H9.1T14D330W0.5
1987/01/18 00:00	H_s=7.45 m, T_p=11 sec, θ_m=0 deg, U_w=29 m/sec, θ_w=340 deg	0 m	H7.5T11D0W0
		0.5 m	H7.5T11D0W0.5
* Wave direction θ_m and wind direction θ_w are in meteorological convention (from). Wind speed U_w is at 10 m above sea surface.			

Annual mean height (H_s=1.5 m) and mean period (T_p=10 sec) at WIS Sta 81137 were simulated for three directions (θ_m = 0°, 320°, and 340°) and two water levels (0 and 0.5 m, MSL). Table 3 presents the average wave conditions selected for wave modeling. Wind forcing was dismissed in the simulation for average wave conditions.

Table 3 Average wave conditions.

Average Wave Condition	Water Level (MSL)	Label
H_s=1.5 m, T_p=10 sec, θ_m=320 deg	0 m	H1.5T10D320W0
	0.5 m	H1.5T10D320W0.5
H_s=1.5 m, T_p=10 sec, θ_m=340 deg	0 m	H1.5T10D340W0
	0.5 m	H1.5T10D340W0.5
H_s=1.5 m, T_p=10 sec, θ_m=0 deg	0 m	H1.5T10D0W0
	0.5 m	H1.5T10D0W0.5

Wave modeling was conducted for all twelve incident wave conditions listed in Tables 2 and 3. In CMS-Wave, default lateral and backward reflection coefficients of 0.5 and 0.3, respectively, were used in model simulations. Calculation of infra-gravity wave forcing was activated for potential long-period swell effects.

MODELS RESULTS

Model results were saved over the entire computational domain, including three engineering wave parameters (significant wave height, peak period, and mean direction). Calculated directional spectra were saved at 70 output locations along nine transect lines (T1-T9) shown in Fig. 7 that cover the areas of interest inside and outside the harbor.

Fig.8, for example, shows CMS-Wave calculated wave fields for Alts 0 to 4 in the incident wave condition of H9.1T14D330W0 (storm wave input of 9.1 m and 14 sec from 330 deg with water level = 0 m). Fig.9, for example, shows CMS-Wave calculated wave heights along T1 (channel centerline) for Alts 0 to 4 in storm event H9.1T14D330W0. Alt 3 generally shows smaller wave height in the entrance channel. B2D and CMS-Wave results are similar inside the harbor. Table 4 provides B2D calculated average wave height reduction from different incident wave directions along the channel centerline (Transect T1) and along the face of the dock (T7) for Alts 1 to 3 as compared to Alt 0. Alt 3 has overall greater wave height reduction than Alts 0, 1, and 2.

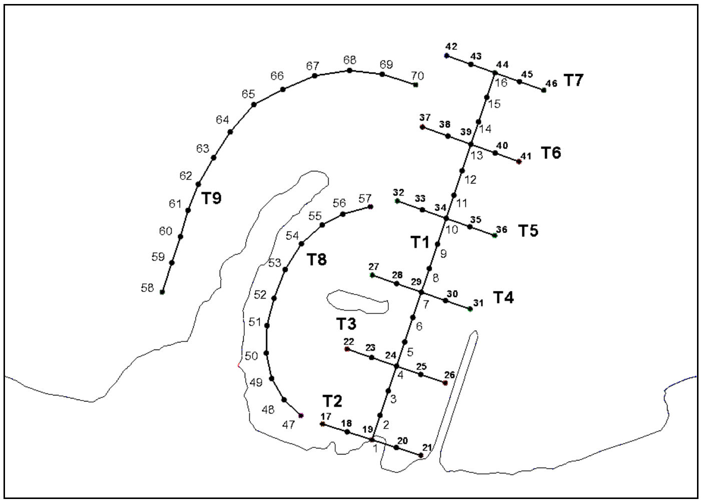

Fig. 7 Output 70 locations along nine transects T1 to T9.

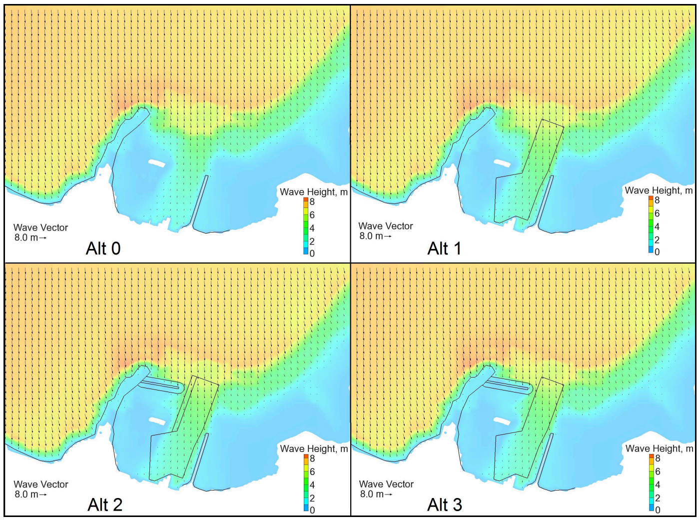

Fig. 8 Harbor wave field for storm event 9.1T14D330W0 (Alts 0 to 4).

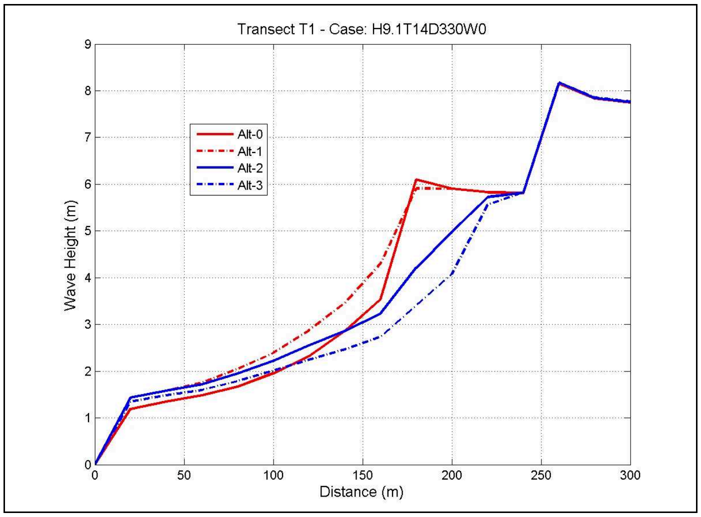

Fig. 9 Model wave heights along T1 for H9.1T14D330W0.

Table 4 Average wave height reductions for Alts 1 to 3 as compared to Alt 0 along the channel centerline (T1) and along dock (T7).

Wave Direction	Channel Centerline (T1)			Dock (T7)		
	Alt 1	Alt 2	Alt 3	Alt 1	Alt 2	Alt 3
315°	6%	25%	30%	12%	27%	30%
337.5°	6%	25%	28%	11%	25%	29%
0°	6%	21%	26%	15%	24%	28%
22.5°	6%	17%	22%	14%	24%	27%

SUMMARY AND CONCLUSIONS

Faleasao Harbor is located on a wide fringing reef on the northwest corner of Tau Island, the largest of the Samoa Islands in the south-central Pacific Ocean. The small turning basin and docking space at the harbor have limited the use of this facility by larger vessels. Waves outside of harbor are consistently large year-round including ocean swells from north sector and wind seas generated by the easterly trade winds. The cyclonic typhoon/hurricane season is during the winter months, and strong tropical storms have caused coastal damage in the harbor surroundings every 3 to 5 years (Demirbilek et al. 2015). Vessels access the harbor through a narrow navigation channel approximately 300 m long, 40 m wide, and 4 m deep. The harbor entrance was protected by an unraveling west breakwater that extends from a rocky natural headland west of the harbor, and a long east jetty along the east side of navigation channel. Both existing west breakwater and east jetty have been deteriorating in recent years that they no longer provide adequate protection to harbor interior from large sea swells and storm waves.

Numerical wave modeling was conducted to investigate the existing harbor configuration (denoted as Alt 0) and three infrastructure modifications (denoted as Alt 1, Alt 2, and Alt 3) which include deepening of the navigation channel and turning basin, and adding structures to the tip of west peninsula (headland) from the existing harbor (Fig. 2). Wave processes in both exterior and interior areas of the harbor were investigated to determine benefits and consequences of proposed infrastructure modifications for improving navigation in the harbor. Design incident wave conditions were based on the offshore wave hindcasting data for 1980-2012 from WIS Sta 81137. Design water levels were based on data from the NOAA Coastal Station 1770000 at Pago Pago, Tutuila.

Two advanced wave models B2D and CMS-Wave were used in the investigation. CMS-Wave, a steady-state directional wave spectral wave, was used to transform offshore waves to the nearshore of Faleasao Harbor. B2D, a Boussinesq type two-dimensional wave model, was used to simulate the waves entering and transforming inside the harbor. Model simulations were completed for three severe storm events and three average wave conditions from four different directions and with respect to two water levels representing the mean and high water levels.

Model wave heights were saved along nine transacts (T1 to T9) covering local areas of interest inside and outside the harbor. Wave height estimates inside the harbor were approximately proportional to the incident wave height. Large storm waves come from difference directions reaching the navigation channel and entering harbor interior have similar heights as such waves are quickly dissipating energy due to the depth-limited condition.

Model results suggested that with adding a new breakwater to the west side of the harbor and repairing existing structures (Alts 2 and 3) would greatly improve navigation in the harbor. As compared to the existing harbor configuration, the average wave height reduction along the navigation channel centerline T1 to the dock front face T7 ranges from 17 to 27 percent for Alt 2 and 22 to 30 percent for Alt 3. There was not a significant change in wave height throughout the harbor from the channel deepening configuration (Alt 1), with 15 percent or less wave height reduction along T1 and T7. Relative larger wave heights inside the harbor correspond to incident waves from north. Because both Alt 2 and Alt 3 had a significant reduction of wave energy inside the harbor, either alternative could be a reasonable long-term solution for improving navigation at the harbor.

In addition to the extent of wave height reduction criterion for improving navigation in Faleasao Harbor, another key factor to consider is the effect of the proximity of structures to the navigation channel. The effects of wave diffraction and reflection are increasingly important when structures are close to a channel, possibly causing local wave height to increase. Model results indicated a potential increase of wave height in the channel near the structures.

Aside from the impacts of dredging on the reefs inside and outside the harbor, the implementation of Alt 1 is straightforward. Sedimentation in this harbor is not a concern, and consequently channel deepening is neither expected to increase the cost of maintenance dredging or create increased sedimentation problems in the back harbor. The implementation of Alt 2 or Alt 3, however, could present a few challenges and consequences. The three potential concerns which are worthy to mention are: 1) increase in wave action at the entrance channel, 2) reduced maneuvering space in the entrance channel, and 3) risk of boats colliding with the structure. These concerns arise because both Alt 2 and Alt 3 structures are expected to reflect more wave energy into the channel. Depending on the characteristics of the superposed incident and reflected waves, the wave heights in the channel could increase or decrease. If structures are protruding too much into the harbor entrance, the navigation channel could be realigned for a safer transit of vessels in and out of the harbor. Minor channel realignment eastward could provide more maneuvering room to avoid grounding and collision of boats with adjacent structures. If the detached spur on the west side were removed, stone from this structure could be used in the construction of the selected infrastructure modification, either Alt 2 or Alt 3. The removal of the existing detached spur would provide additional maneuvering space to the boats in the very narrow channel and allow future widening of the channel to accommodate access to harbor by larger vessels.

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