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Tedious Creek Small Craft Harbor: CGWAVE Model Comparisons Between Existing and Authorized Breakwater Configurations

by Michael J. Briggs, Barbara P. Donnell, Zeki Demirbilek, and Robert D. Carver

PURPOSE: This Coastal and Hydraulics Engineering Technical Note summarizes numerical model comparisons between existing and authorized breakwater configurations at Tedious Creek, MD. The numerical model CGWAVE was used to predict wave heights and directions inside the harbor to determine if there are any significant differences between the two configurations.

BACKGROUND: Tedious Creek is a small estuary on the eastern shore of Chesapeake Bay in Dorchester County, MD (Figure 1). It provides anchorage to more than 100 commercial and recreational vessels. The primary anchorages are the county boat dock (CD) and the public piers (PP), both on the south shore. Because of its orientation, storm waves may cause substantial damage.

In 1994, the U.S. Army Engineer District, Baltimore, and the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL) conducted hydrodynamic model investigations to determine if the proposed breakwater would have any adverse navigation or environmental effects. An analytical model and the RMA2 numerical model were used in the design to optimize the gap width and breakwater alignments. The Baltimore District wrote a Section 107, Feasibility Report and Integrated Environmental Assessment in March 1995 suggesting that a breakwater could provide a cost-effective solution. The authorized project design included a breakwater gap of 91 m (300 ft) for the main channel. An additional gap was included midway along the length of both north and south sides of the new breakwater to improve water circulation and quality.

The existing as-built breakwater differed in geometry from the plans tested in 1994 because of foundation problems encountered during construction in 1997. As a result, the north breakwater was shorter with a 30-m- (100-ft-) wider gap (i.e., 122-m (400-ft) gap) in the main entrance. Because of local concerns, a monitoring effort was initiated in 2001 to test the hypothesis that (a) the existing as-built gap will provide a functional harbor from the standpoint of wave attenuation, circulation, sedimentation, and wetland impacts, (b) the 1997 improvements are structurally sound, (c) the numerical models accurately predict prototype performance, (d) navigation and the environment will not be adversely impacted by sedimentation from the improvements, and (e) local wetland areas are not adversely impacted. Wave data are being collected in FY03 as part of the Monitoring Completed Navigation Projects (MCNP) Program. Numerical model results will be compared with these field data.

CGWAVE MODEL SETUP: CGWAVE is a general purpose, state-of-the-art wave prediction model based on the mild slope equation that is used to model waves in harbors, open coasts, inlets, islands, and fixed and floating structures. It includes the effects of wave refraction, diffraction, and

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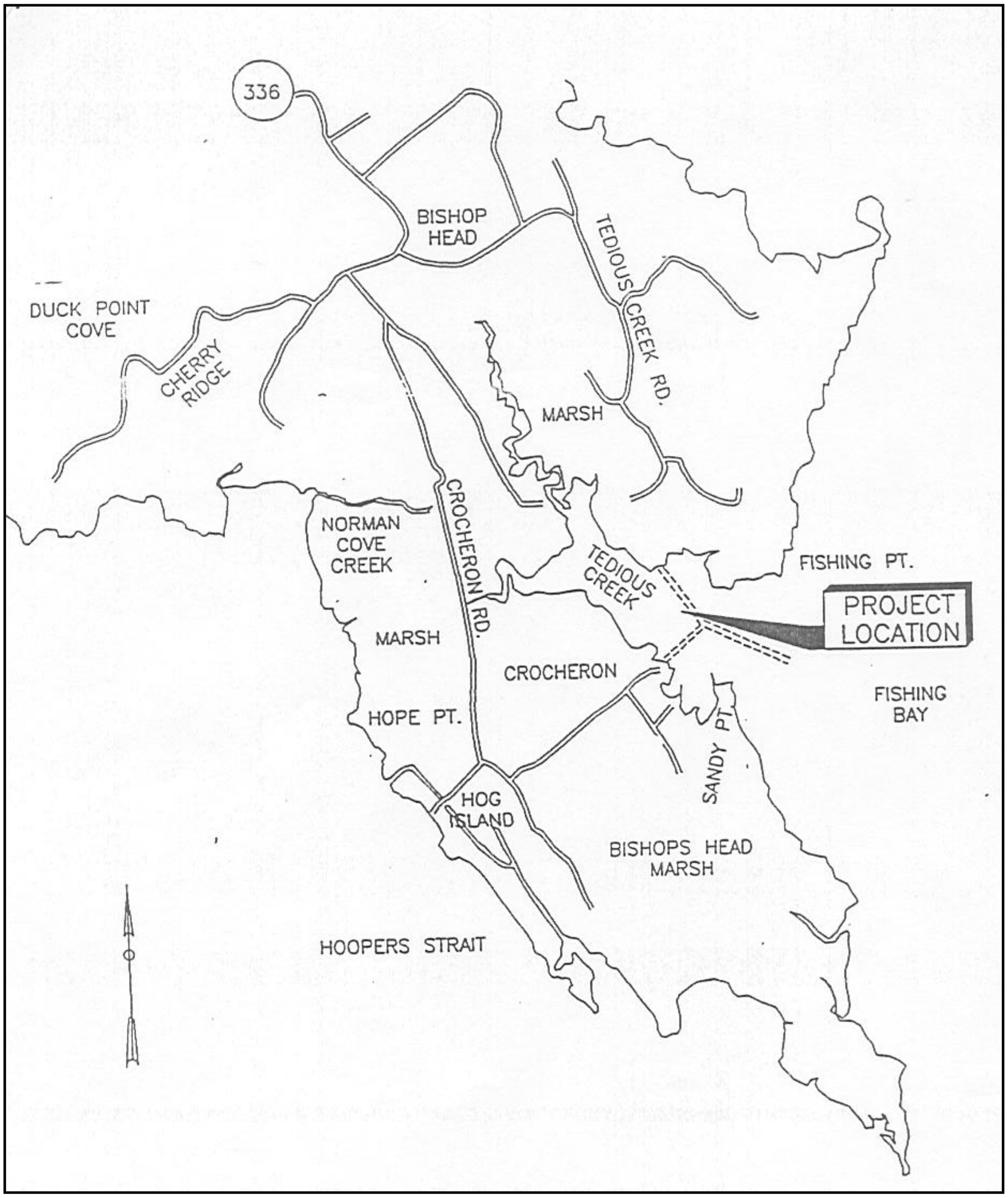


Figure 1. Map of Tedious Creek, MD

dissipation from bottom friction, wave breaking, nonlinear amplitude dispersion, and harbor entrance losses. CGWAVE is a finite element model that is interfaced with the Department of Defense Surface-Water Modeling System (SMS) for graphics and efficient implementation (pre- and post-processing).

Figure 2 shows the orientation of the CGWAVE model domain relative to Tedious Creek and the adjacent countryside. The brown line represents the model boundaries for the harbor and the blue line the ocean or seaward water boundary. The CGWAVE model requires a minimum of 6 to 10 elements per wavelength. Since the harbor area is large and shallow and wave periods as small as

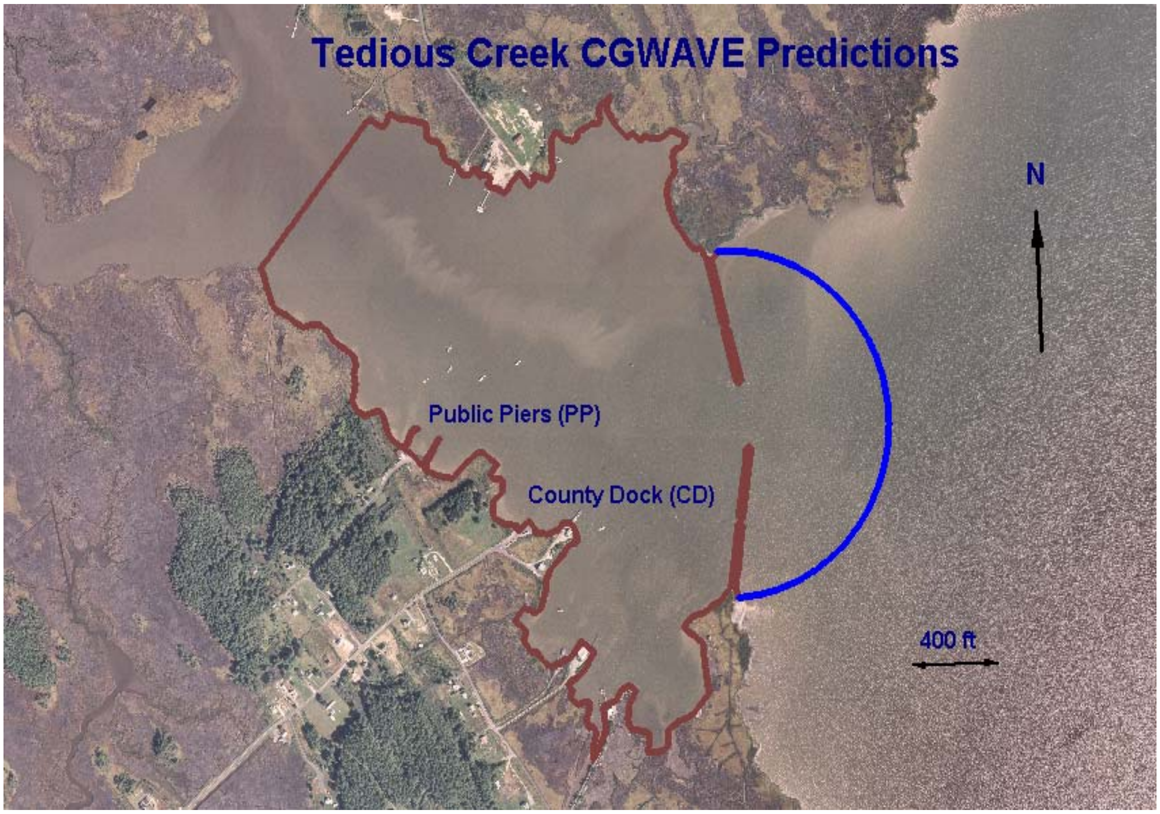


Figure 2. CGWAVE model for Tedious Creek, MD, with existing as-built gap of 122 m (400 ft)

6 sec are prevalent, the required grid size was 1.9 m (6.1 ft). Therefore, it was decided to limit the model size to cover only the most critical areas inside and outside the harbor. The area within the brown boundaries is more than adequate to model the wave conditions inside the harbor.

Bathymetric data were collected by CHL in August 2001 to provide an accurate baseline grid for the modeled area inside and offshore of the breakwaters. The entire Tedious Creek estuary is shallow, with depths less than 2.7 m (8.9 ft). The area outside the ocean boundary was not surveyed, but was represented by contours from bathymetric charts of the area. These bathymetric contours were used to model the one-dimensional (1-D) bathymetric lines offshore of the breakwaters required by CGWAVE. Figure 3 shows a contour plot of water depth for a representative storm water level of 1.0 m (3.3 ft) mllw in the existing configuration.

Mean and spring tides range from 0.7 m (2.4 ft) to 0.9 m (3.0 ft), respectively. The 5-year water level, including tide and storm effects, is 1.1 m (3.7 ft) above mllw (TC Report 1995). Thus, a water level of 1.0 m (3.3 ft) mllw was selected as a representative worst case of normally occurring tide and storm levels at Tedious Creek. Since storm wave heights are directly related to water level at this shallow site, only the 1.0-m (3.3-ft) water level was modeled.

Two different model grids were created in CGWAVE. The existing as-built model included a breakwater gap of 122 m (400 ft). The authorized project model has a breakwater gap of 91 m (300 ft).

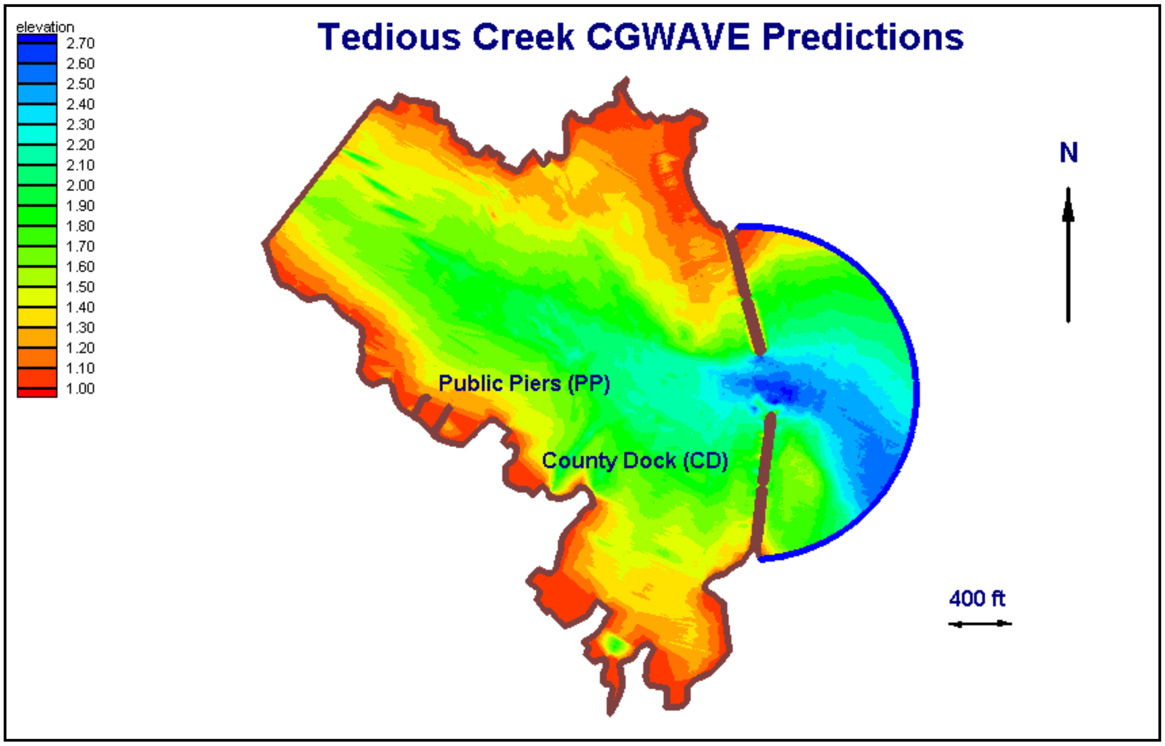


Figure 3. Tedious Creek bathymetry with water level of 1.0 m mllw for existing configuration

Nine different wave conditions, composed of three wave periods and three wave directions, were selected for study based on harbor orientation, limited field measurements, local observations, and previous analysis (OCTI 2001). Wave periods $T = 6$, 10, and 16 sec were selected as representative of the range of wave periods occurring in the harbor. The OCTI study (2001) used a JONSWAP spectrum with a peak period in the range of 8 to 10 sec. The $T = 6$ sec was chosen as the minimum period for use of CGWAVE. The $T = 16$ sec value was selected as the worst-case swell waves that might propagate into the harbor from Atlantic storms. Mean wave directions of $\bar{\theta} = 135$, 180, and 225 deg represent waves propagating to the northwest, west, and southwest (angles measured counterclockwise from the east), respectively. The OCTI study (2001) used these direction limits, with waves from the southwest considered the worst case for the CD even though they also tested waves from 210 deg (west-southwest). Waves traveling to the west and southwest are most likely to affect the PP and CD, respectively, since they have a clear path through the breakwater gap. According to the Section 107 Feasibility Report (1995), 5-year storm significant wave heights traveling to the southwest to northwest range from $H_{m0} = 0.5$ m (1.6 ft) to 0.7 m (2.3 ft). Fifty-year storm heights varied from $H_{m0} = 0.6$ m (2.1 ft) to 1.5 m (4.9 ft). A representative value of 1 m was selected as the incident wave height H_I at the offshore grid boundary. All modeled waves were regular (i.e., monochromatic).

The CGWAVE includes wave reflection from solid boundaries. Reflection coefficients of $C_r = 0.0$, 0.1, 0.5, and 0.9 were selected for the open ocean, inner bay perimeter, rubble-mound breakwater, and PP, respectively. As mentioned previously, the CGWAVE model requires small element sizes in shallow-water regions for accurate description of short-period waves.

CGWAVE SENSITIVITY: Because the local interest was in the areas near the CD and the PP, two transects (T1 and T2) were selected between these two facilities and the breakwater entrance (BE). Figure 4 shows the orientation of these two transects for both existing and authorized model layouts. The T1 is 481 m (1,579 ft) long between the CD and the BE and T2 is 673 m (2,207 ft) between the PP and the BE.

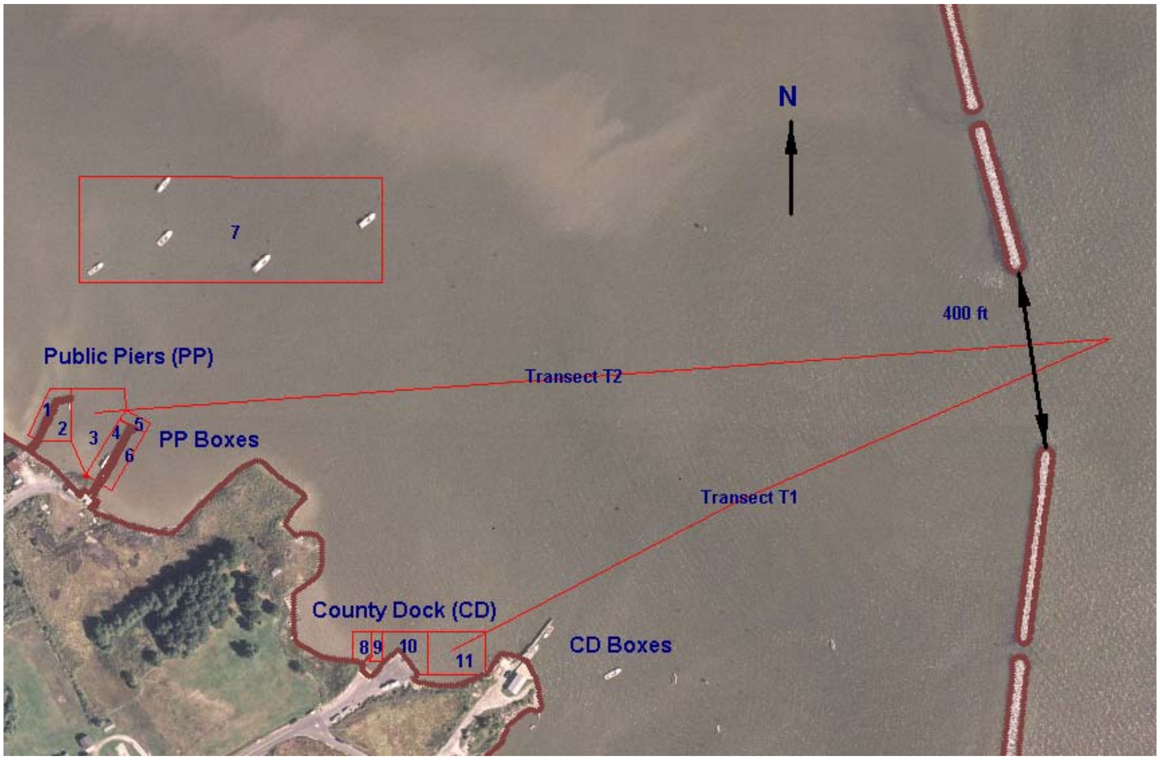
The CGWAVE model has options to include bottom friction (BF) and wave breaking (WB). The first step in the model calibration was to run some test cases to quantify their effect on the predicted wave heights H inside the harbor. Thus, the $T = 6$ sec waves traveling to the west (i.e., $\bar{\theta} = 180$ deg) were run for base cases (a) without BF or WB (none), (b) with WB only, (c) with BF only, and (d) combined BF and WB (BFWB).

Figure 5 shows the wave height predictions along T1 and T2 for each of the four sensitivity parameter combinations. As expected, wave height was larger for the "none" case (i.e., linear mode) without BF and WB. Of course, in the linear mode, model predictions would be unrealistic as these two wave phenomena are present in nature and would naturally limit the wave heights. Inclusion of BF was more significant than WB. Even though the difference between BF and BFWB was slight, it was decided to include the combined effects of both phenomena in comparison of the two configurations.

CGWAVE CALIBRATION: CHL conducted a limited field study from April 27 to July 21, 2001, with three wave gages (Figure 6). A NORTEK Aquadopp directional wave gage (PUV-type) measured incident wave conditions outside the breakwater in an average depth of 2.2 m (7.2 ft) mlw. Two unidirectional pressure gages measured transformed wave conditions inside the breakwater in 1.7 m (5.6 ft) mlw (Gage 215) and 1.3 m (4.3 ft) mlw (Gage 212). Gage 215 lay on transect T1. The sampling frequency was 4 Hz, with a sampling interval every 3 hr, for all three gages.

Figure 7 is a time series of incident wave period, significant wave height, and wave direction. Measured PUV wave directions were converted from wave direction from which waves travel, measured clockwise from north, to CGWAVE conventions. Figure 8 shows transmitted wave heights for Gages 212 and 215. Since this was a milder time of the year and there were no major storms, incident wave conditions were fairly benign (i.e., in the range of $T = 2$ to 5 sec, $H_s < 0.5$ m, and average wave direction of 118 deg or waves traveling to north-northwest. The transmitted wave heights were even smaller, with a maximum of 0.31 m (1.1 ft) and averages of 0.06 m (0.2 ft).

Because these waves were small, it was difficult to compare them to CGWAVE predictions. A few limited comparisons were made and are shown in Figure 9 for the two transmitted gage locations. Measured incident wave parameters ranged from $2.03 \le T \le 4.75$ sec, $0.07 \le H_s \le 0.27$ m, and $135 \le \theta \le 221$ deg. An attempt was made to select the largest wave period and height combinations. An equivalent significant wave height and exact wave period and direction were used as input to CGWAVE. The model predictions were averaged over a 30-m (100-ft) square box around each field gage location (Figure 6) to allow for location anomalies and the contouring algorithm in the model. Considering that CGWAVE was designed for wave periods of the order of 5 sec or larger, the agreement was good.



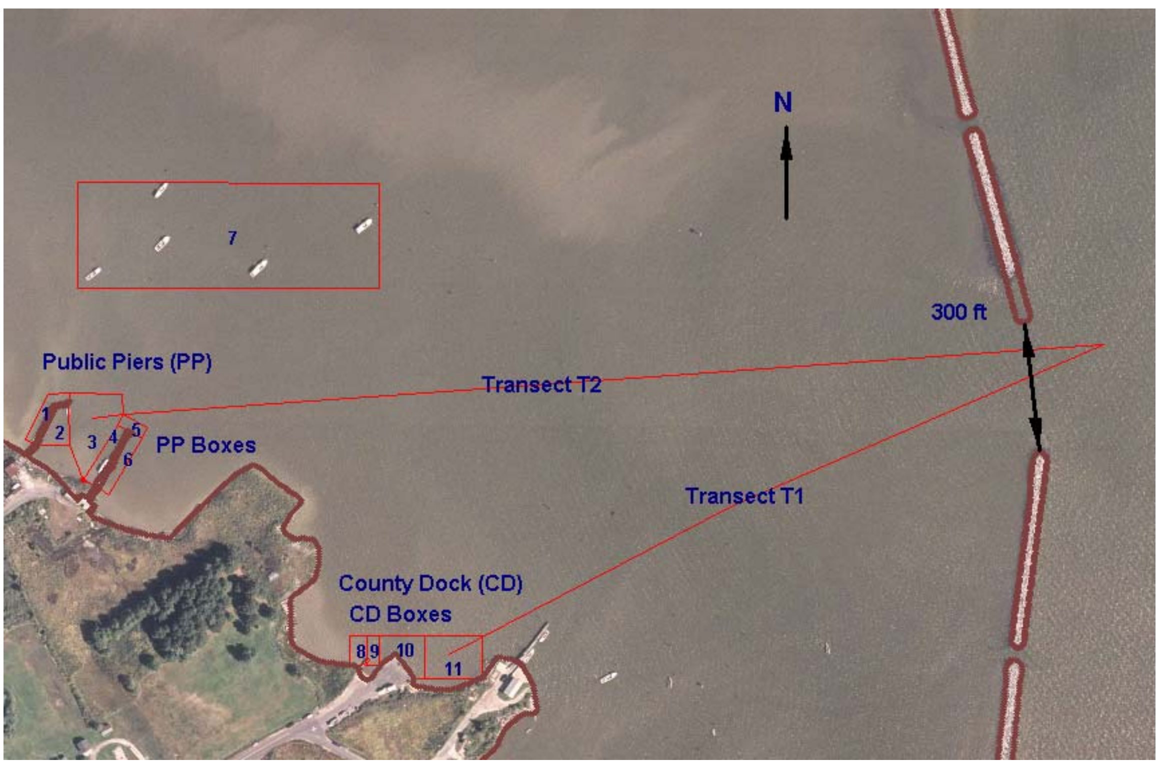


Figure 4. Orientation of transect lines T1 and T2 and 11 boxes for (a) existing breakwater with 122-m (400-ft) gap and (b) authorized breakwater with 91-m (300-ft) gap

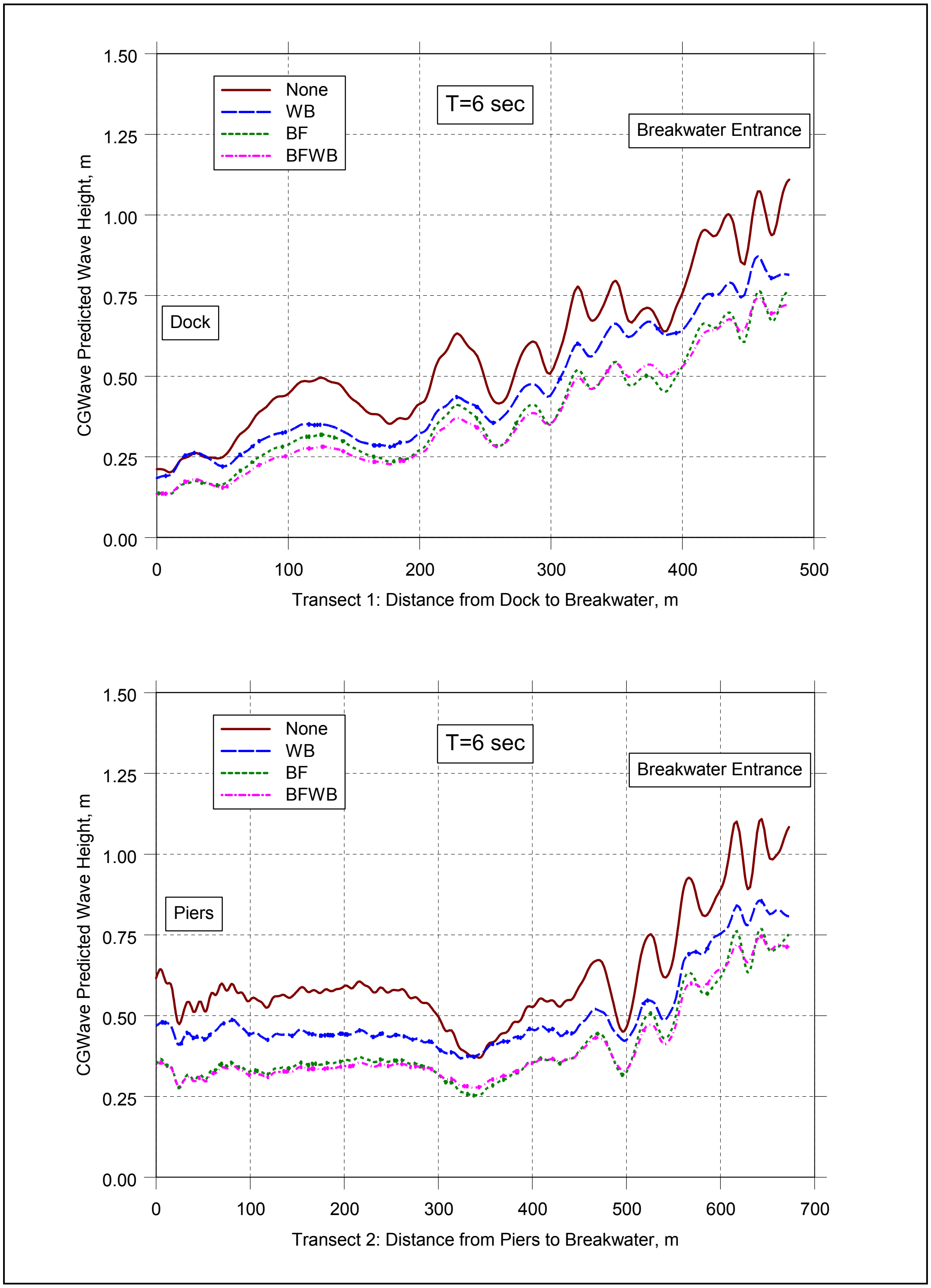


Figure 5. CGWAVE wave heights for no breaking (none), wave breaking (WB), bottom friction (BF), and both (BFWB) for T = 6 sec, H_i = 1 m, water level of 1 m mllw, and wave direction of $\overline{\theta}$ = W (180 deg) along (a) transect T1 and (b) transect T2

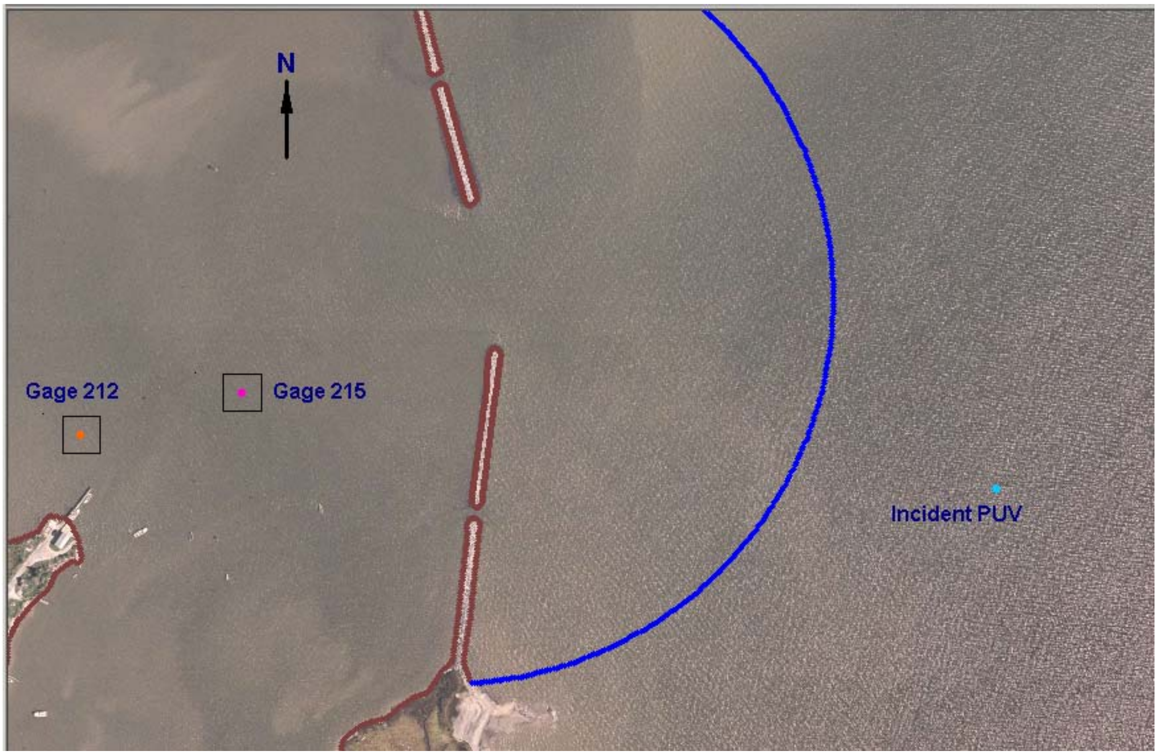


Figure 6. Field gage locations, April to July 2001

EXISTING AS-BUILT BREAKWATER WAVE HEIGHTS: The existing as-built breakwater gap was 122 m (400 ft). In this section, predicted wave heights within the harbor area from the CGWAVE model are presented for nine wave conditions. Because a distribution of historical wave conditions is not available for this location, all wave conditions are assumed to occur with equal probability. Waves with a $T = 6$ sec, however, are probably the most typical wave conditions due to the shallow depths and the orientation of the harbor within Chesapeake Bay.

Figure 10 is a contour plot of the wave height H for $T = 6$ sec waves and three wave directions traveling to $\overline{\theta} = 135$ (NW), 180 (W), and 225 (SW) deg, respectively. The constant-length vectors illustrate wave directions within the domain. The incident wave height is 1.0 m (3.3 ft) on the offshore boundary and decreases as waves propagate into the harbor. Larger wave heights occur to the north for waves traveling to the northwest, to the west and vicinity of the PP for waves traveling to the west, and to the southwest and vicinity of the CD for waves traveling to the southwest. The wave patterns are similar for the longer wave periods (not shown), and display slightly different penetration patterns of wave energy.

Figures 11 and 12 show the predicted wave heights H along T1 and T2, respectively, for the three wave periods $T = 6$, 10, and 16 sec for the existing configuration. The three curves on each plot represent the three different wave directions $\overline{\theta} = 135$ (NW), 180 (W), and 225 (SW) deg, respectively. For transect T1 going to the CD, waves traveling to the southwest (green, short dash line) are the highest in the inner part of the harbor. Waves traveling to the west (blue, dash line) become higher in the vicinity of the BE. The crossover point between these two wave directions moves closer to the BE as wave period increases. Waves traveling to the northwest (red, solid line)

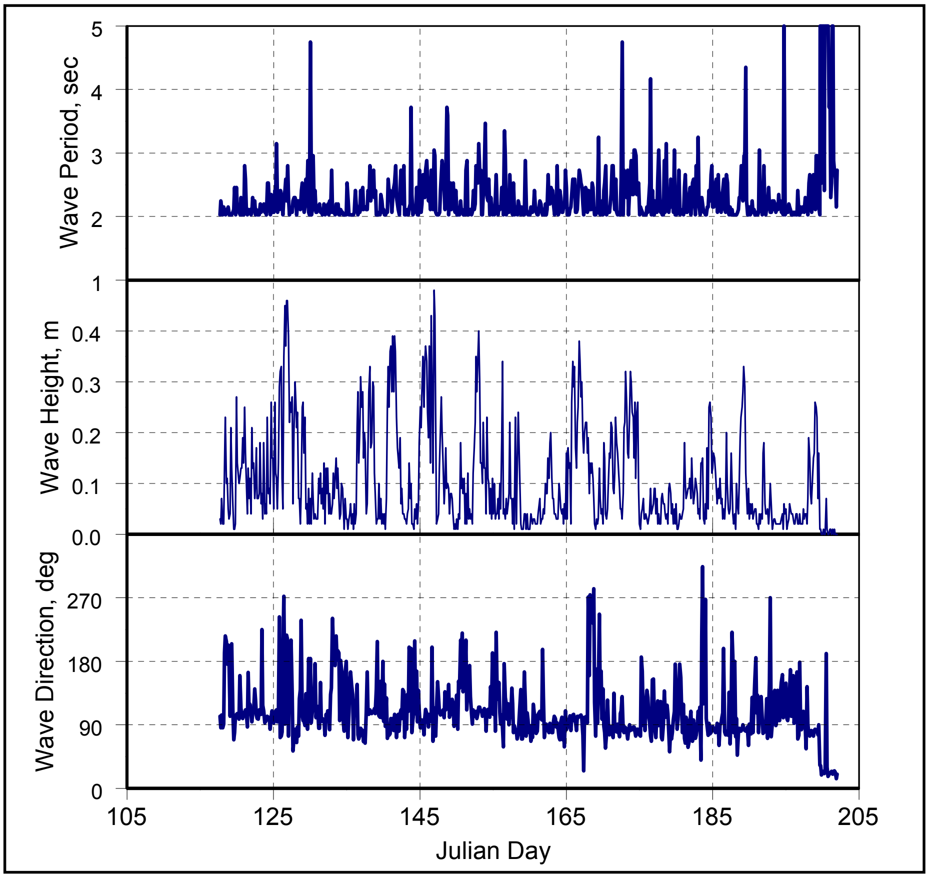


Figure 7. Measured incident PUV directional gage wave parameters

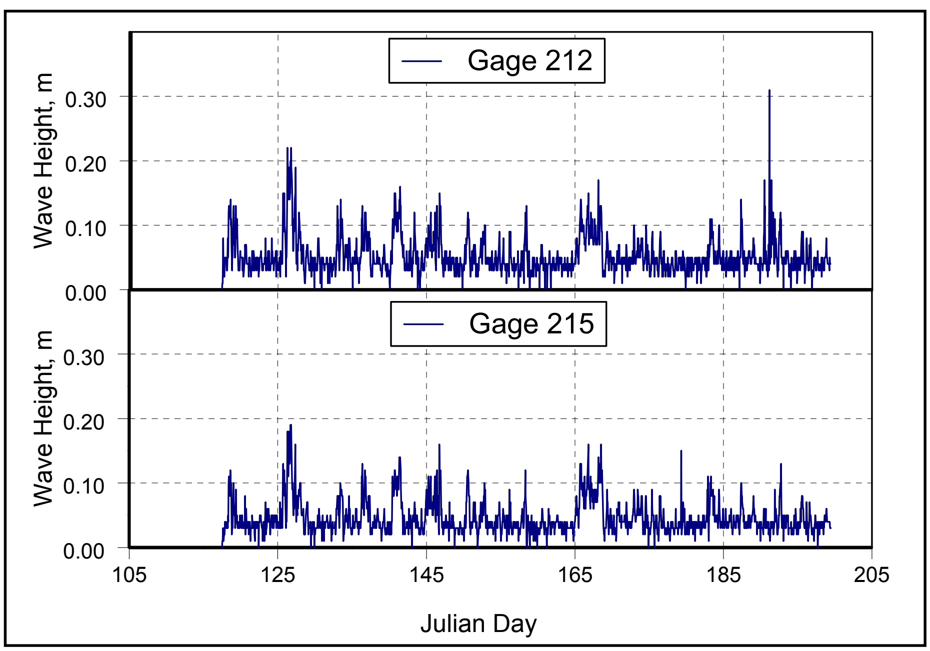


Figure 8. Measured transmitted wave heights for gages 212 and 215

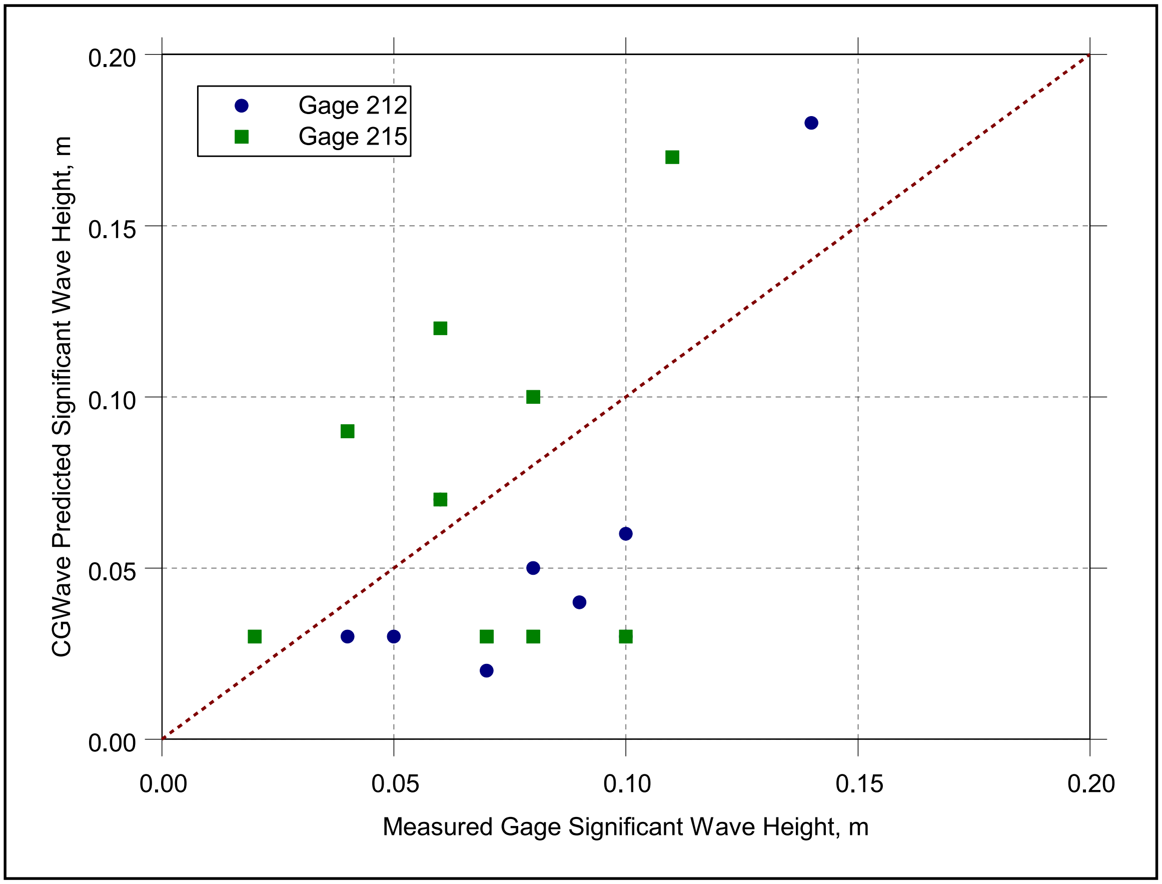


Figure 9. Comparison of CGWAVE predicted wave heights with measured field sites

are smaller since they propagate away from the area of T1. For T2 going to the PP, waves traveling to the west are the highest throughout the harbor region for all wave periods. Waves traveling to the other two directions are nearly the same for the first 400 to 500 m (1,312 to 1,640 ft) from the PP, where the waves traveling to the southwest are higher.

Wave height statistics were calculated along T1 and T2 in an attempt to quantify wave heights. The CGWAVE model predicted 414 wave heights along the 481-m- (1,578-ft-) long T1 and 616 along the 672-m- (2,205-ft-) long T2 transect. The minimum (H_{Min}), maximum (H_{Max}), average ($\overline{H}$), and standard deviation wave height (H_σ) for transects T1 and T2 are listed for all wave conditions in Table 1. Of course, the H_{Max} occurs near the BE in most cases, which is outside the protection of the breakwater. Based on the data, the average wave height along T1 will be in the range of 0.31 ±0.02 m

Table 1
Wave Height Statistics for Transects T1 and T2

Parameter	T1	T2
Existing Configuration		
H_{Min}	0.01 m	0.08 m
H_{Max}	0.78 m	0.76 m
$\overline{H}$	0.31 m	0.28 m
H_σ	0.11 m	0.11 m
Authorized Configuration		
H_{Min}	0.01 m	0.03 m
H_{Max}	0.81 m	0.86 m
$\overline{H}$	0.27 m	0.24 m
H_σ	0.09 m	0.12 m

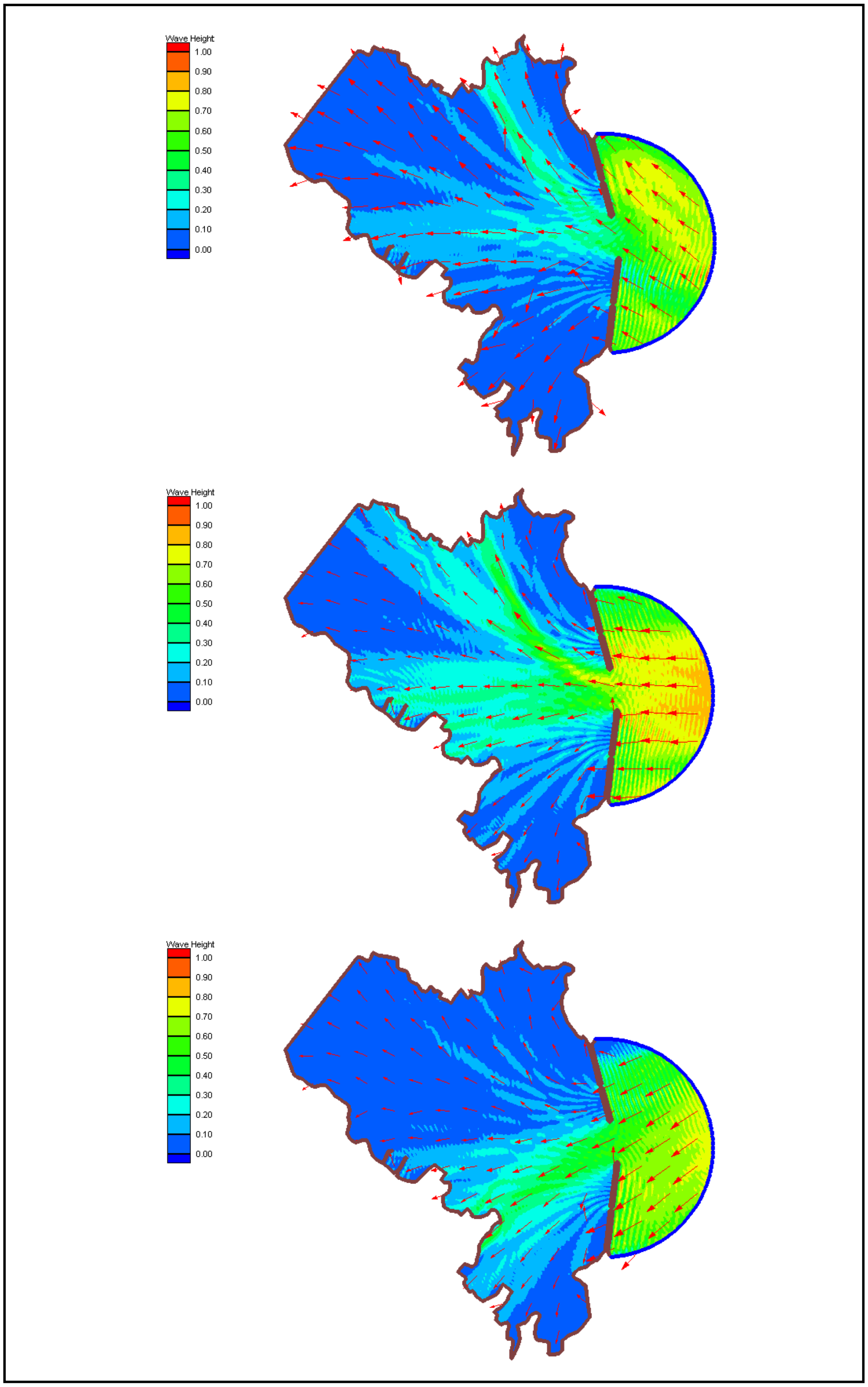


Figure 10. CGWAVE wave height predictions for existing configuration with wave conditions of T = 6 sec, H_I = 1 m, water level of 1 m mllw, and wave directions of (a) NW (135 deg), (b) W (180 deg), and (c) SW (225 deg)

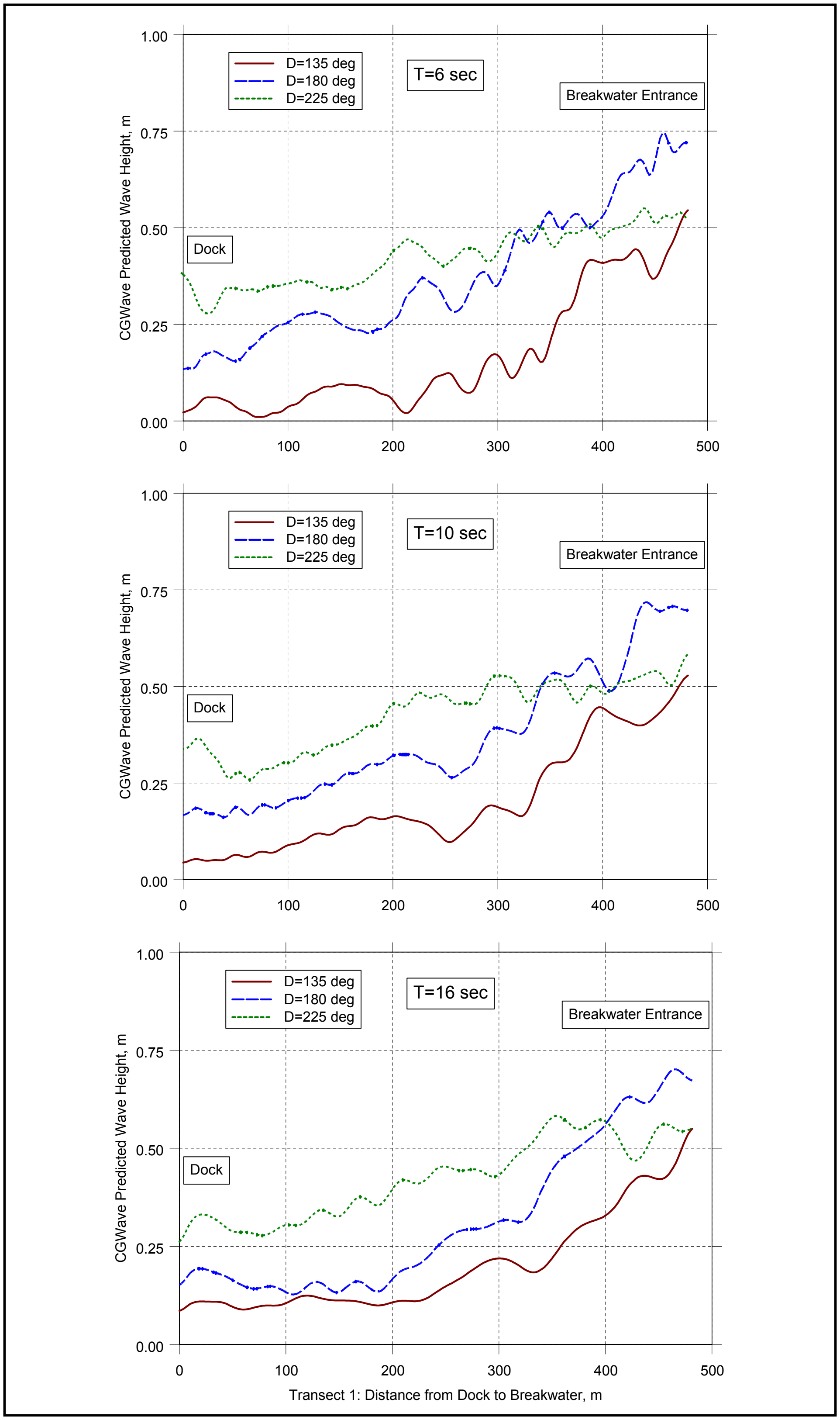


Figure 11. CGWAVE wave height predictions along transect T1 for existing configuration with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

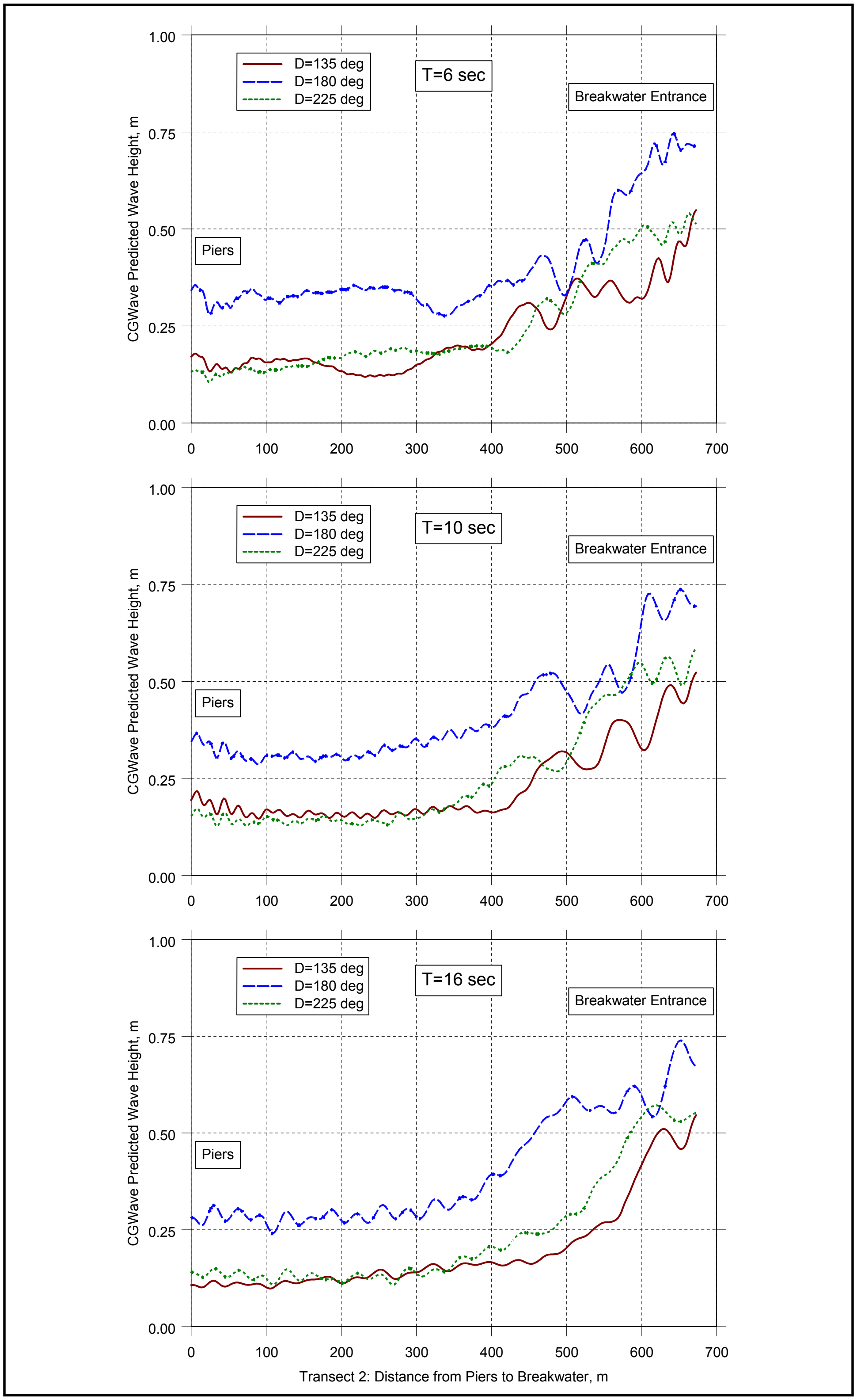


Figure 12. CGWAVE wave height predictions along transect T2 for existing configuration with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

with 95 percent confidence. The average wave height along T2 will be in the range of 0.28 ±0.01 m with 95 percent confidence.

The two transects provide a general overview of wave height within the harbor. However, because of the significant variability in wave height along each one as a function of position and water depth, it is difficult to compare wave energy between the two configurations based on an average wave height along these transects. Another approach was to average the wave heights within limited areas or boxes adjacent to the PP and CD. Each box contains many nodes from the CGWAVE model, each with a predicted wave height value. Figure 4 shows a set of seven boxes (i.e., boxes 1 to 7) in the vicinity of the PP and four boxes (i.e., boxes 8 to 11) adjacent to the CD. Boxes 1 and 2 are adjacent to the westerly pier, boxes 4 to 6 the easterly pier, box 3 in between the two piers, and box 7 contains the offshore docking area. Boxes 8 and 9 are in the vicinity of the boat ramp of the CD and boxes 10 and 11 are to the east. The end points of T1 and T2 can be seen in the interior of boxes 3 and 11, respectively.

Figure 13 shows the average wave heights in each box $\bar{H}$ for the three wave periods. The PP boxes (1 to 7) are to the left of the vertical red line and the CD boxes (8 to 11) are to the right. For the PP boxes, the highest wave heights occur for waves traveling to the west (180 deg). For the CD boxes, the highest heights occur for waves traveling predominantly to the southwest (225 deg).

The maximum wave heights $\bar{H}_{Max}$ and their box locations from Figure 13 are shown in Table 2 for the boxes in the PP and CD areas. Averaged over all boxes in the PP area, the maximum average wave heights $\bar{H}_{All}$ = 0.23, 0.26, and 0.23 m for T = 6, 10, and 16 sec, respectively. All maximum values are for waves traveling to the west. Averaged over all boxes in the CD area, the maximum average wave heights $\bar{H}_{All}$ = 0.26, 0.25, and 0.23 m for T = 6, 10, and 16 sec, respectively. All maximum values are for waves traveling to the southwest for the CD boxes. Finally, the 95 percent confidence intervals for average wave height inside all boxes for all wave conditions are 0.16 ± 0.02 m in the PP boxes and 0.16 ±0.03 m in the CD boxes. In general, the box area wave heights correlate well with the predicted values for the two transects. The average wave heights for the boxes are smaller than the transect averages since they only cover the shallower areas that have experienced greater energy dissipation (e.g., further wave diffraction behind the breakwater, energy losses due to bottom friction and wave breaking, etc.).

AUTHORIZED BREAKWATER WAVE HEIGHTS: The authorized breakwater gap was 91 m (300 ft), or 30 m (100 ft) shorter than the existing breakwater gap. The analysis in this section is similar to the previous section for the existing configuration. Figure 14 is a contour plot of the H for the T = 6 sec waves and three wave directions, similar to Figure 10. The wave patterns for all wave periods are similar to the existing breakwater, except that the smaller gap reduces the extent of the wave incursion into the harbor.

Figures 15 and 16 show the predicted wave heights H along T1 and T2, respectively, for the three wave periods T = 6, 10, and 16 sec for the authorized configuration. For transect T1 and waves going to the CD, the narrower gap significantly reduces wave energy inside the harbor for waves traveling to the southwest (green short dash line). This is in agreement with OCTI (2001) findings.

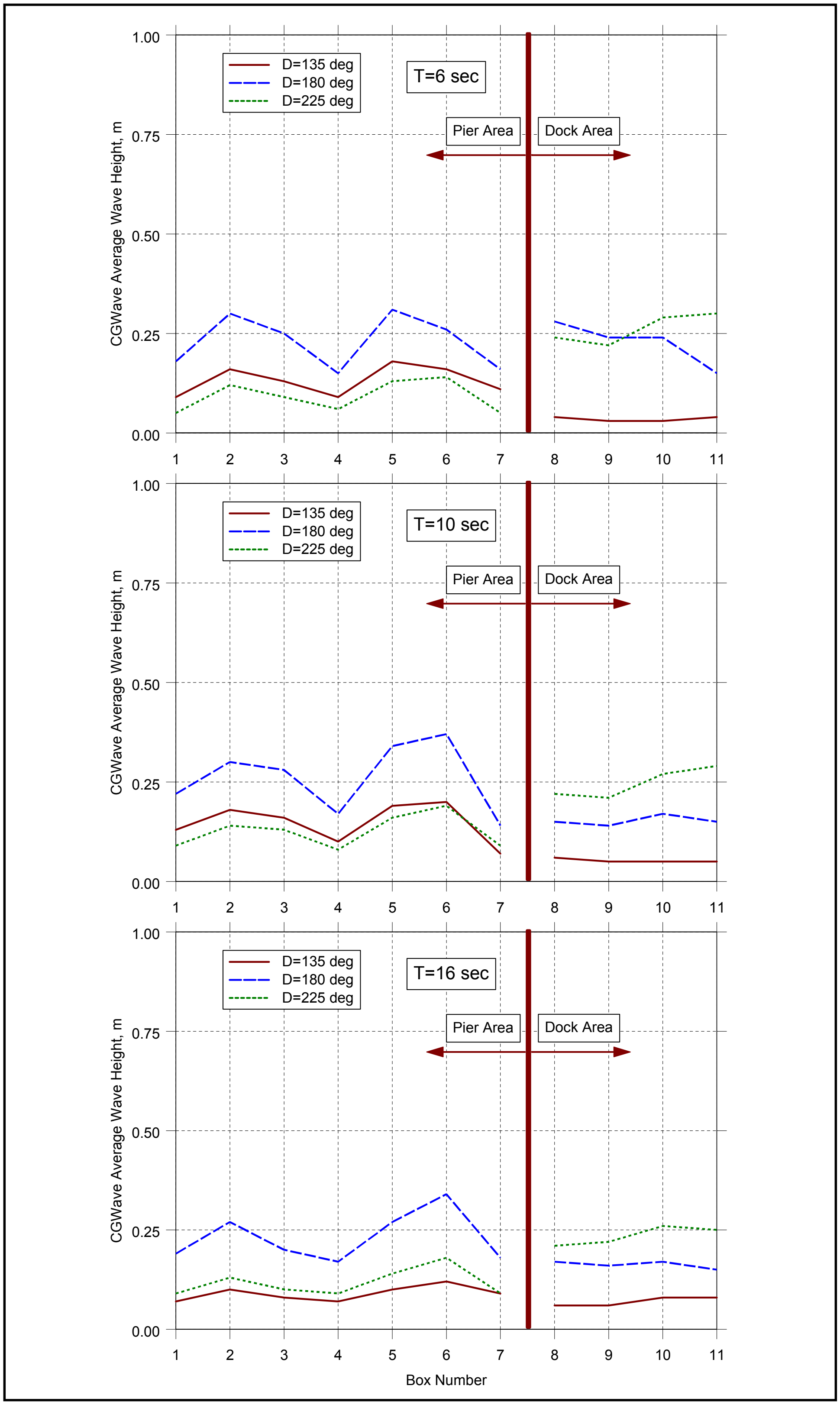


Figure 13. CGWAVE average wave heights in box areas for existing configuration for waves with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

Although they had run some tests with waves traveling midway between west and southwest (equivalent to west-southwest or $\overline{\theta}$ = 210 deg), these waves did not prove to be worse than the southwest waves ($\overline{\theta}$ = 225 deg). The largest waves are now traveling to the west (blue, dash line). The difference in wave height for waves traveling to the west and waves traveling to the southwest decreases as wave period increases. For T2 and waves going to the PP, the largest waves are traveling to the west.

Table 2
Maximum Average Wave Heights in Box Areas

Parameter	PP Boxes	CD Boxes
Existing Configuration		
T = 6 sec	0.31 m (Box 5)	0.30 m (Box 11)
T = 10 sec	0.37 m (Box 6)	0.29 m (Box 11)
T = 16 sec	0.34 m (Box 6)	0.26 m (Box 10)
Authorized Configuration		
T = 6 sec	0.33 m (Box 5, 6)	0.23 m (Box 8)
T = 10 sec	0.38 m (Box 6)	0.20 m (Box 10)
T = 16 sec	0.30 m (Box 6)	0.21 m (Box 10)

The CGWAVE model provided 421 wave heights along the 481-m- (1,578-ft-) long T1 and 610 along the 672-m- (2,205-ft-) long T2 transect. Wave height statistics are again summarized in Table 1 for all wave conditions along the two transects. Based on the data, the average wave height along T1 will be in the range of 0.27 ±0.01 m with 95 percent confidence. The average wave height along T2 will be in the range of 0.24 ±0.01 m with 95 percent confidence.

As before, a more meaningful analysis is obtained by looking at the boxes near the high use areas in the vicinity of the PP and CD. Figure 17 shows the $\overline{H}$ for the authorized configuration for the three wave periods. The maximum wave heights occur for waves traveling to the west for both PP and CD boxes. This represents a change from the existing configuration for the CD boxes where the maximum heights occurred for a wave direction to the southwest.

Again, the $\overline{H}_{Max}$ and their locations from Figure 17 are shown for the PP and CD boxes in Table 2. Averaged over all PP boxes, the maximum average wave heights $\overline{H}_{All}$ = 0.24, 0.25, and 0.20 m for T = 6, 10, and 16 sec, respectively. All maximum values are for waves traveling to the west. Averaged over all CD boxes, the maximum average wave heights $\overline{H}_{All}$ = 0.19, 0.18, and 0.20 m for T = 6, 10, and 16 sec, respectively. All maximum values are for waves traveling to the west. Finally, the 95 percent confidence interval for average wave height inside all boxes for all wave conditions is 0.13 ±0.02 m in both the PP and CD areas.

COMPARISON OF BREAKWATER CONFIGURATIONS: In the previous plots, the CGWAVE predicted wave heights H were shown for each transect, box, wave condition, and breakwater configuration. In this section, a comparison of the predicted wave heights between the existing 122-m (400-ft) gap and the authorized 91-m (300-ft) gap breakwater is presented. Because of the variability along the two transects (as previously discussed), only the wave heights in the boxes are compared.

Wave height differences H_{Δ} between the existing (E) and authorized (A) configurations are shown for the PP and CD boxes in Figure 18. Negative differences indicate that the existing configuration has a smaller predicted wave height than the authorized configuration. Therefore, only the positive

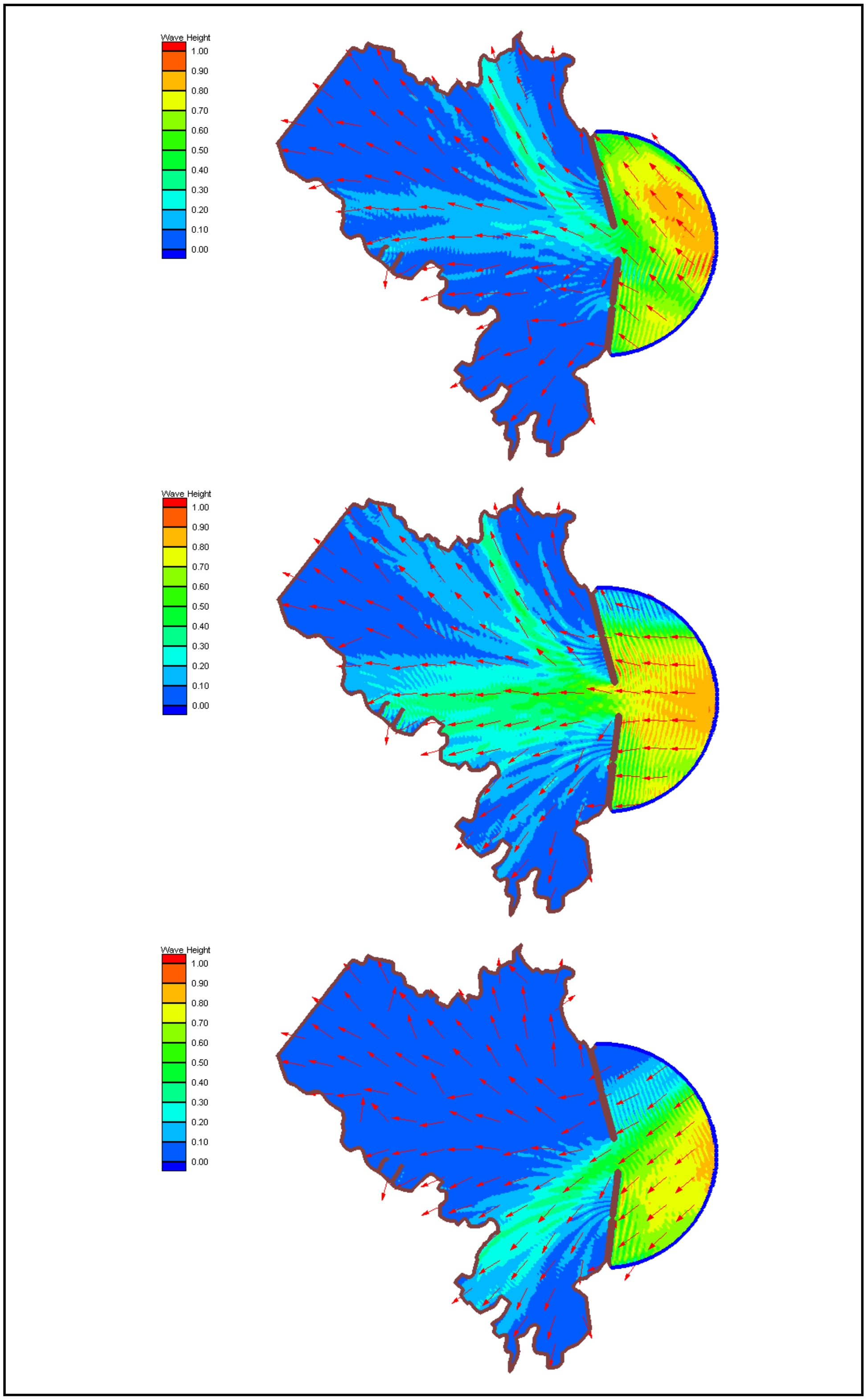


Figure 14. CGWAVE predictions for authorized configuration with wave conditions of T = 6 sec, H_I = 1 m, water level of 1 m mllw, and wave directions of (a) NW (135 deg), (b) W (180 deg), and (c) SW (225 deg)

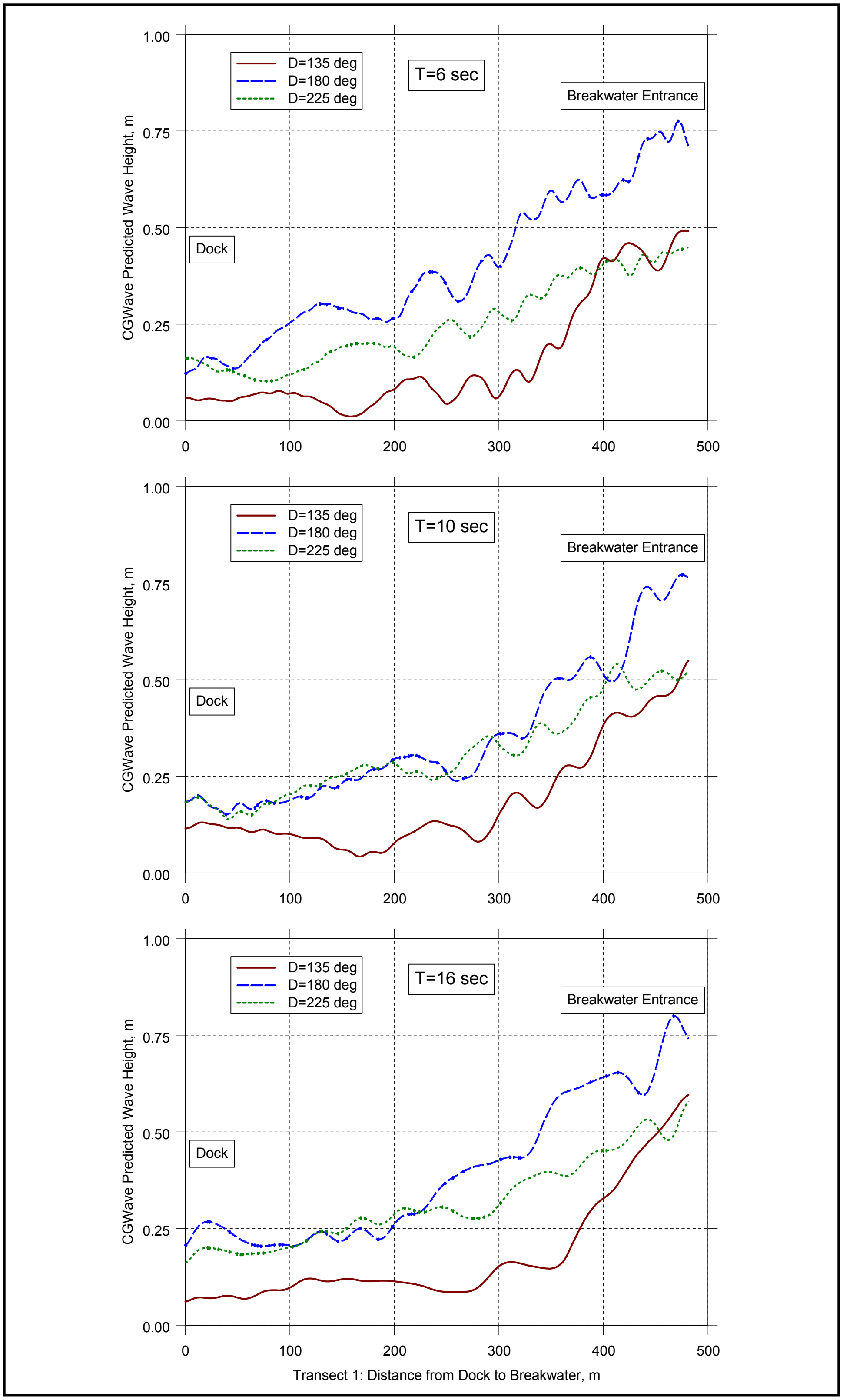


Figure 15. CGWAVE wave height predictions along transect T1 for authorized configuration with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

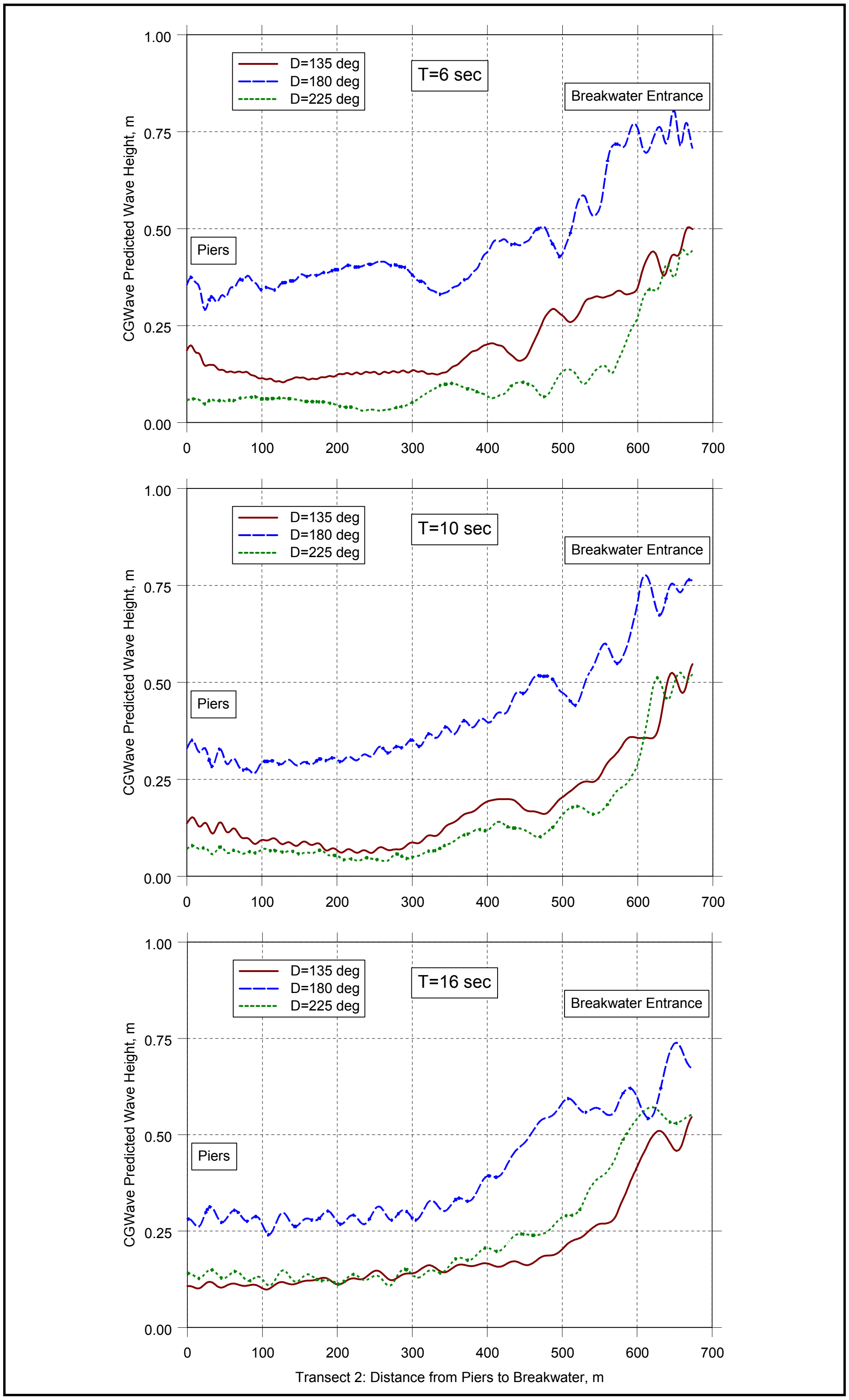


Figure 16. CGWAVE wave height predictions along transect T2 for authorized configuration with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

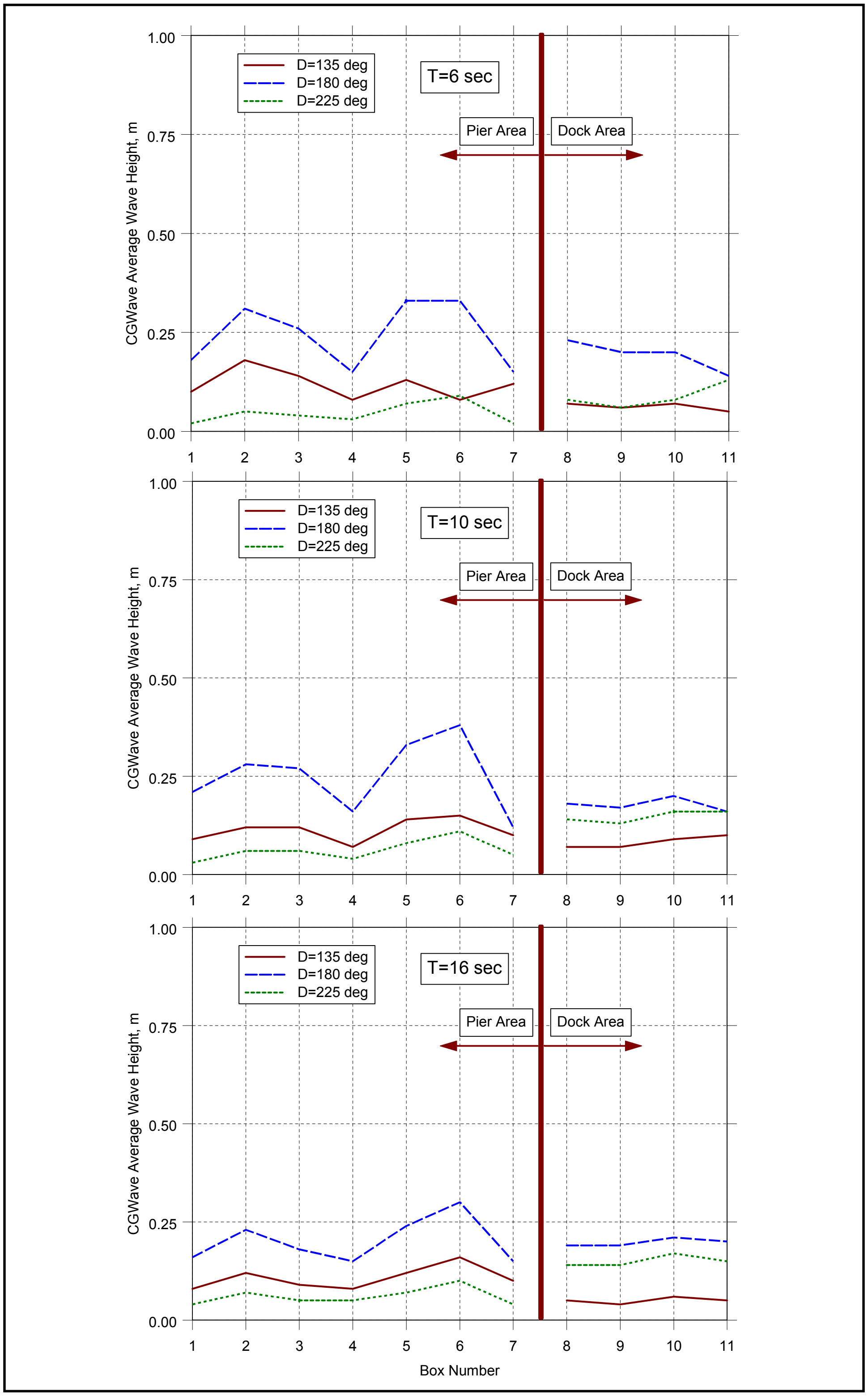


Figure 17. CGWAVE average wave heights in box areas in authorized configuration for waves with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

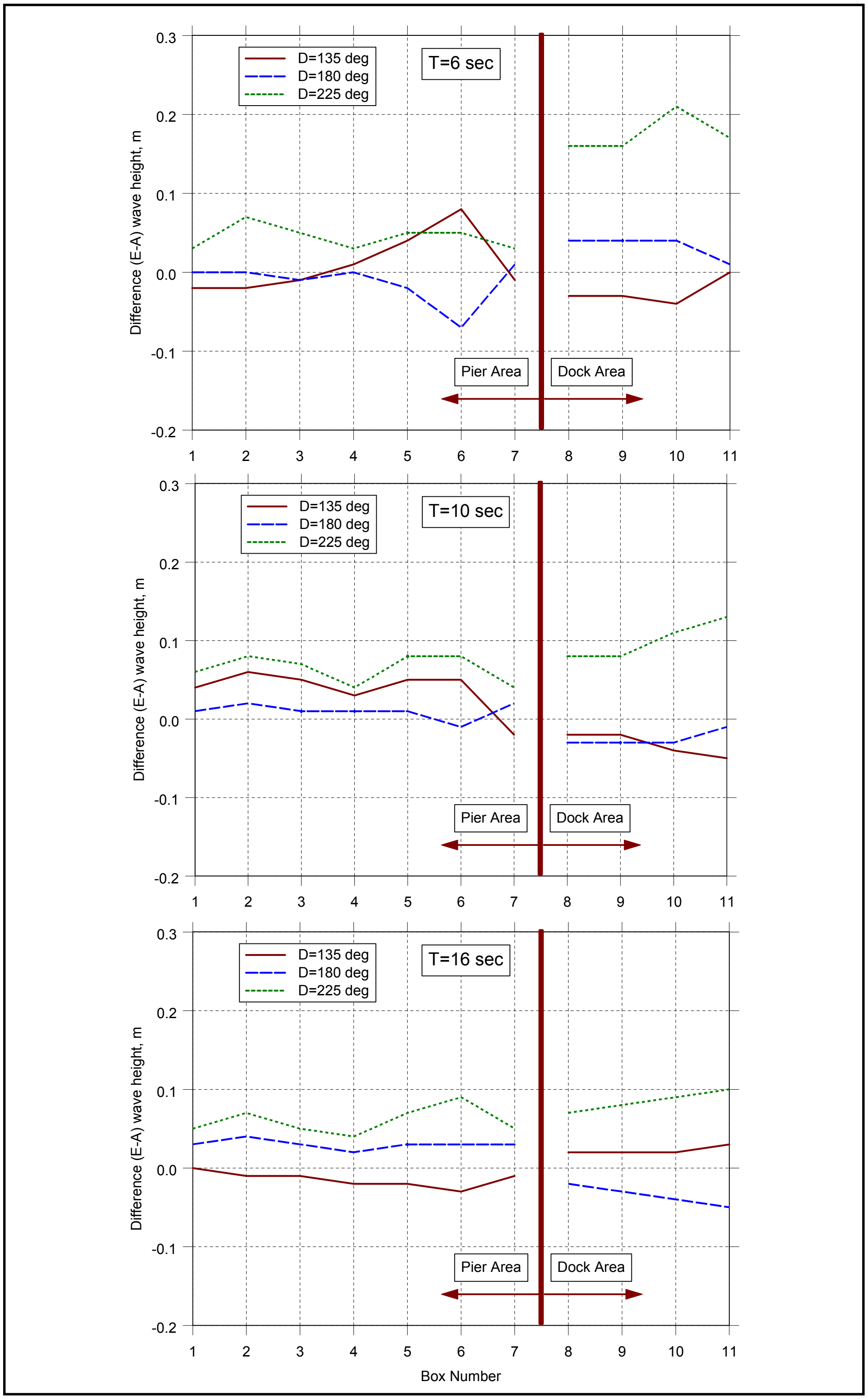


Figure 18. Difference wave heights in box areas between existing and authorized configurations for waves with H_I = 1 m, water level of 1 m mllw, and (a) T = 6 sec, (b) T = 10 sec, and (c) T = 16 sec

differences are of interest to the local residents of Tedious Creek since they imply that the authorized configuration would have reduced the wave energy in the harbor.

In general, the maximum difference wave heights $H_{\Delta Max}$ are not very large and occurred for southwest waves for both the PP and CD area boxes. For the PP boxes, the $H_{\Delta Max}$ = 0.08 m in box 6 for T = 6 sec; $H_{\Delta Max}$ = 0.08 m in boxes 2, 5, and 6 for T = 10 sec; and $H_{\Delta Max}$ = 0.09 m in box 6 for T = 16 sec. Averaged over all boxes, the maximum difference wave heights $\bar{H}_{\Delta}$ = 0.04, 0.06, and 0.06 m for T = 6, 10, and 16 sec, respectively. For the PP boxes, all values are for waves traveling to the southwest except for T = 6 sec (NW). For the CD boxes, the $H_{\Delta Max}$ = 0.21 m in box 10 for T = 6 sec; $H_{\Delta Max}$ = 0.13 m in box 11 for T=10 sec; and $H_{\Delta Max}$ = 0.10 m in box 11 for T = 16 sec. Averaged over all boxes, the $\bar{H}_{\Delta}$ = 0.18, 0.10, and 0.08 m for T = 6, 10, and 16 sec, respectively. All values are for waves traveling to the southwest for the CD boxes. Finally, the 95 percent confidence interval for average difference wave height inside all boxes for all wave conditions is $\bar{H}_{\Delta}$ = 0.03 ±0.01 m. In summary, the wave height reduction that would have been afforded by the smaller entrance gap had the authorized configuration been constructed is insignificant.

COMPARISON TO PREVIOUS STUDIES: The Offshore and Coastal Technologies, Inc. (OCTI 2001) performed a numerical model study of Tedious Creek, MD, for the Baltimore District in 2001. They used the Army Corps STWAVE shallow-water directional spectral model to investigate wave conditions in the vicinity of the CD for (a) pre-project or no-breakwater, (b) existing as-built project with 122-m (400-ft) gap, and (c) authorized project with 91-m (300-ft) gap. The STWAVE finite difference model had a grid spacing of 15.2 m (50 ft), which is much larger than the CGWAVE spacing. The STWAVE model is appropriate for open coast and deepwater applications, and may not be suitable for shallow depths where diffractions, reflection, and nonlinear dispersion could be important.

A JONSWAP spectrum with 30 frequencies and 3.3 peak enhancement factor and Cosine-4th directional spreading with thirty-five 5–deg direction bins was used. They looked at waves from nine directions from southwest to southeast, three wave heights from 0.5 to 2 m (1.6 to 6.6 ft), and five water levels from 0 to 1.8 m (0 to 6 ft). Not all combinations were run. Most of the runs were for waves traveling to the southwest, wave height of 1 m (3.3 ft), and water level of 0.73 m (2.4 ft). The extreme storm case had a wave direction of southwest, height of 2 m (6.6 ft), and water level of 1.8 m (6 ft).

As a base case, OCTI ran a “no-breakwater” case of the original harbor before the breakwater was constructed. They found that the existing jetties reduce the incoming wave heights by as much as 70 percent versus a no-breakwater condition. For the location near the CD that OCTI selected, this is equivalent to a 0.3-m (1.0 ft) wave height from an incident 1-m (3.3-ft) wave offshore of the breakwaters. This is comparable to the results obtained with CGWAVE for the existing gap. A “no-breakwater” case was not run using CGWAVE since the breakwater exists and this was not an alternative to be considered.

OCTI found that wave heights were increased as much as 50 percent at high tide, but negligibly at low tide. This is why CHL selected only the worst-case high-tide level in this study. Wave breaking was the important wave process that contributed to this result for typical daily wave conditions of 0.30 to 0.61 m (1 to 2 ft).

They found that waves traveling to the southwest were the worst-case conditions for waves in the vicinity of the CD. CHL also found this to be true due to the geometry of the harbor and wave refraction.

Finally, OCTI believes that some of the locals' concerns about larger waves may come from locally generated waves in the creek that travel to the south. This is a condition that may occur daily and can produce waves as large as 0.61 m (2 ft). Unfortunately, the breakwaters at the harbor entrance are not designed for waves from this direction, so no amount of gap closure would alleviate this wave condition. Because these waves develop by the wind blowing over a suitable fetch length, the only type of protection that could be afforded would require some type of jetty(s) along the northern side of the entrance channel inside the harbor or a detached breakwater inside the harbor north of the PP and/or CD.

SUMMARY: This technical note has described results from the CGWAVE numerical model study for predicting wave heights in Tedious Creek Harbor, MD. A new breakwater was constructed with an existing as-built gap of 122 m (400 ft) between the breakwater sections on either side of the entrance. An authorized gap of 91 m (300 ft) was originally proposed, but not constructed due to geological and construction concerns. Wave height predictions from the CGWAVE model were compared between the two configurations.

A series of nine regular wave conditions with wave periods of $T = 6$, 10, and 16 sec, wave directions of $\overline{\theta} = 135$ (NW), 180 (W), and 225 (SW) deg, and incident wave height of $H = 1$ m were selected as representative wave conditions in Tedious Creek. Predicted wave heights were compared along two transects (T1 and T2) from the breakwater entrance (BE) to the county docks (CD) and to the public piers (PP) and 11 rectangular boxes in the vicinity of the CD (four boxes) and PP (seven boxes). The two transects give a general overview of wave heights inside the harbor, but exhibit significant variability due to the changes in water depth along each one. Averaging wave height in the smaller boxes in the vicinity of the CD and PP provides a reasonable way of quantifying the differences in wave energy in the areas of concern to the local residents.

For the existing configuration, larger wave heights occur to the north for northwest waves, to the west and vicinity of the PP for west waves, and to the southwest and vicinity of the CD for southwest waves. For both transects, the largest wave height was less than 0.78 m (2.6 ft) and the average wave height was less than 0.31 m (1.0 ft). The maximum wave heights in any box for any wave condition were less than 0.37 m (1.2 ft) and 0.30 m (1.0 ft) for the PP and CD boxes, respectively. Finally, the 95 percent confidence intervals for average wave height inside all boxes for all wave conditions are 0.16 ±0.02 m in the PP area and 0.16 ±0.03 m in the CD area.

For the authorized configuration, the narrower gap reduces waves traveling to the southwest more than to the west along both transects. The difference in wave height for waves traveling to the west and waves traveling to the southwest decreases as wave period increases, however. The effect of the smaller gap was minimal on overall wave height reduction, in agreement with OCTI's results. The largest wave height along the two transects was 0.86 m (2.8 ft), with an average slightly less than the existing configuration. The difference in maximum wave heights is probably due to reflections at the BE from the longer breakwater in the authorized configuration. The maximum wave height in any of the boxes for any wave conditions in the PP and CD areas were 0.38 m (1.3 ft) and 0.23 m (0.8 ft), respectively. Finally, the 95 percent confidence interval for average wave height inside all boxes for all wave conditions is 0.13 ± 0.02 m (0.42 ± 0.06 ft) in both the PP and CD areas.

Wave height differences were calculated between the wave heights predicted for the existing 122-m (400-ft) gap and authorized 91-m (300-ft) gap. Because of the variability along the two transects, only the wave heights in the boxes were compared. In some cases, the existing configuration had lower wave heights. Only the positive differences were reported here as these represent cases where the authorized configuration would have resulted in smaller waves inside the harbor. In general, the maximum difference wave heights are not very large and occurred for southwest waves for both the PP and CD area boxes. The largest wave height differences were less than 0.09 m (0.3 ft) and 0.21 m (0.7 ft) for the PP and CD boxes, respectively. Finally, the 95 percent confidence interval for average difference wave height inside all boxes for all wave conditions was 0.03 ±0.01 m (0.09 ± 0.03 ft). In summary, the wave height reduction that would have been afforded by the smaller entrance gap had the authorized configuration been constructed is insignificant.

Comparisons with the OCTI numerical STWAVE model study are in general agreement with the wave heights and directions predicted by their model.

ADDITIONAL INFORMATION: For additional information, contact Dr. Michael J. Briggs (Voice: (601) 634-2005, e-mail: Michael.J.Briggs@erdc.usace.army.mil) or Ms. Barbara Donnell (Voice: (601) 634-2730, e-mail: Barbara.P.Donnell@erdc.usace.army.mil). This work was completed as part of the MCNP Program. Additional information may be obtained from: *http://chl.wes.army.mil/research/navigation/mcnp_site/default.htm*

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