Coupled BOUSS-2D and CMS-Wave Modeling Approach for Harbor Projects

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the coupled application of two advanced coastal wave models, BOUSS-2D and CMS-Wave, for harbor applications. The two models have different computational features and capabilities that are complementary and the combined usage of these models is advantageous for applications to U.S. Army Corps of Engineers (USACE) navigation projects. The coupling of two models is illustrated in this Technical Note for two harbors.

BACKGROUND: Ports and harbors include entrance channels, approach channels, harbor interiors, turning basins, infrastructure, berths, docks and mooring areas that allow ships to access basins and surrounding supporting facilities. Harbors can be located either on the coast or in inland water bodies such as in the Great Lakes or along rivers and inter-coastal waterways. Waves reaching ports and harbors can experience strong shoaling, refraction, diffraction and reflection caused by jetties and breakwaters that protect navigation channels and inlets. Large coastal breakwaters are sometimes constructed outside harbors and ports, intended to block high-energy waves. Waves propagating through navigation channels and inlets that penetrate into the ship basins and marinas can cause dangerous surges (seiching) and hazardous berthing and mooring conditions.

Navigation and harbor projects often deal with widening, deepening and channel sedimentation issues, as well as evaluation of structural alternatives and port expansion scenarios. Recent developments in numerical wave and hydrodynamic modeling have greatly aided these efforts. For harbors and ports, efficient and accurate wave modeling is paramount because waves at entrance channels, inlets, harbors and structures affect navigation safety, shoaling of channels and siltation of harbors, stability of jetties and breakwaters, and efficiency of port operations. Because field data collection studies in high-traffic areas to support these efforts can be challenging and costly, advanced wave models are nowadays frequently used to evaluate these and other engineering problems in a cost efficient manner. This is the objective of the modeling approach described in this note.

MODELING APPROACH: Numerical wave models BOUSS-2D and CMS-Wave may be used together (coupled) to evaluate potential scenarios for structure rehabilitation in various coastal conditions. The theoretical background and user manuals for BOUSS-2D are available in previous reports and CHETNs (Demirbilek et al. 2005a, b; Nwogu and Demirbilek, 2001). CMS-Wave (Lin et al. 2008; Lin et al. 2011; Demirbilek et al. 2007) is part of the Coastal Modeling System (CMS) for simulating combined waves, currents, sediment transport, and morphology change at coastal inlets, estuaries, and river mouths (Demirbilek and Rosati 2011). These models can simulate wave processes in navigation channels, erosion problems at coastal inlets, and aid in design and

operation of harbors, port expansion, and infrastructure modifications. BOUSS-2D is a two-dimensional (2-D) phase-resolving wave model that employs a time-domain solution of fully nonlinear Boussinesq-type equations for waves propagating in water of variable depth. CMS-Wave, on the other hand, is a 2-D phase-averaged, steady-state spectral wave transformation model based on the wave-action balance equation. For harbor applications, in addition to modeling wave shoaling, bottom friction, wave breaking and dissipation processes, these models represent combined wave diffraction-refraction, full/partial reflection and transmission, nonlinear wave-wave interactions, infra-gravity waves, wave runup and overtopping of structures, and wave-current interactions. While BOUSS-2D calculates both waves and wave-induced currents simultaneously, CMS-Wave calculates wave-induced currents by coupling with the CMS-Flow (Demirbilek and Rosati 2011), a hydrodynamic and sediment transport model. Both wave models have been verified and validated with laboratory and field data and have been applied extensively in many Corps projects (Demirbilek and Rosati 2011; Lin et al. 2011).

For two harbor studies discussed herein, BOUSS-2D was coupled to CMS-Wave, a spectral model that calculates the change in the local wave energy (but not the wave phase information) occurring during transformation of waves from deepwater buoys to the shallow water project site. Significant wave heights calculated with CMS-Wave is a meaningful measure of the change in local wave energy level, while the actual wave height in certain areas, particularly near structures, can be predicted more accurately by BOUSS-2D. However, because BOUSS-2D generally requires comparatively longer computational times and smaller spatial domains, CMS-Wave is applied regularly to obtain estimates of wave parameters for project planning and evaluation studies. The estimates for final design in shallow water may be verified with BOUSS-2D, which is an advanced wave model capable of representing complex physics of nonlinear wave processes nearshore. For large spatial coastal applications, CMS-Wave could be applied in a nested mode using two grids: a coarse parent grid in the open coast area that provides input wave conditions to a more refined child grid covering inlets, harbors and structures. The child grid may also be used as a BOUSS-2D grid. The saved wave parameters or two-dimensional wave spectra from the parent grid at the boundary of child grid may also be used as input to BOUSS-2D for a detailed investigation of waves in planning, navigation and flood damage reduction studies. In this modeling approach, CMS-Wave performs a dual function: (1) it uses a regional scale largeer and coarser grid to transform deepwater buoy wave conditions to the project site and provides boundary conditions for BOUSS-2D, and (2) uses the CMS-Wave child grid over a smaller local domain that is highly refined to calculate wave parameters nearshore.

The capabilities of the two wave models are complimentary and their coupling is necessary in many coastal projects. The coupling of these two wave models is demonstrated in the following sections for two recent harbor projects studied by the USACE District, San Francisco and the Regional Sediment Management (RSM) Program. Another reason for considering two wave models, aside from their complementary capabilities, is in such cases where field data are not available to validate CMS-Wave. When field data are unavailable, it is prudent to use a second model to check estimates developed by one wave model. BOUSS-2D is used in the following harbor applications to confirm CMS-Wave predictions because it has been extensively verified and validated with field data and is shown usually to produce more reliable estimates. Conversely, because BOUSS-2D is resource-demanding and applicable to only shallow and transition water depths, its coupling with CMS-Wave is necessary to define incident boundary wave conditions for the calculation of nearshore waves in inlets, ports, harbors, and marinas. The offshore boundary of

the BOUSS-2D grid should be placed shoreward of the location where water depth begins to influence wave propagation (e.g., depth approximately less than half the wavelength). A proper child grid of CMS-Wave may also be used as BOUSS-2D grid, with minor adjustments.

HARBOR APPLICATIONS

Pillar Point Harbor and, Half Moon Bay, CA: Pillar Point Harbor is located at the northern edge of Half Moon Bay (HMB), approximately 33 km (21 miles) south of San Francisco and 66 km (41 miles) north of Monterey Bay. It is a protected harbor of refuge with two rubble-mound outer breakwaters, and was constructed in 1961. The length of east and west breakwaters is approximately 4,500 ft and 3,600 ft, respectively. In addition, three rubble-mound inner breakwaters were constructed in the 1980s. The present Pillar Point Harbor project requires modeling of waves, hydrodynamics and sediment transport at HMB as part of a harbor structure and shoreline erosion study. Two models are used to better understand the complex wave patterns present at the harbor entrance and the effect of wave climate on structures and eroding beaches. The investigation includes combination of field data collection and numerical models. For wave modeling, both BOUSS-2D and CMS-Wave were selected to simulate waves in HMB and the harbor complex. Figure 1 is an aerial photo of Pillar Point Harbor and Half Moon Bay, CA, that shows the shoreline where erosion control studies are in progress.

In this application, a rectangular grid of 471 x 849 cells was used for BOUSS-2D and CMS-Wave. Square cells were 4 m long. Directional wave spectra available from NOAA Buoys 46026 (San Francisco), 46012 (Half Moon Bay) and 46042 (Monterey Bay) were transformed with CMS-Wave to the seaward boundary of the model grid. Wave spectra used for wave-current interaction had 30 frequency bins (0.04 to 0.33 Hz with 0.01-Hz increment) and 35 direction bins (covering a half-plane with 5-deg spacing). Wave diffraction, reflection, and runup were calculated in CMS-Wave model simulations. CMS-Wave and CMS-Flow were run in coupled mode to simulate wave-current interaction. Figure 2 shows the location map for HMB, NDBC buoys and NOAA tide gauges. Figure 3 shows the wave model grid domain and bathymetry.

Figure 1. Google Earth image of Pillar Point Harbor and Half Moon Bay, CA.

Figure 2. Pillar Point Harbor project site location showing buoy and gage locations in relation to the study area.
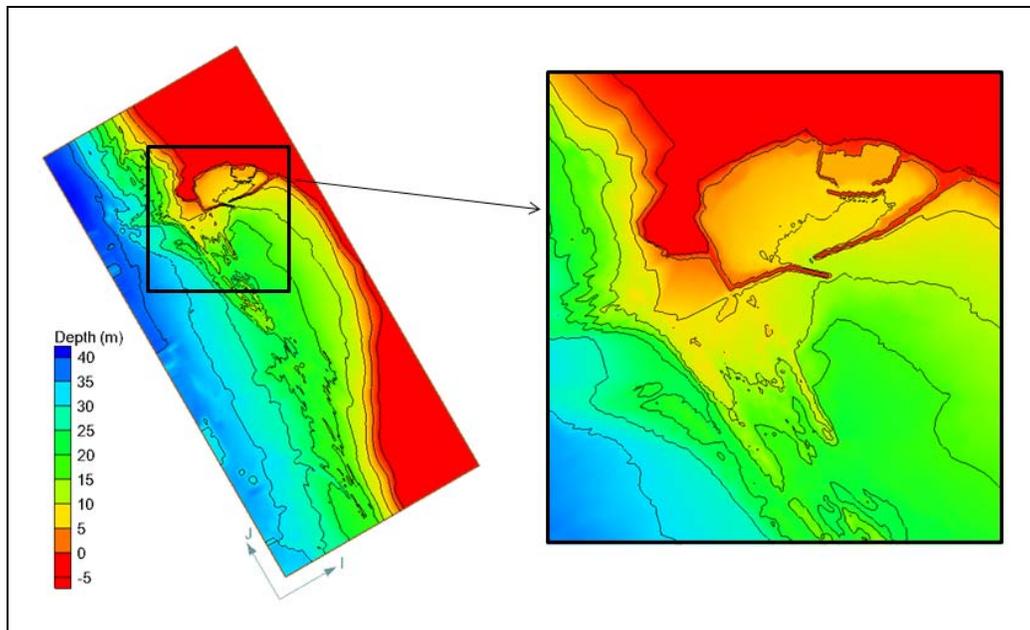

Figure 3. Rectangular grid domains for wave models; full domain (left) and zoom-in showing detailed structures and bathymetry (right).

Figure 4 shows wave fields calculated by BOUSS-2D and CMS-Wave for an incident swell condition from the southwest (significant wave height, H_s = 2 m; associated peak wave period, T_p =14 sec; associated peak direction, Θ_p = 225 deg relative to true north). Note the dotted line along the centerline of the harbor entrance channel shown in Figure 4. Significant wave heights calculated by two models along this centerline of harbor entrance channel are shown in Figure 5, where the "zero" on the transect is the start (offshore) end of the line. Because field data were not

available to validate CMS-Wave, the inter-comparison of two model results was used to evaluate the model's reliability. The wave heights calculated by both models in Figure 4 are similar, and there are differences between two model results in the rocky outcrop area outside the harbor to the west, where sharply changing bathymetry (see Figure 4) causes waves to break over the rocky offshore bathymetry. These differences are caused by different wave dissipation mechanisms (breaking and bottom friction) used in the models. A maximum difference of about 0.5 m between model results is depicted in Figure 5, which is considered good agreement and results in wave/current patterns correspond to general characteristics of what is known about the area under this wave condition, so models perform as expected without any surprises. BOUSS-2D solves the continuity and momentum equations to obtain surface wave propagation parameters and depth-averaged current field at the same time. Figure 6 shows a bird-eye view of the wave-induced current magnitude and vector field calculated by BOUSS-2D.
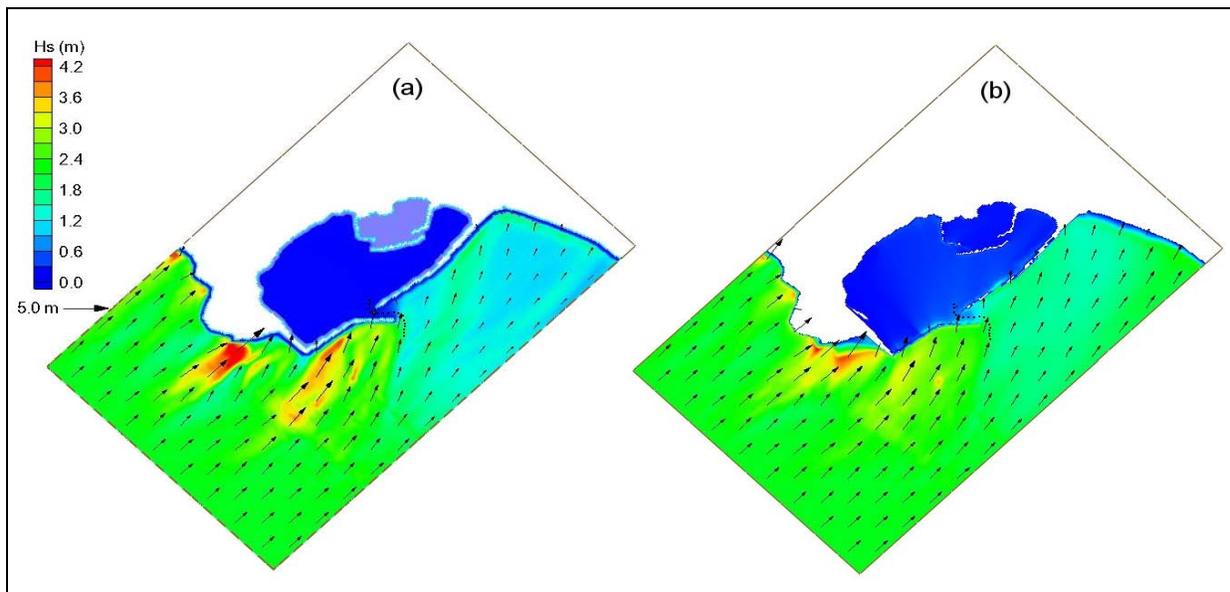

Figure 4. Calculated wave fields by (a) BOUSS-2D, and (b) CMS-Wave at Pillar Point Harbor for H_s = 2 m, T_p = 14 sec, θ_p = 225 deg (from SE)
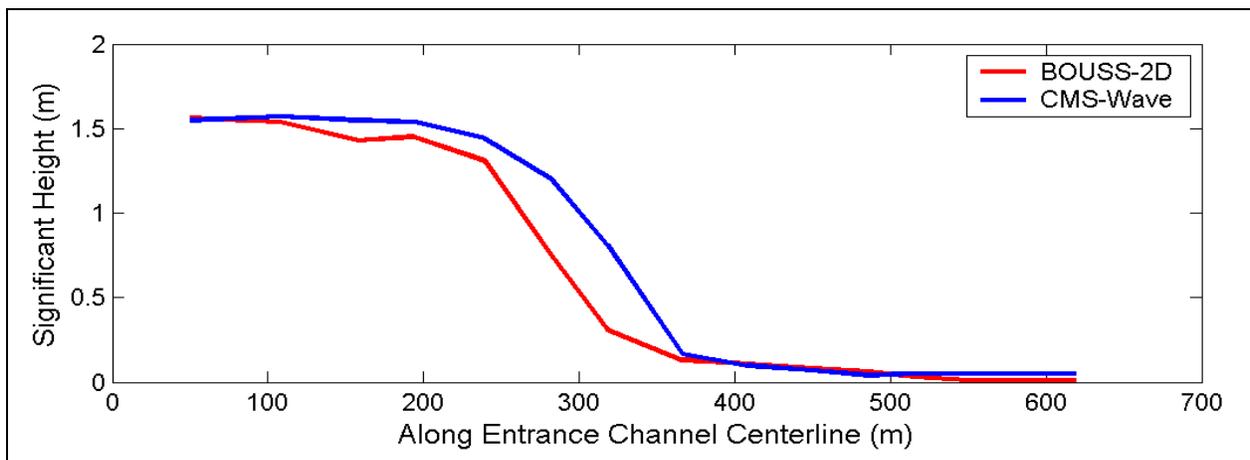

Figure 5. Comparison of calculated wave heights along the entrance channel centerline at Pillar Point Harbor.
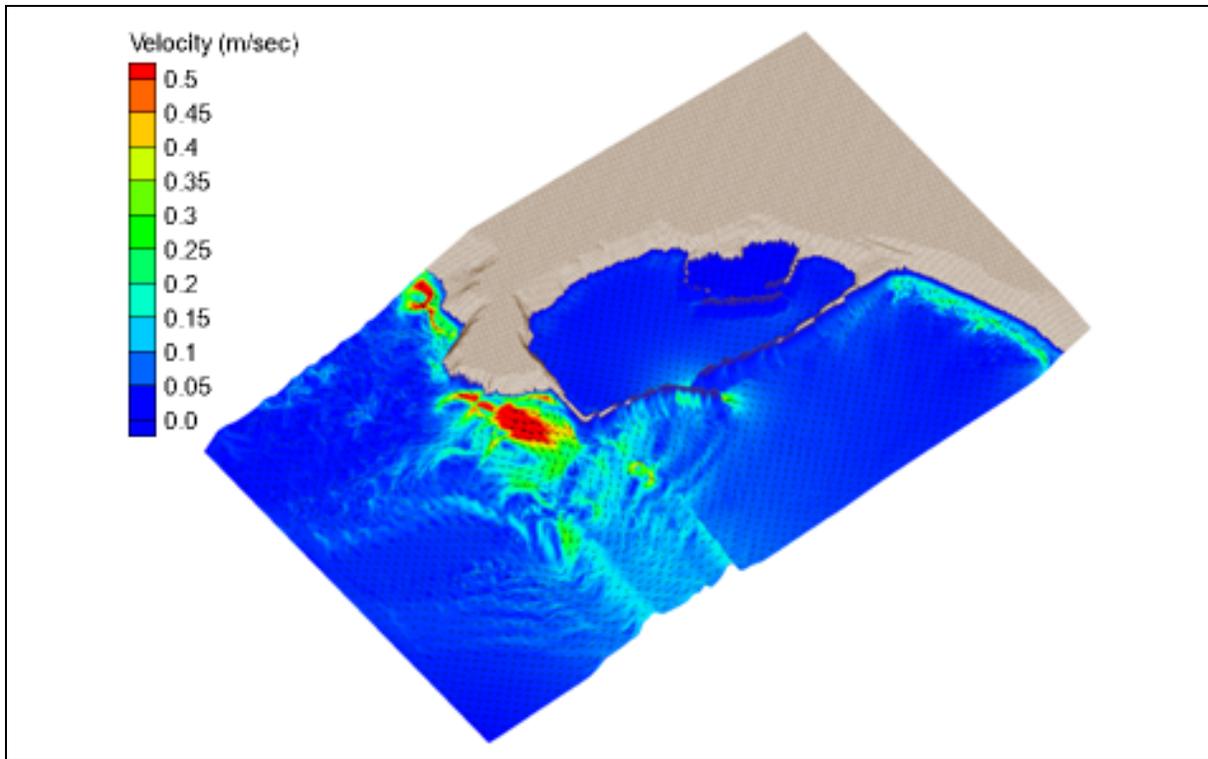
Figure 6.   BOUSS-2D calculated wave-induced current vector field.

Point Judith Harbor, RI: Point Judith Harbor is also a harbor of refuge located on the southern Rhode Island coastline approximately 16 km (10 miles) southwest of Newport and 15 km (9 miles) north of Block Island. It was built in 1910, when USACE completed construction of three rubble-mound breakwaters along the open coast to provide a refuge for shipping traffic between Boston and New York. The 4-km long breakwaters have two entrance openings for access to the harbor, with the east entrance being deeper than the west entrance. The NOAA nautical chart and aerial photo of Point Judith Harbor are shown in Figure 7.

Figure 7.   NOAA nautical charts and Google Earth image of Point Judith Harbor, RI.

The Point Judith Harbor breakwaters have deteriorated through time. This is evidenced by excessive sedimentation that occurred inside the south end of the harbor, caused both by wave transmission through and overtopping of the structure. Both BOUSS-2D and CMS-Wave were applied to investigate ocean waves arriving, transmitting, and overtopping the damaged breakwaters and how repair of these structures would reduce wave energy inside the harbor. The numerical modeling involves a CMS-Wave parent grid to transform the Global Reanalysis of Ocean Waves (GROW) 6-min-grid hindcast data from offshore Station 373 to nearshore locations for input to a coastal child grid that covers the Point Judith Harbor. CMS-Wave parent and child grid domains are shown in Figure 8.
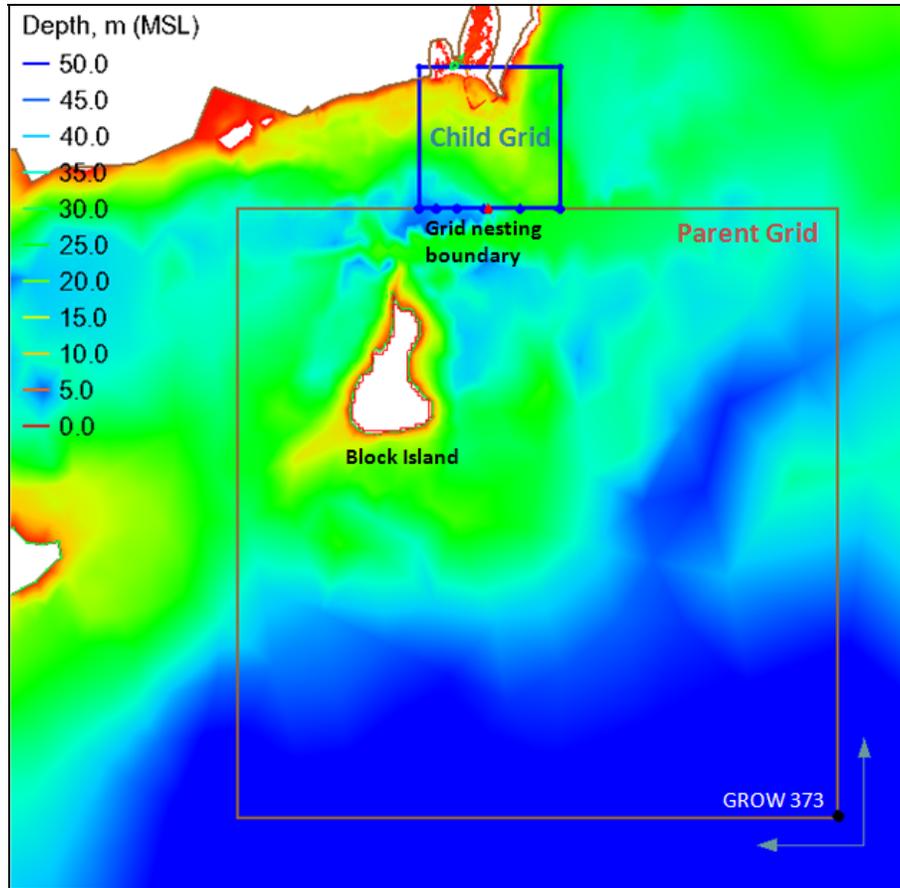

Figure 8.   CMS-Wave parent and child grid domains.

The CMS-Wave parent grid in this application consists of 171 x 174 rectangular cells of 250 m x 250 m. The grid starts at the 55-m depth contour offshore and ends at the 35-m depth nearshore, and covers 43 km alongshore and 44 km cross-shore distance. The child grid domain is a square area of 10 km x 10 km with a constant cell size of 10 m in the breakwater area and variable cell sizes of 10 to 100 m elsewhere. Bathymetric data used were from NOAA, USACE, and USGS surveys representing the 2009-2010 condition of the harbor.

Wave spectral conditions used in this study covered a half-plane with 35 direction bins of 5-deg spacing and 30 frequency bins (0.04 to 0.24 Hz with 0.007-Hz increments). Wave diffraction, reflection, and runup were implemented in the CMS-Wave model simulations. An incident spectral

wave condition with H_s= 2 m, T_p = 12 sec from SSE was used as input to BOUSS-2D and the CMS-Wave local child grid. Calculated wave fields by both models are compared in Figure 9. The significant wave heights calculated by two models along the center-line of the harbor main entrance channel (black dots at the west entrance in Figure 9) are compared in Figure 10. CMS-Wave gives slightly higher wave heights inside the harbor than BOUSS-2D because of the different treatment of wave transmission and runup mechanisms calculated for breakwaters in each model. At the start of the entrance channel centerline, where "zero" in Figure 10 is offshore, both models calculate similar wave height estimates (1.5 m), but results deviate half-way along the channel (~400 m), and the largest differences between the model results occur at the end of centerline (~700 m), with a maximum difference less than 0.4 m. Models performed in accordance with the expectations, and there were no surprises.
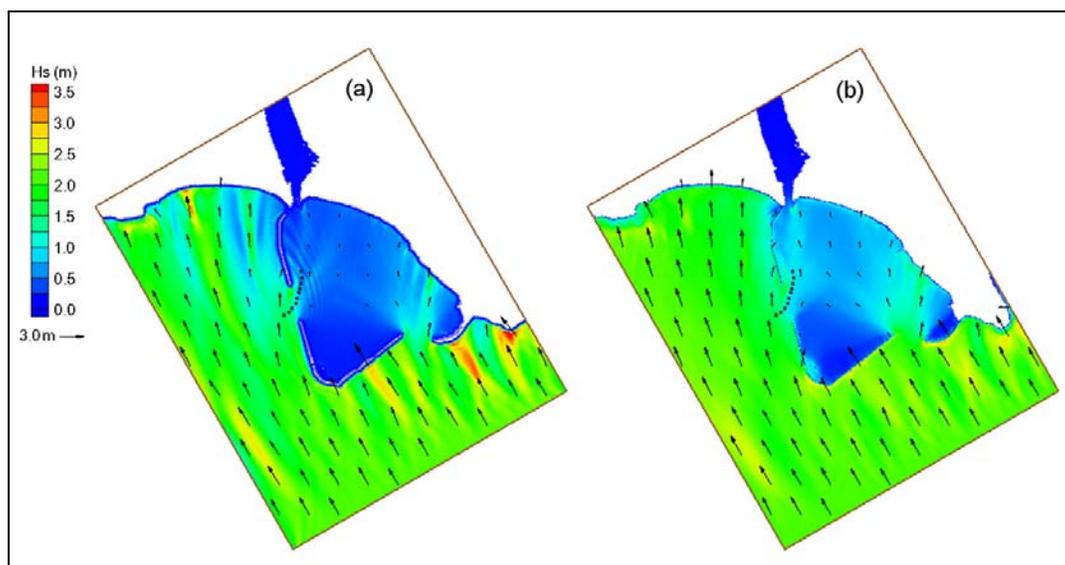

Figure 9. Calculated wave fields by (a) BOUSS-2D, and (b) CMS-Wave at Point Judith Harbor for incident wave from SSE (θ_p =135 deg) with H_s=2 m and T_p =12 sec.
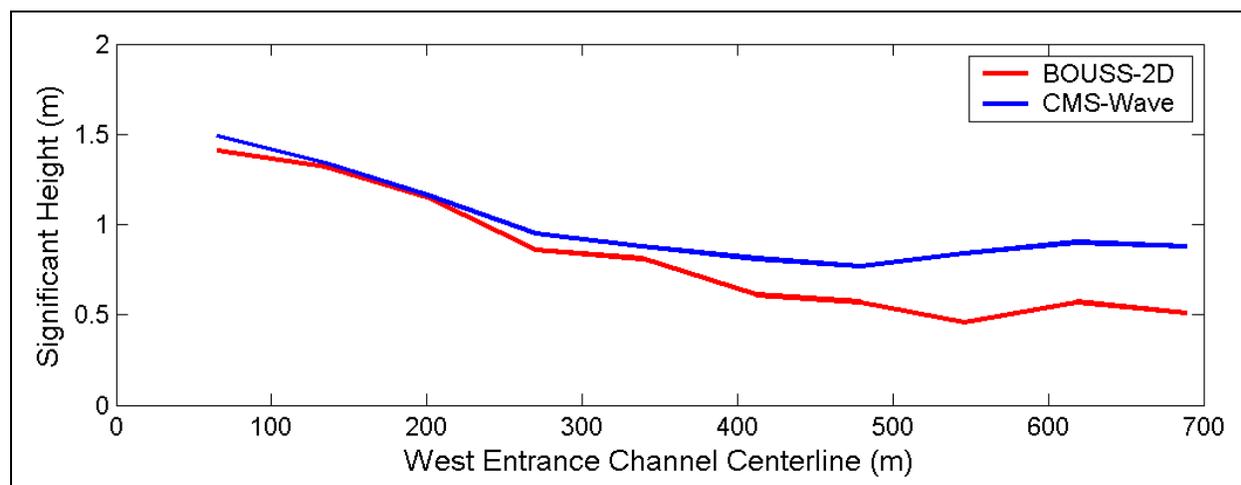

Figure 10. Calculated wave heights along the west entrance channel centerline at Point Judith Harbor.

CONCLUSIONS: This CHETN describes the overall framework of wave modeling estimates for two harbors, obtained by combining (coupling) two different classes of wave models. BOUSS-2D is a nonlinear time-domain, multi-directional random wave propagation model for shallow-water, whereas CMS-Wave is a frequency-domain spectral wave transformation for regional and coastal inlet applications. Both models include advanced features required for wave-structure interaction processes in harbor projects, including wave diffraction, reflection, transmission, and wave run-up/overtopping at jetties and breakwaters. However, as discussed herein, each model has disadvantages which can be minimized through coupling together and cross-checking each other as described herein. For the first study at Pillar Point Harbor, CA, the two models were applied with BOUSS-2D generating "validation data" which was used to check the CMS-Wave and CMS-Flow results. The coupling of the wave and flow models was necessary at this site because of the adjacent beach erosion study. Models were applied with default values of parameters and no attempt was made to calibrate or match input parameters. Point Judith Harbor, RI, is the second site, where a regional CMS-Wave model provided boundary conditions to BOUSS-2D and CMS-Wave child grid for design wave estimates for the rehabilitation of harbor breakwaters and wave estimates in the interior of harbor. As has been demonstrated in this CHETN, wave height fields obtained with both models inside the harbors are similar. The maximum difference in predicted wave height by two models is less than 20 percent of the incident wave height, suggesting that CMS-Wave estimates in the interior of harbor are reliable. The comparison of BOUSS-2D and CMS-Wave estimates to field data for harbors will be discussed in an upcoming technical report.

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