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Comparisons of Physical and Numerical Model Wave Predictions with Prototype Data at Morro Bay Harbor Entrance, California

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) summarizes comparisons of physical and numerical model wave predictions with prototype data obtained at Morro Bay Harbor Entrance, CA. Physical and numerical model investigations were initially conducted at the U.S. Army Engineer Research and Development Center (ERDC) as reimbursable studies for the U.S. Army Engineer District, Los Angeles, and prototype data were obtained during a monitoring effort at the site that was conducted as part of the Monitoring Completed Navigation Projects (MCNP) Program. Validation of physical and numerical models used in design with prototype data increases confidence levels in these tools for future applications.

BACKGROUND: Morro Bay Harbor is located on the central coast of California about midway between Los Angeles and San Francisco. The harbor is protected from the effects of the open ocean by a Federal navigation project consisting of two permeable, rubble-mound breakwaters, an inner harbor groin, and a stone revetment. The navigation channel commences at the gap formed by the outer breakwaters and extends through a bay via three channel reaches. An aerial view of the harbor entrance is shown in Figure 1.

Figure 1. Aerial view of Morro Bay entrance

Prior to the latest entrance channel improvements, Morro Bay Harbor was known as one of the most dangerous in the United States with numerous injuries, deaths, and vessel damages occurring due to steep and breaking wave conditions in the entrance. Entrance problems experienced were due to a combination of exposure to storm wave conditions and bathymetry in the entrance. A feasibility study (U.S. Army Engineer District, Los Angeles, 1991) considered a wide array of navigation improvements. Since structural alternatives lacked economic justification, channel modifications, which were expected to allow large waves to pass through the entrance without breaking and steepening, were selected for the design (USAED, Los Angeles, 1994). In December 1995, entrance channel improvements were completed that consisted of construction of a deepened, expanded entrance channel. The authorized depth increased from -4.9 m (-16 ft) to –9.1 m (-30 ft). However, the plan also provided for advanced maintenance dredging to a depth of –12.2 m (-40 ft). In addition, a –9.1-m-deep (-30-ft-deep) deposition basin was dredged north of the south breakwater.

PREDICTED DESIGN PERFORMANCE: Initial modeling of the Morro Bay project was conducted using the ERDC numerical model HARBD (Harbor, Deep Water). Representative incident wave conditions were input, and the model was used to determine wave action near the entrance and inside the outer harbor for both existing and improved conditions (Kaihatu, Lillycrop, and Thompson 1989). The HARBD model provided valuable information relative to wave conditions in the Morro Bay entrance; however, it was noted the model had limitations. At the conclusion of the numerical investigation, a physical model study was recommended to gain an accurate prediction of absolute wave heights in the harbor entrance and broken wave propagation through the proposed dredged channel configurations.

A 1:90-scale, three-dimensional hydraulic model of Morro Bay Harbor entrance was constructed and tested at ERDC to investigate the design of proposed channel depth modifications to improve navigation conditions and reduce maintenance dredging costs (Bottin 1993). Representative wave conditions (unidirectional, spectral waves) from various directions as well as steady-state ebb tidal currents were reproduced in the model. The impact that proposed depth changes had on wave conditions in the entrance was addressed. Results indicated that the initially proposed, deepened entrance channel was effective in reducing wave heights in the entrance; however, wave heights at the head of the south breakwater were significantly increased. The deepened entrance allowed more wave energy to reach the structure, as opposed to breaking and losing energy as with the existing contours. After studying numerous configurations, an optimum channel configuration was selected that resulted in improved navigation conditions and had no negative impact on the existing structures. The configuration recommended in the physical model investigation was the one constructed in the prototype in December 1995.

PROTOTYPE DATA: Prototype wave gauges were deployed at Morro Bay on 11 September 1998 (Garcia 2001). They consisted of a directional gauge outside the harbor (designated CA002), a nondirectional pressure gauge inside the harbor entrance (designated CA001), and a nondirectional buoy in the exposed harbor entrance (Figure 2). The directional gauge, CA002, was a short-baseline pressure gauge array deployed at a water depth of 14.3 m (47 ft). This depth corresponded to that used for incident wave conditions in the physical and numerical models. The gauge was bottom-mounted and data were collected for 2,048 sec every 2 hr and stored

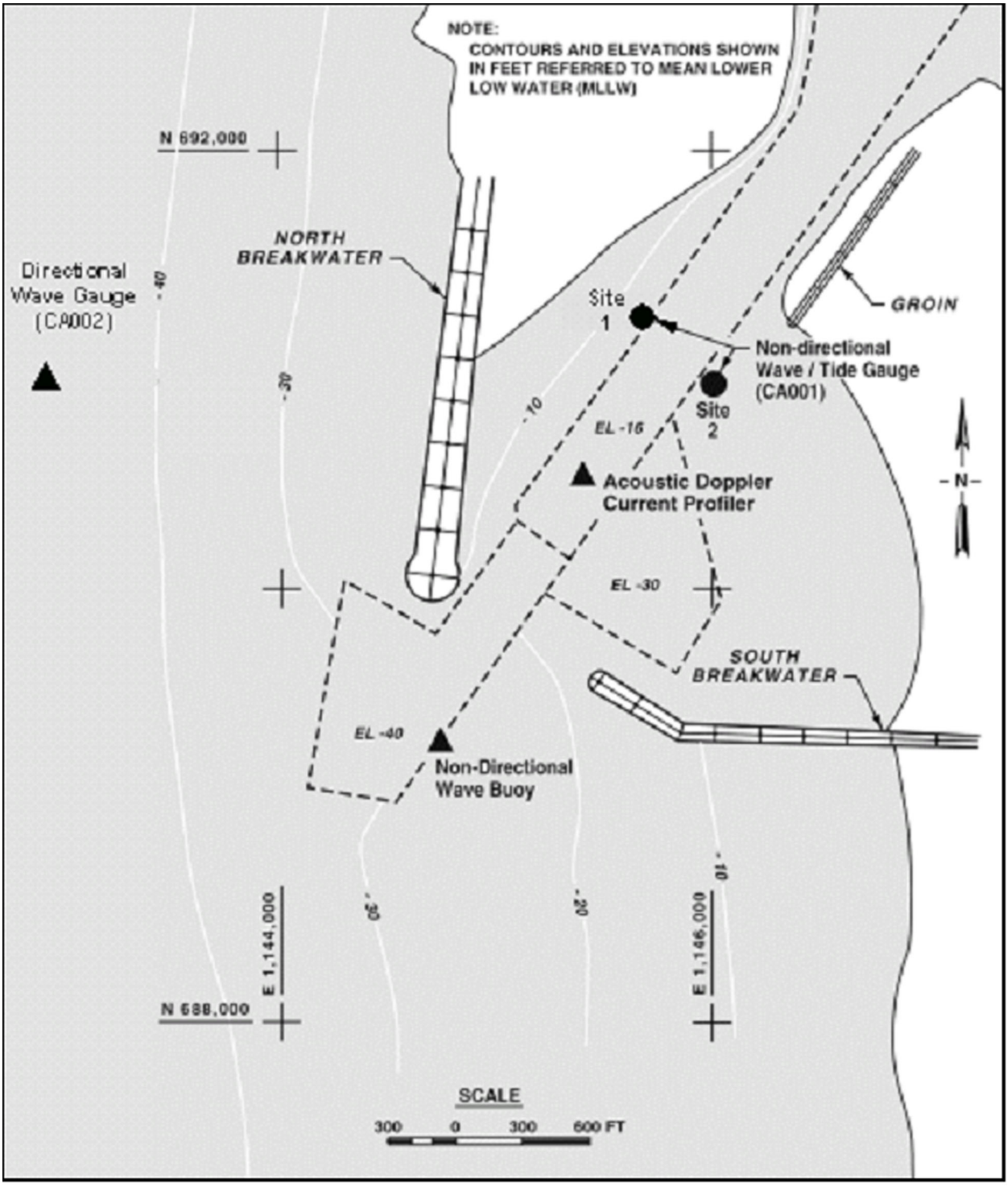

Figure 2. Prototype gauge locations at Morro Bay

internally. In this mode of operation, the gauge capacity was sufficient to store 12 months of data. The gauge was serviced four times during the monitoring period. Data recording ceased on 22 November 1998 during the onset of a winter storm. The gauge was reactivated during a service visit on 24 March 1999. Directional data ceased on 8 June 1999, but nondirectional data

(for CA002) continued until the gauge failed during a major storm on 28 October 1999. Nondirectional data recording resumed after a service visit on 6 April 2000. The nondirectional gauge inside the harbor entrance, CA001, was a single bottom-mounted pressure gauge. Wave data were recorded internally on the same schedule as Gauge CA002. Initial deployment was along the western edge of the navigation channel (Site 1, Figure 2). Data from initial deployment are available from 11 September 1998 to 8 February 1999. The gauge was reactivated on 24 March 1999 and continued collecting data until 25 Jan 2000. The gauge was moved to Site 2 and reactivated on 6 April 2000 and continued collecting data until the end of the gauging program. The nondirectional buoy was a Waverider accelerometer buoy at the landward edge of the deepened, exposed entrance. The buoy gauge was chosen because a bottom-mounted gauge at this location would be overly vulnerable to vessel traffic and bottom sediment movement. The buoy transmitted data in real-time to a receiver placed in a nearby office. Buoy data were processed by a contractor to give wave parameters every 20 min. The gauge failed on 22 November 1998, during the same storm that affected Gauge CA002. The gauge was reactivated and operated during the brief period 1-20 May 1999. It was again reactivated on 19 July 1999 and continued collecting data until an intense storm on 31 Jan 2000.

Since outages of Gauge CA002 and the absence of directional data during much of the monitoring period limited its usefulness for defining incident wave conditions at the project site, other possible sources of incident wave data were pursued. Two consistently maintained offshore directional wave gauge sites are available within a reasonable distance from Morro Bay (Figure 3). North of the project site, the National Oceanic and Atmospheric Administration (NOAA) National Data Buoy Center (NDBC) operates a directional wave buoy near Monterey, CA. South of the project site, the Scripps Institution of Oceanography (SIO) collects directional data at the Harvest Platform, a Texaco Oil Company oil-production facility. Two directional wave gauges operated at Harvest Platform within the monitoring program time period: a spatial array of pressure gauges and an accelerometer buoy. Both the Monterey buoy and Harvest Platform gauges provide directional wave data seaward of localized nearshore transformation effects. With the wind and wave climate characteristic to the California coast, especially the large spatial extent of major storms, it was reasonable to consider these gauges as possible sources of incident offshore waves at Morro Bay.

The NDBC directional wave buoy has been collecting directional data since 1991, with occasional short gaps. A rose plot of significant wave heights during the years 1995-2000 depicts wave climate characteristics (Figure 3). Waves generally approach from directions between west and north-northwest. A secondary component of wave climate is evident from the south-southwest, but this component is overshadowed by the more commonly-occurring and typically more energetic waves from northwest. Waves recorded at the NDBC buoy may be reasonably representative of deepwater offshore wave conditions at Morro Bay; however, they must be transformed into shallow nearshore waters representative of the entrance to Morro Bay before they can be considered comparable to data from the Morro Bay directional Gauge CA002. Bottom contours seaward of Gauge CA002 are sufficiently shallow to affect approaching waves and are reasonably straight and parallel. A standard wave transformation program based on a directionally-spread wave condition propagating over straight, parallel bottom contours was applied to the NDBC buoy data obtained during 1995-2000. Results were compared to Gauge CA002 during the times it was operational. An example comparison is shown in Figure 4.

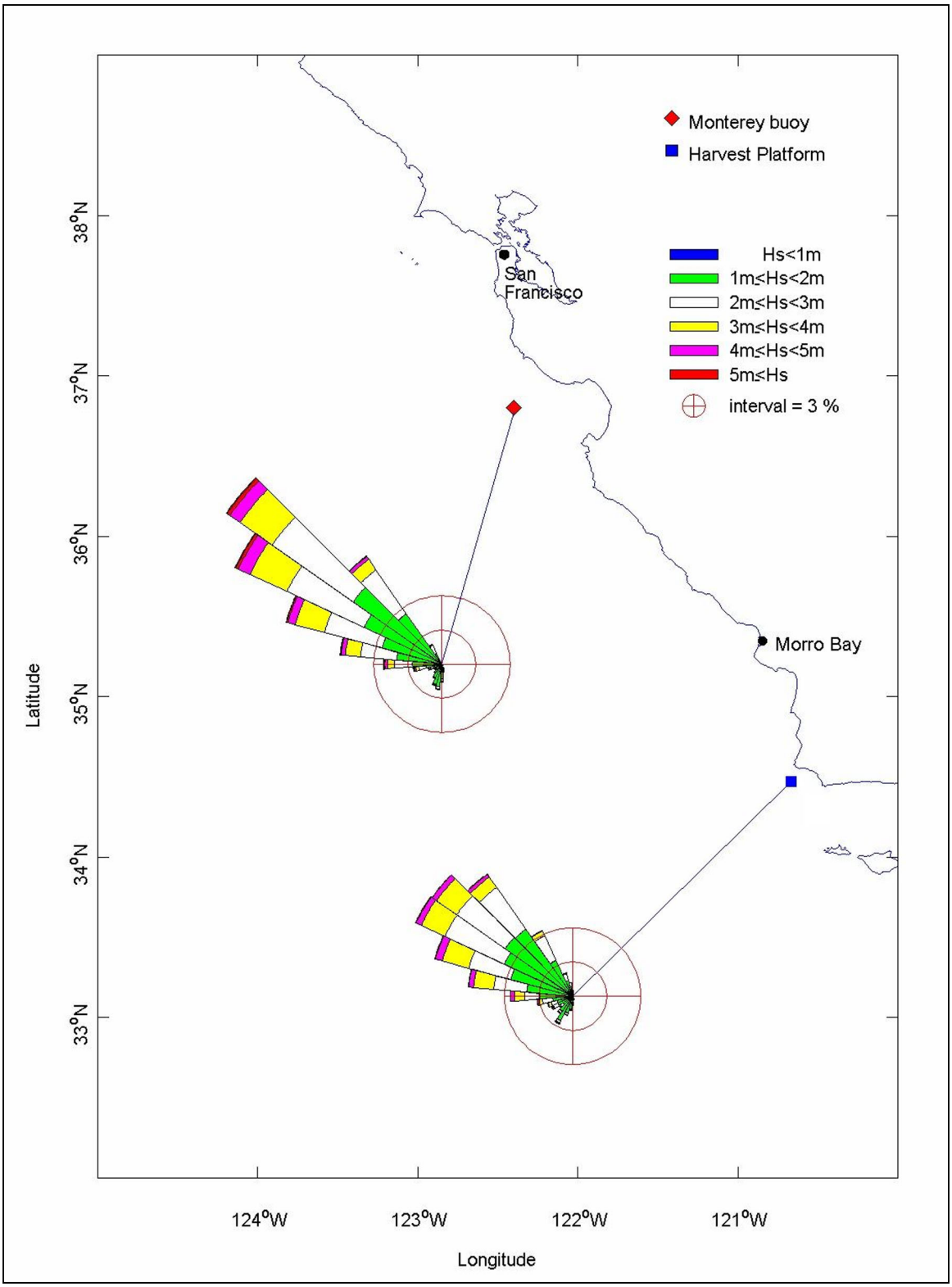

Figure 3. Wave roses of significant heights, NDBC Monterey buoy 1995-2000 and harvest array 1993-1995

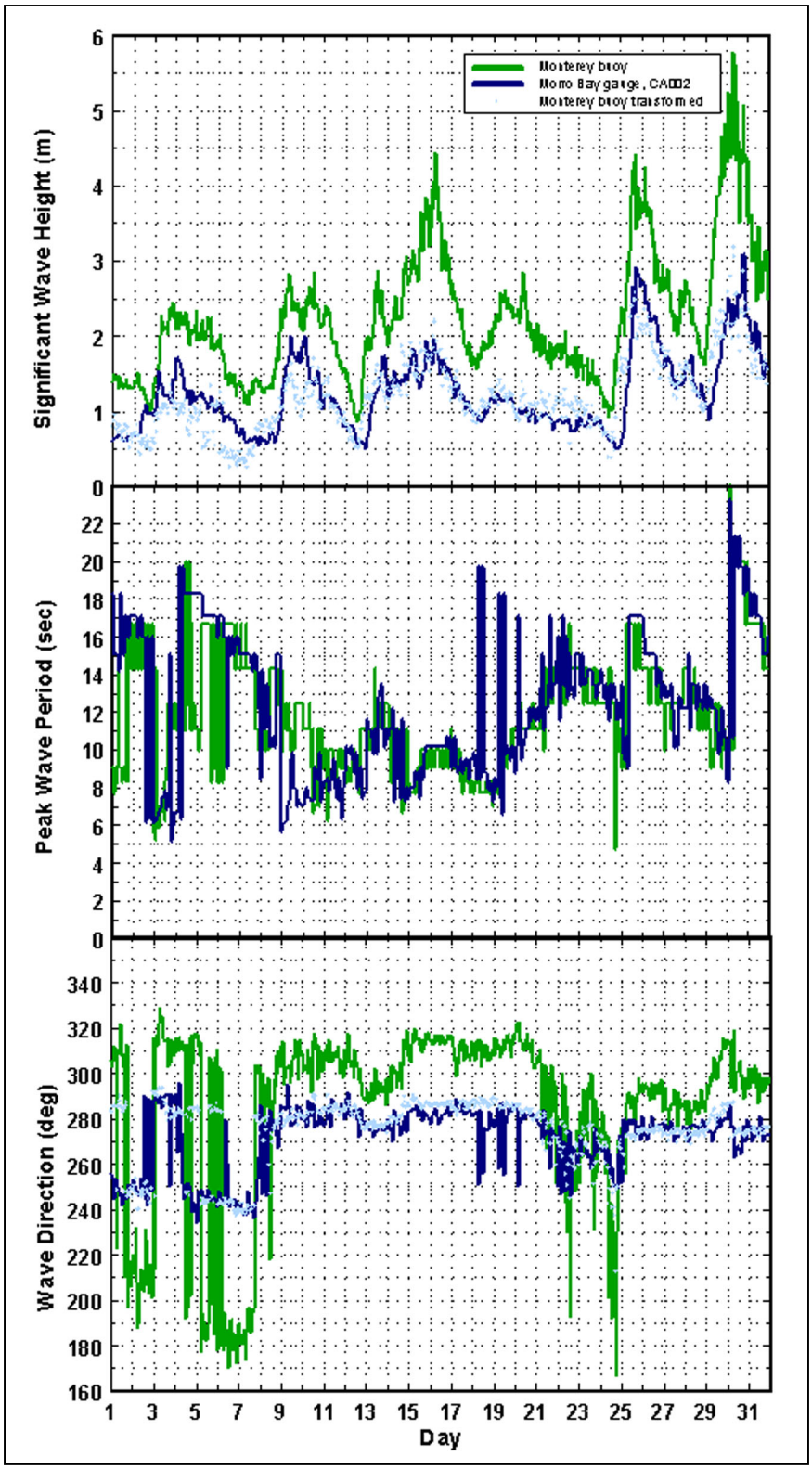

Figure 4. Comparison of wave parameters from NDBC Monterey buoy and Morro Bay Gauge CA002, Oct 98

The transformed NDBC buoy significant heights, peak periods, and directions generally compare very well with Gauge CA002 data and were accepted as a reasonable auxiliary source of nearshore incident waves for Morro Bay Harbor.

The high-resolution array at the Harvest Platform collected directional data between November 1991 and January 1999, with several lengthy gaps in 1996 and 1997. The array was accidentally hit by a vessel on 28 March 1998, and reliable directional data are not available after that date. A rose of plot of significant wave heights during the years 1993-1995 shows wave climate characteristics (Figure 3). As with the NDBC buoy, wave climate is dominated by waves from northwesterly directions, with a small secondary component of wave climate rotated slightly more toward the west. Overall, wave climate is remarkably similar at the two deepwater gauge locations. The directional buoy at Harvest Platform began operation in November 1995, and it is still operational. After a large gap from March 1996 until March 1998, the buoy has provided a consistent, reliable record of directional waves to augment and extend the array data. Waves from the Harvest Platform gauges were transformed, using the transformation approach as used for the NDBC buoy data, to be comparable to wave data from the Morro Bay directional Gauge CA002. An example comparison between the Harvest Platform data and Gauge CA002 data is shown in Figure 5. Transformed significant wave heights, peak periods, and directions generally compare very well. The data also compares well with transformed NDBC buoy data. As with the NDBC buoy data, the transformed Harvest Platform data were accepted as a reasonable auxiliary source of nearshore incident waves for Morro Bay Harbor.

With directional wave data from the NDBC buoy and Harvest Platform transformed to be representative of nearshore incident waves at Morro Bay Harbor, a continuous incident wave record can be reconstructed over the full time period since the harbor entrance was modified. A time-history of nearshore significant wave height from available sources is summarized in Figure 6.

The inner harbor gauge deployed under the monitoring program operated successfully during most of the time frame. It provided significant height and peak period wave parameters. The gauge was well-protected from incident ocean waves and significant heights were generally low. The second location for the gauge in the latter stages of the monitoring was more exposed than the initial location, but significant wave heights were still relatively low. Energetic events at Gauge CA001 appeared to be more related to local winds than to incident ocean wave conditions. Peak periods were usually representative of either incident ocean waves or much longer period oscillations affecting the semienclosed harbor area with comparable or greater energy than the residual ocean waves.

COMPARISON OF PROTOTYPE AND PHYSICAL MODEL WAVE ESTIMATES: The modified entrance channel design for Morro Bay Harbor was based primarily on physical model experiments; however, numerical model experiments played a role in early phases of project development. Both physical and numerical model studies included the transformation of incident waves over local entrance bathymetry, through the breakwater gap, and into the protected harbor area. One monitoring study objective was to use prototype data to evaluate the accuracy and effectiveness of the model studies. Comparison to physical model studies is considered in this section and numerical models studies is considered in the next section.

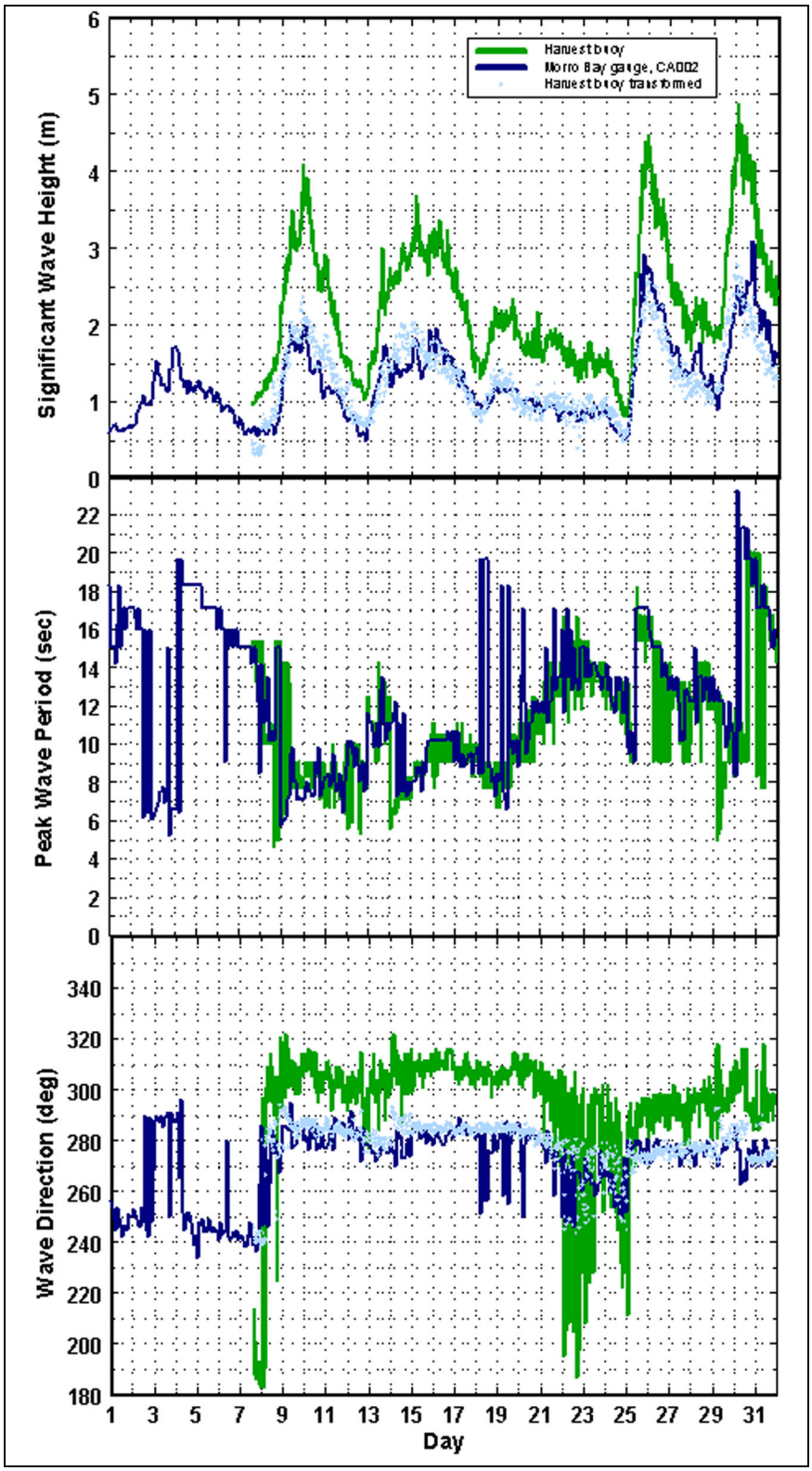

Figure 5. Comparison of wave parameters from Harvest gauges and Morro Bay Gauge CA002, October 1998

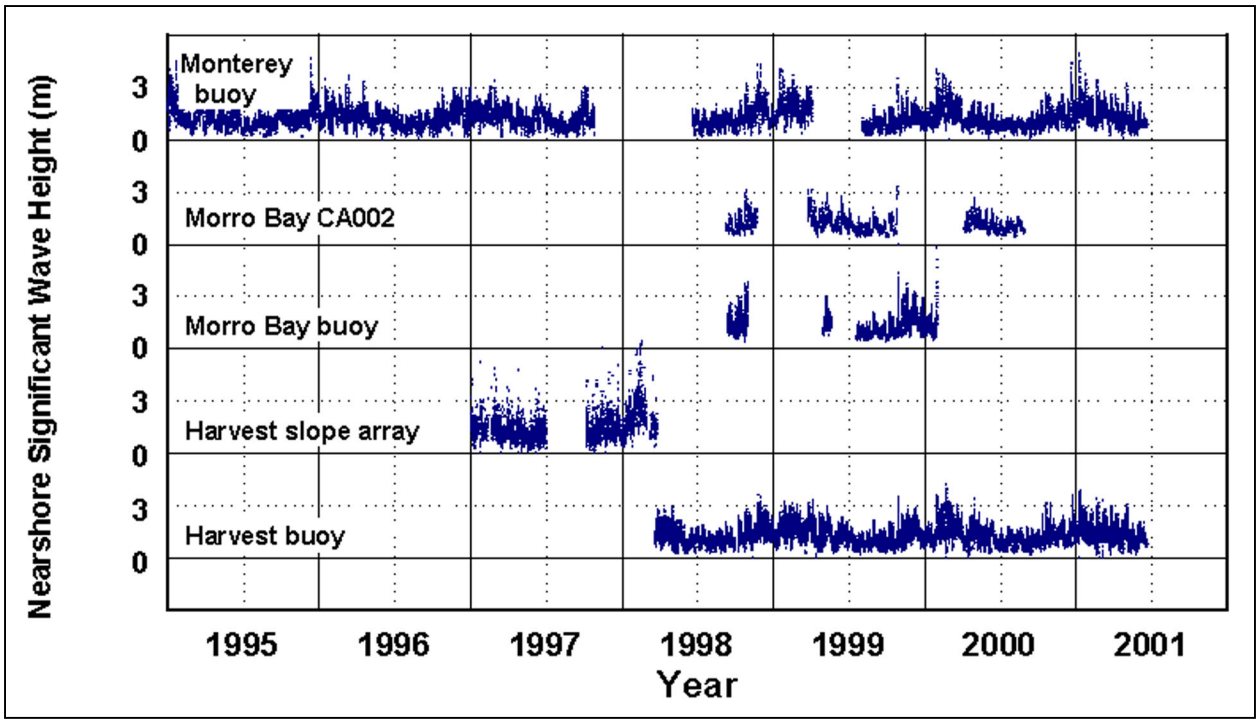

Figure 6. Time-history of nearshore significant wave height from available sources

Directional wave Gauge CA002 was situated near the seaward boundary of the physical and numerical models. It serves as the incident wave condition. The nondirectional buoy at the entrance and the inner harbor gauge, CA001, provide wave data within the physical and numerical model domains.

Prototype cases for comparison were selected on the following criteria at the outer gauge: significant wave height greater than or equal to 2 m (6.6 ft) (minimum significant wave height in physical model experiments was 2.4 m (7.9 ft)); peak period within 0.5 sec of a physical model experiment; and peak wave direction within 5 deg of a physical model experiment. Data from the nondirectional buoy and inner harbor gauge for these cases were compared to corresponding physical and numerical model estimates. Since selected prototype cases with concurrent data from both shoreward gauges were for incident wave directions of 275 deg, only the 275-deg physical model cases were considered for comparison. Additional criteria for selecting physical model cases were: "Plan 14" configuration (matches prototype project), spectral experiments, and still-water level (swl) of 0.0 m. Physical model experiments with the 0.0-m (swl) did not include tidal currents.

Comparisons are presented as wave height variation along the navigation channel center line. Distance along the center line is measured from a reference point seaward of the entrance (Figure 7). Prototype and physical model wave heights were converted to "amplification factor" by dividing channel wave heights by corresponding incident wave height. Comparison plots for peak periods of 12, 15, 17, and 20 sec are provided in Figures 8-11. The prototype nondirectional buoy and inner harbor gauge data are shown as single points in each plot, located at distances of

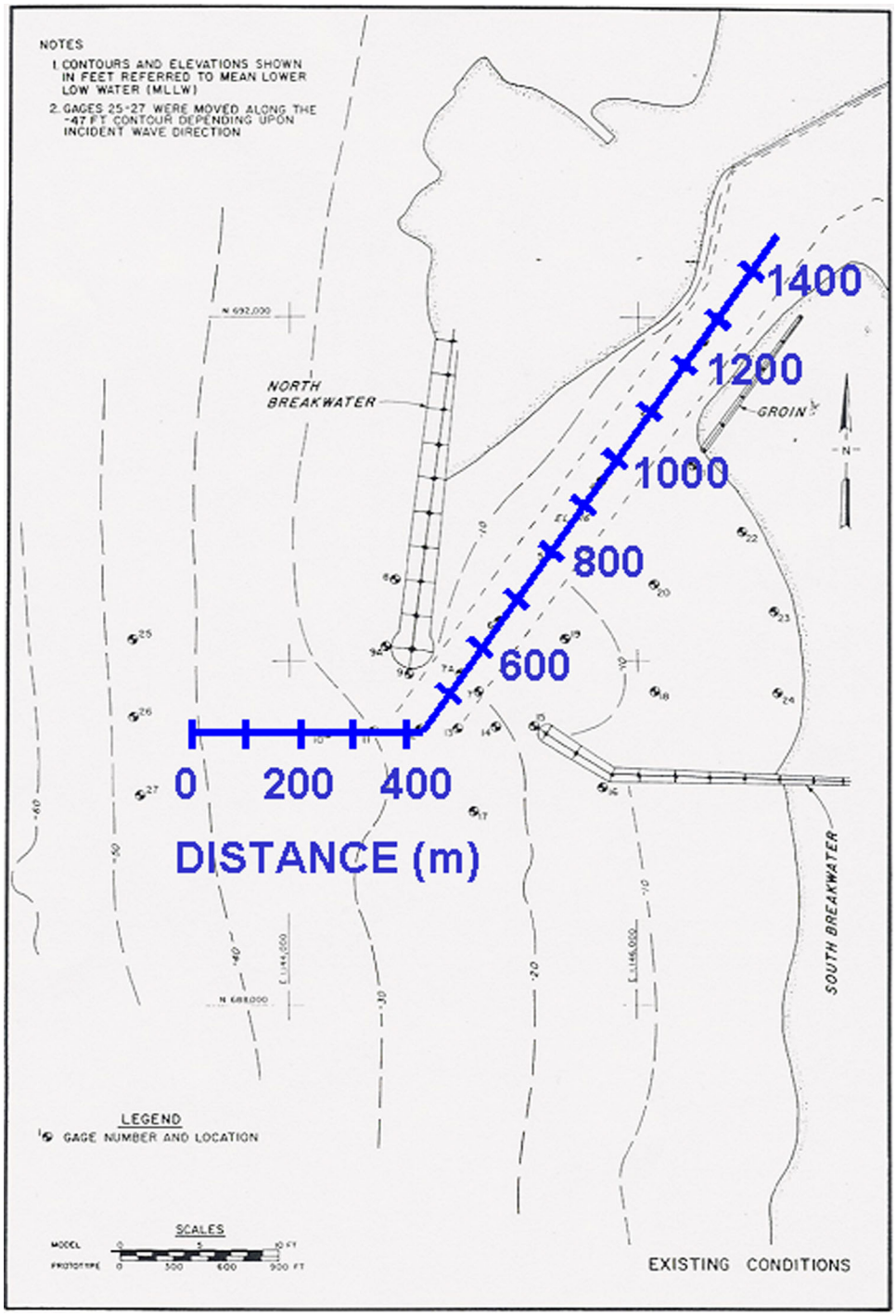

Figure 7. Reference distance along channel center line for model comparisons superimposed on physical model layout

400 m and 975 m, respectively. Each prototype point represents the average amplification factor for all matching prototype cases.

Wave height transformation along the physical model channel is generally consistent with the limited prototype data. At the nondirectional buoy location, the physical model indicates wave

heights comparable to the incident wave height, or slightly lower. The prototype gauge shows wave heights 10 to 20 percent higher than incident. The discrepancy may be due to several factors. The model gauge was located in the center of the dredged entrance, whereas, the prototype gauge was located shoreward of the dredged area, in shallower water, since it could not be placed in the navigation channel. Waves shoaling over the dredged slope would be expected to increase in height. In addition, bathymetry in the prototype changes with time and the entrance area was somewhat shallower than the ideal project depths molded into the physical model. Tidal currents probably also influenced the prototype data. The prototype gauge is in line with ebb current jets flowing out of the entrance gap. Interactions between ebb currents and incoming waves would tend to increase wave height in the prototype.

At the inner harbor gauge location, physical model wave heights tend to be comparable to or higher than the prototype data. Overall, the physical model effectively predicted decay of wave height between incidence and this sheltered location. Differences in wave gauge locations may contribute to model/prototype differences. Physical model wave gauges were located in the center line of the channel, whereas, the prototype inner harbor gauge, for practical reasons, was placed along the channel flank, in a more protected location. Inner gauge site 1 was used for these comparisons.

COMPARISON OF PROTOTYPE AND NUMERICAL MODEL WAVE ESTIMATES: Numerical model results are also shown in the comparison plots (Figures 8-11). The original HARBD model results are for the wave period and direction at the model boundary best matching physical model wave parameters. Alternative 6 in the original HARBD study was used as a best match to the project condition. HARBD was run only for regular (monochromatic) waves. HARBD results show a diminishing wave height as waves progress from incidence into the sheltered part of the channel. HARBD results are close to nondirectional buoy results, but considerably higher than the inner harbor gauge results. Wave height amplification factors are greater for HARBD than for the physical model at all but the most inner end of the channel. HARBD, as applied in the original study, suffered several major limitations, including regular (monochromatic) waves, no wave breaking, and restricted grid size and coverage area. The regular wave representation can lead to strong reflection patterns, wave heights significantly greater than incident wave height outside the harbor entrance, and erratic wave height variations over short distances. The lack of wave breaking in HARBD is also a serious limitation for the Morro Bay Harbor application that may lead to overprediction of wave heights.

The most current technology for numerical harbor wave modeling, CGWAVE (Demirbilek and Panchang 1998), was activated and run for four comparison cases as part of this monitoring study. CGWAVE results are also shown in Figures 8-11. CGWAVE runs were designed to match physical model experiments, including unidirectional, spectral waves, similar bathymetry, and wave breaking. The CGWAVE model domain extended significantly further seaward than the HARBD domain in previous studies. CGWAVE results compare much more favorably than HARBD results with physical model data. This is partly attributable to CGWAVE being a more comprehensive model and partly to CGWAVE being expressly configured to match physical model conditions. CGWAVE matches the inner harbor prototype gauge well. As with the physical model, it falls below the nondirectional buoy data, helping to support the explanation that gauge placement, shoaling, and currents may be affecting the prototype data at this location.

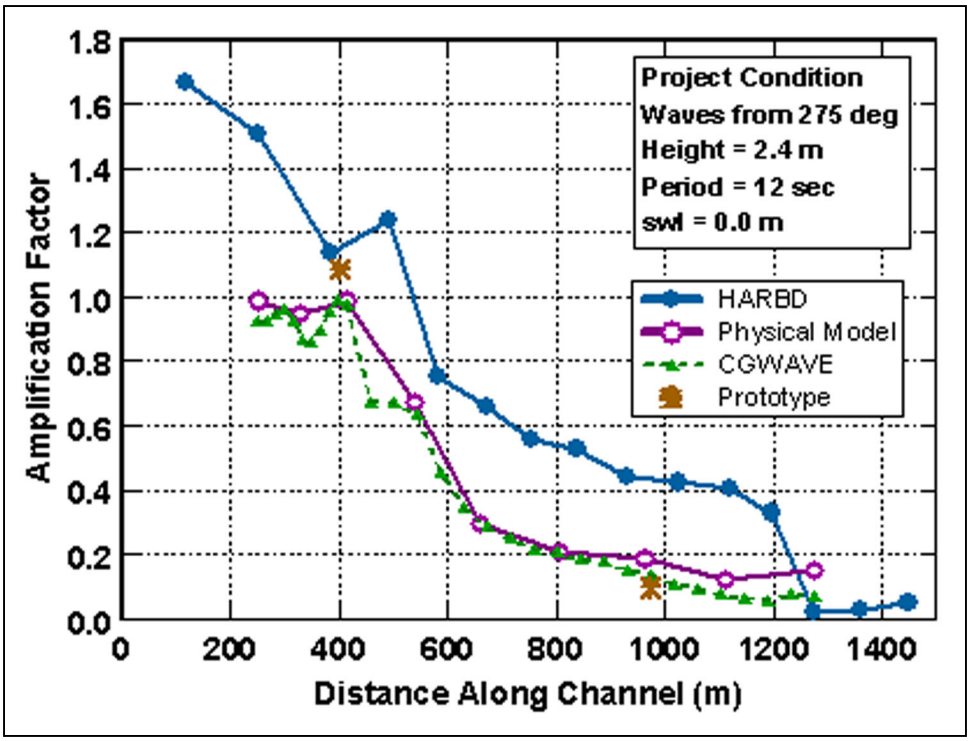

Figure 8. Comparison of model and prototype wave height amplification factor, waves from 275 deg azimuth, T = 12 sec

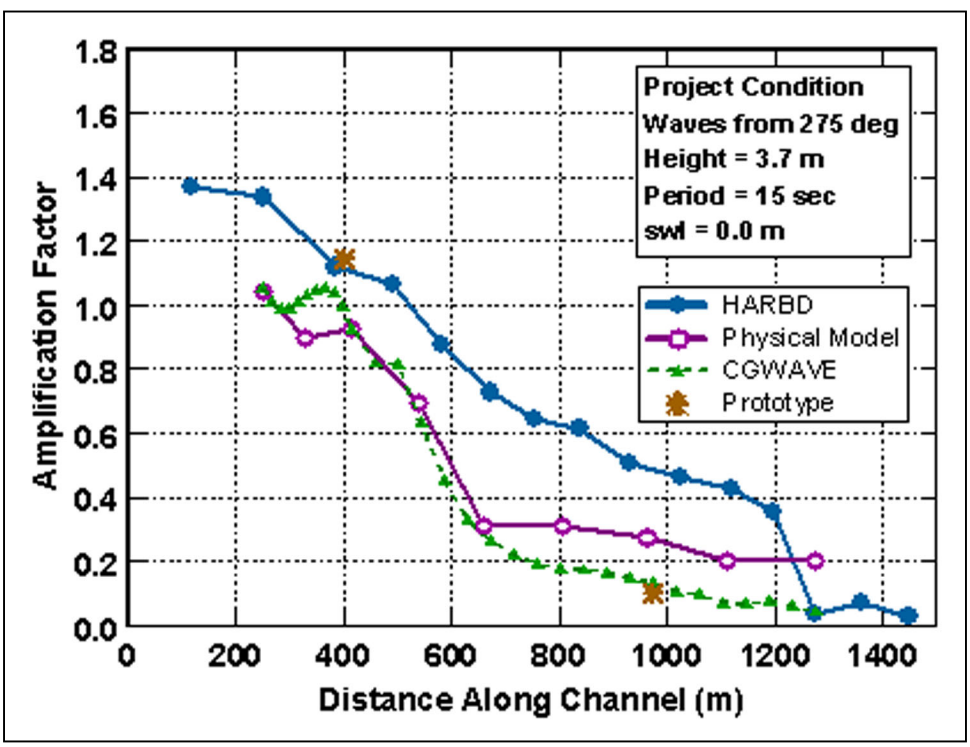

Figure 9. Comparison of model and prototype wave height amplification factor, waves from 275 deg azimuth, T = 15 sec

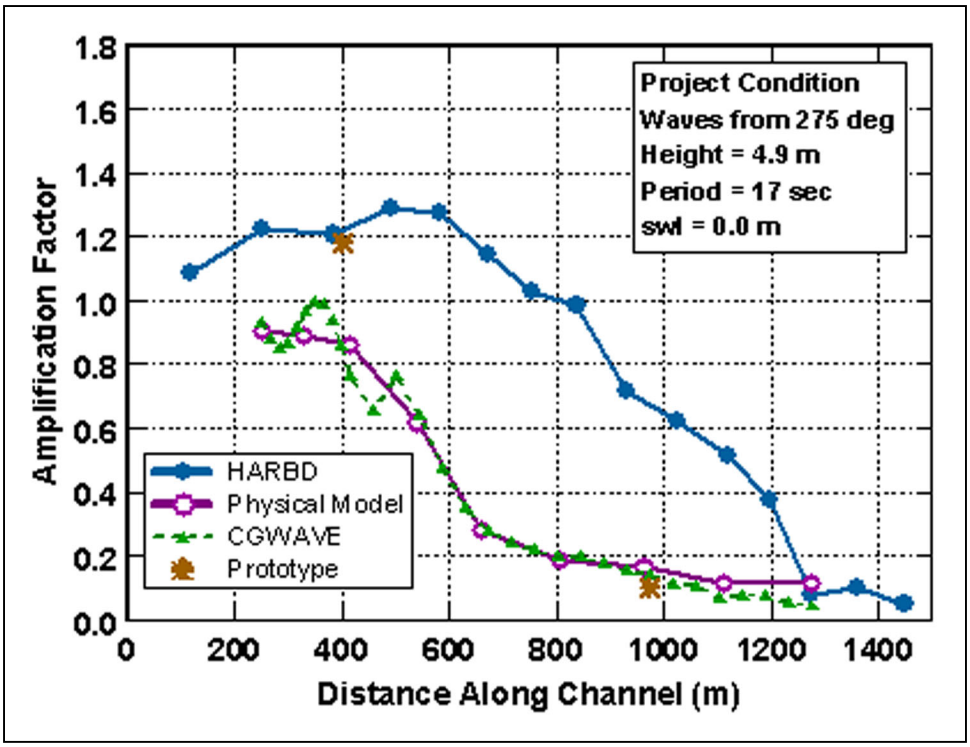

Figure 10. Comparison of model and prototype wave height amplification factor, waves from 275 deg azimuth, T = 17 sec

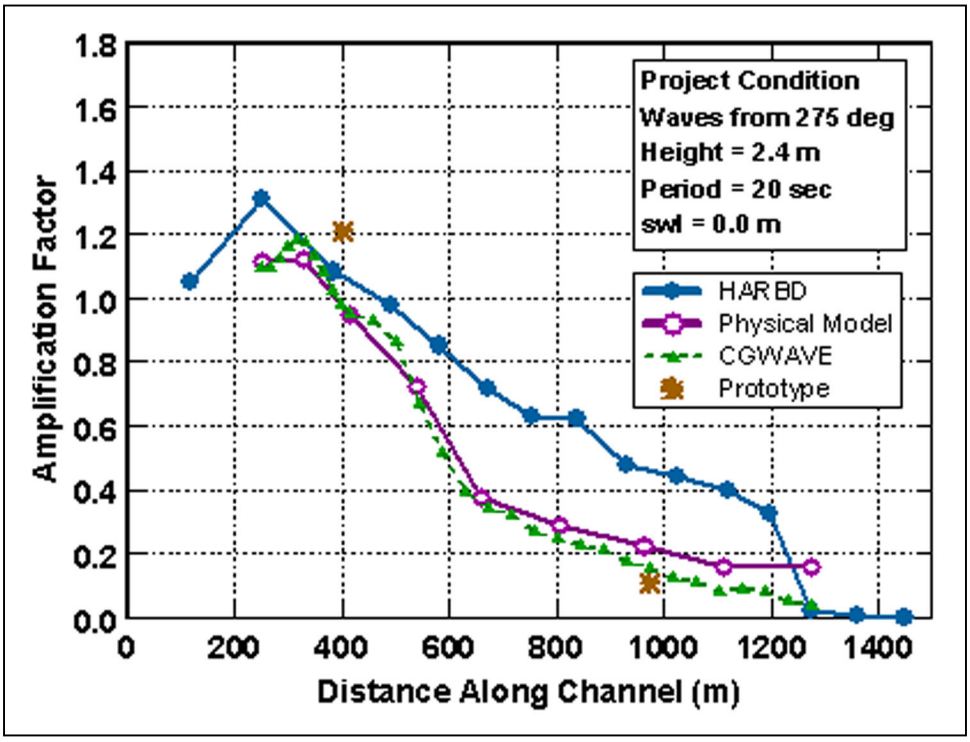

Figure 11. Comparison of model and prototype wave height amplification factor, waves from 275 deg azimuth, T = 20 sec

Some CGWAVE results show an oscillatory variation seaward of the breakwater gap. This variation disappeared in results from some additional runs with directionally spread, rather than unidirectional spectra (not shown). Prototype waves are directionally spread, and physical models may induce some directional spreading, even when wave generators are run in a unidirectional mode.

SUMMARY: Prototype data were analyzed from several sources to determine incident wave characteristics offshore of the Morro Bay Harbor entrance. For similar incident wave conditions, prototype data at two gauge locations within the harbor entrance were compared with physical and numerical model results. Physical model data revealed wave heights slightly lower at the outer gauge location and slightly higher at the inner gauge location when compared to the prototype. The difference is probably due to the actual gauge locations. In the physical model, gauges were positioned in the center of the channel. It was not possible to locate prototype gauges in the channels due to navigation hazards. The outer prototype gauge was placed in shallower water shoreward of the entrance than the model gauge where an increase in wave height would be expected due to shoaling. The inner prototype gauge location was placed in a more protected area than the model gauge where decreased wave heights would be expected. Considering these factors and noting transformations of wave energy through the entrance, it appears that the physical model wave data obtained through the entrance were an accurate representation of the prototype.

Comparison of the initial HARBD numerical model results to field and physical model data indicates wave heights in the Morro Bay entrance were overestimated. The lack of wave breaking and the use of monochromatic waves were limitations and probably contributed to the overprediction of wave heights for HARBD. A comparison of CGWAVE, the most current numerical harbor wave model, results with field and physical model data reveals wave heights to be much more comparable in the Morro Bay Harbor entrance and much improved over the original HARBD model.

ADDITIONAL INFORMATION: Questions relative to this CHETN may be addressed to Dr. Edward F. Thompson at (601-634-2027), FAX (601-634-3433), or e-mail: *thompse@wes.army.mil* or, Mr. Robert R. Bottin, Jr., at (601-634-3827), FAX (601-634-4827), or e-mail: *bottinr@wes.army.mil*. CGWAVE modeling for Morro Bay Harbor was performed by Mr. Steve Bratos and Dr. Zeki Demirbilek. More detailed information on this study may be obtained from (Thompson, Bottin, and Shak 2002). This technical note should be cited as follows:

> Bottin, R. R., Jr. and Thompson, E. F. (2002). "Comparisons of physical and numerical model wave predictions with prototype data at Morro Bay Harbor Entrance, California," ERDC/CHL CHETN I-65, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
> *http://chl.wes.army.mil/library/publications/chetn/*

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