Journal of Coastal Research	11	3	744–753	Fort Lauderdale, Florida	Summer 1995

Numerical Modeling of Harbor Response to Waves

Edward F. Thompson† and Lori L. Hadley‡

†Coastal Engineering Research Center
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180, U.S.A.

‡Coastal Engineering Research Center
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180, U.S.A.

ABSTRACT

THOMPSON, E.F. and HADLEY, L.L., 1995. Numerical modeling of harbor response to waves. *Journal of Coastal Research*, 11(3), 744–753. Fort Lauderdale (Florida), ISSN 0749-0208.

Both short (up to 25-sec period) and long (25-sec to 10-min period) waves can cause damaging conditions in harbors. Harbors of all sizes are affected, ranging from small recreational harbors to large commercial harbors. The U.S. Army Corps of Engineers has many years of experience with harbor wave concerns and has developed powerful and complementary numerical and physical modeling tools. The CE numerical model, described in this paper, can be used effectively to answer many engineering questions about harbor wave response. Two examples are presented of numerical model studies to evaluate the relative level of short wave protection provided by different breakwater configurations. Two additional examples illustrate model applications to evaluate long wave-induced harbor oscillations.

ADDITIONAL INDEX WORDS: *Coastal engineering, harbor hydrodynamics, harbor oscillations, long waves, short waves, computer programs.*

INTRODUCTION

Harbors by definition afford protection to vessels from winds, waves, and currents. The protection is never complete since there must be an opening in the harbor's defensive walls through which vessels can enter and exit. The opening width must be at least sufficient to insure safe passage; collision with the harbor walls would be disastrous. In some harbors, economic or other factors dictate an entrance even wider than required for safe navigation.

Wave energy passes freely through a harbor entrance and often causes visible motion inside the harbor. For severe events, the wave motions can create serious damage to vessels, piers, and wharfs in the harbor. Some harbors with inadequate protection regularly experience lower levels of damage, such as undue wear and breakage of mooring lines.

Waves in harbors are conveniently separated into two basic classes based on their origin and periods of motion. The term *short waves* denotes waves with periods ranging from about 1 sec to 25 sec. Short waves are generated by the wind, either due to local winds (referred to as *sea waves*) or by winds at some distant location (*swell waves*). *Long waves* have periods between about 25 sec and 10 min. They arise from a variety of processes, including nonlinear interactions between short wave components.

The U.S. Army Corps of Engineers (CE) has a significant interest in harbors as part of the CE mission in both civil works and military engineering. The CE designed and continues to maintain many small boat harbors around the U.S. Some aspects of deep-draft commercial harbors have also been a CE concern, most notably the mammoth Los Angeles–Long Beach harbor complex in California.

Harbor design and modification is typically done with great care to insure that the completed project will provide adequate protection from waves. The CE has developed and refined two complementary modeling tools for assessing the performance of existing and proposed harbor configurations. The physical modeling tool involves construction of a scale model of the harbor and subjecting it to comparably sized, artificially-generated waves (BRIGGS, 1993). The numerical modeling tool, the focus of this paper, requires computerized solution of equations which approximate the harbor response to incident waves. These modeling tools should be applied even for rela-

94026 received 22 February 1994; accepted in revision 29 March 1994.

tively simple harbor shapes when the study has large economic consequences and accurate results are essential. A combination of physical and numerical modeling is usually preferred for investigating the full range of wave conditions in a harbor (LILLYCROP *et al.*, 1993b).

Numerical models are most useful for very long period wave studies, initial evaluations of harbor conditions, comparative studies of harbor alternatives, and revisiting harbors documented previously with field and/or physical model data. For example, numerical models have been used effectively to select locations for field wave gages (to achieve adequate exposure and avoid oscillation nodes) and to identify, from many alternatives, the few most promising harbor modification plans for fine tuning in physical model tests. LILLYCROP *et al.* (1993b) suggested that numerical modeling is preferrable to physical modeling for periods longer than 400 sec. Both modeling tools can be used effectively for shorter period oscillations.

The objectives of this paper are to provide an overview of the natural processes involved in harbor wave response, the CE numerical model, and several typical applications. References which give more in-depth information are included throughout. The following section concentrates on natural processes related to both short and long waves. The CE numerical model for harbor response to waves is presented in the next section. This is followed by sections on short and long wave applications. Each section includes several examples illustrating the use of the model. The final section provides a summary.

PROCESSES

Short Wave Processes

On the average, most of the wave energy in a large water body resides in the short wave range of periods. The waves are generated by the action of wind blowing across the water surface due to a variety of meteorological processes (*e.g.*, THOMPSON and LEENKNECHT, 1994). Short waves in deep water can grow very large under strong, sustained wind conditions, reaching significant heights of over 15 m and individual wave heights exceeding 30 m (*e.g.*, GILHOUSEN, 1993).

Short waves incident to a harbor entrance are usually diminished by their passage over shallow continental shelf and nearshore waters. However, they can still carry considerable energy. Wave climate incident to a harbor entrance can vary greatly depending on the harbor exposure and local bathymetry. Incident significant wave heights of 1–2 m are not unusual at most harbors. Harbors which face the open ocean may routinely experience waves of that magnitude and sometimes endure significant heights of 5–10 m.

In passing from open water into a harbor, short waves diffract around the tips of the entrance walls. The process is comparable to diffraction of light waves around solid objects and may be calculated similarly. Wave height drops rapidly as waves travel deeper into the shadow zone. The height of waves coming straight through the entrance also decreases further into the harbor as the waves give up some of their energy to the shadow regions.

Waves throughout the harbor are also affected by the shallow bottom configuration and characteristics of the harbor land-water boundaries. Some harbor surfaces, such as vertical concrete and sheet pile walls, reflect incident wave energy back into the harbor, creating amplified and confused conditions in their vicinity. Other boundaries, such as sandy beaches and marshy areas, absorb and dissipate nearly all of the short wave energy which approaches them. Most harbor surfaces reflect a moderate amount of wave energy. Reflected energy can contribute significantly to problem conditions in a harbor.

Long Wave Processes

In sharp contrast to short waves, the long waves incident to a harbor typically contain little energy. Energy at long wave periods can come from a variety of sources including the following: nonlinear interactions between short wave components; moving or fluctuating atmospheric pressure systems; shifting wind stresses on the water surface; longshore-propagating edge waves; eddies arising from currents passing by the harbor entrance; and underwater seismic activity. Waves generated by seismic disturbances are often called *tsunamis.*

Long waves are amplified in shallow water. The origins and characteristics are much less known and understood for long waves than for short waves; one can expect long wave significant heights at harbor entrances to be at most about 50 cm and usually much less (BOWERS, 1992; OKIHIRO *et al.*, 1992).

Long waves at harbors propagate at a speed given by the shallow water dispersion relation

$$C = \sqrt{gd} \tag{1}$$

where

C = wave speed,
g = acceleration due to gravity,
d = water depth.

The corresponding wavelength is

$$L = CT = \sqrt{gd}T \tag{2}$$

where

T = wave period.

Thus wavelength increases linearly with wave period. Wavelengths for long waves are of the same order of magnitude as harbor dimensions. For example, a 90-sec wave in 10-m deep water has a wavelength of nearly 0.9 km. The diffraction process, which scales with wavelength, becomes inconsequential for most long wave cases. On the scale of a long wave, the farthest reaches of the harbor are usually just a short distance inside the entrance.

Reflection from harbor boundaries is a critical concern for long waves. High reflection can be expected at every solid boundary because on the scale of a long wave, the boundaries all resemble vertical walls.

The long wavelengths and high reflections give rise to standing wave patterns which can encompass part or all of a harbor. For most periods, long waves are not a problem in a harbor because of their meager energy. However, there are always a few specific periods which correspond to natural resonance modes of the harbor or portions of the harbor. Long wave energy at these periods is amplified inside the harbor, sometimes by a factor of three or more.

When harbors are subjected to energetic long waves at resonant periods, strong oscillations and consequent problems can rapidly develop. Vertical motions are generally small, but horizontal motions can be large. Oscillation characteristics are generally controlled by basin size, shape, and water depth. The phenomenon is also referred to as harbor surging and *seiching*.

Harbor oscillations can be a significant problem for inner harbor components and moored vessels within a harbor basin. Resonant periods characteristic of moored vessels often fall into the same range of periods as harbor oscillations. Harbor oscillations can create dangerous mooring conditions which include breaking of mooring lines, damage to fender systems, vessel collisions, and delays of loading and unloading operations. A comprehensive discussion is provided by RAICHLEN and LEE (1992).

NUMERICAL MODEL

Since both short and long waves can cause interruptions and damage in harbors, it is important to give them proper consideration in designing new harbors or modifying existing ones. A flexible and economical tool for investigating harbor response to short and long waves is the CE numerical model HARBD.

Based on linear wave theory, the HARBD model is applicable to harbors of arbitrary size, shape, and depth. CHEN and MEI (1974) initially developed the model as a steady state, hybrid element model for calculating long wave response in a shallow offshore harbor. HOUSTON (1981) modified the model formulation to accommodate short as well as long waves by solving BERKHOFF'S (1972) mild slope equation. The model was further adapted by CHEN (1986) to include the effects of bottom friction and variable boundary reflection. The resulting HARBD model, documented by CHEN and HOUSTON (1987) and LILLYCROP (1993), has been applied in numerous harbor oscillation, tsunami, and short wave applications (*e.g.*, BRIGGS *et al.*, 1992; HOUSTON, 1978; LILLYCROP and BOC, 1992).

The model incorporates many of the important processes affecting harbor wave response. Diffraction, reflection, and wave transformation over a variable-depth bottom are all treated, within the confines of the mild slope equation and grid-determined spatial resolution.

However, the model includes some limitations which make it less accurate or unsuitable for some applications. Nonlinear processes such as wave breaking and overtopping and transmission past harbor walls are not included. Effects of currents and wave-current interactions are not modeled. The model does not account for long wave entrance losses (THOMPSON *et al.*, 1993).

The HARBD model domain is divided into two regions. The primary region (Region A) consists of the harbor itself as well as a portion of the adjacent nearshore area (Figure 1). This region is bounded on the seaward side by a 180-deg semicircle and covered by a triangular finite element grid mesh. The required grid resolution is determined by the shortest wave period to be modeled, the shallower depths of interest in the harbor, and the model-recommended minimum resolution of six grid elements per wavelength.

Each element in the model domain (Region A)

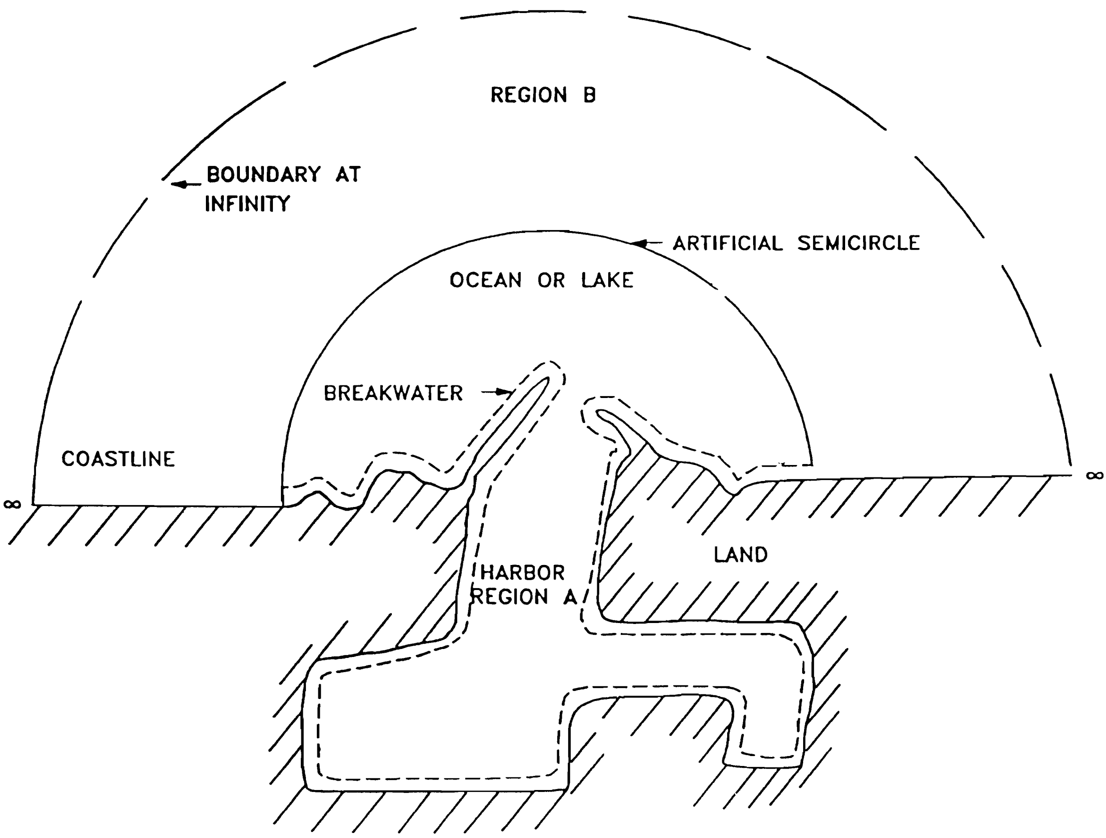

Figure 1. Definition sketch of harbor regions.

is assigned a water depth and bottom friction coefficient. The bottom friction coefficient is taken as zero for short waves. For long waves, which interact more strongly than short waves with the bottom, it is typically set to either zero or a small, constant value over the domain. Model long wave results are mildly sensitive to the choice of bottom friction coefficient.

Elements located on solid boundaries are also assigned a reflection coefficient, ranging from zero to one. Reflection coefficients for short waves may span the full possible range, and model results are quite sensitive to the particular values used. For long waves, which strongly reflect from harbor boundaries, the reflection coefficient is set equal to one.

The secondary region (Region B) is a semi-infinite far region extending beyond the semicircular boundary to infinity in all horizontal seaward directions (Figure 1). This region is considered to have straight, semi-infinite coastlines, a constant water depth, and no bottom friction.

In addition to the finite element grid, bathymetry, and friction and reflection information, the HARBD input file includes wave conditions to be tested. These consist of a series of wave height, period, and direction triplets. The model is linear except in its treatment of bottom friction, so specification of wave height becomes important only when bottom friction is non-zero. Each triplet represents one incident wave condition, applied uniformly along the semicircular boundary.

Model output consists of an amplification factor (ratio of local wave height to incident wave height) and a corresponding phase at every node within the harbor domain. The phase represents the difference between local phase and the phase

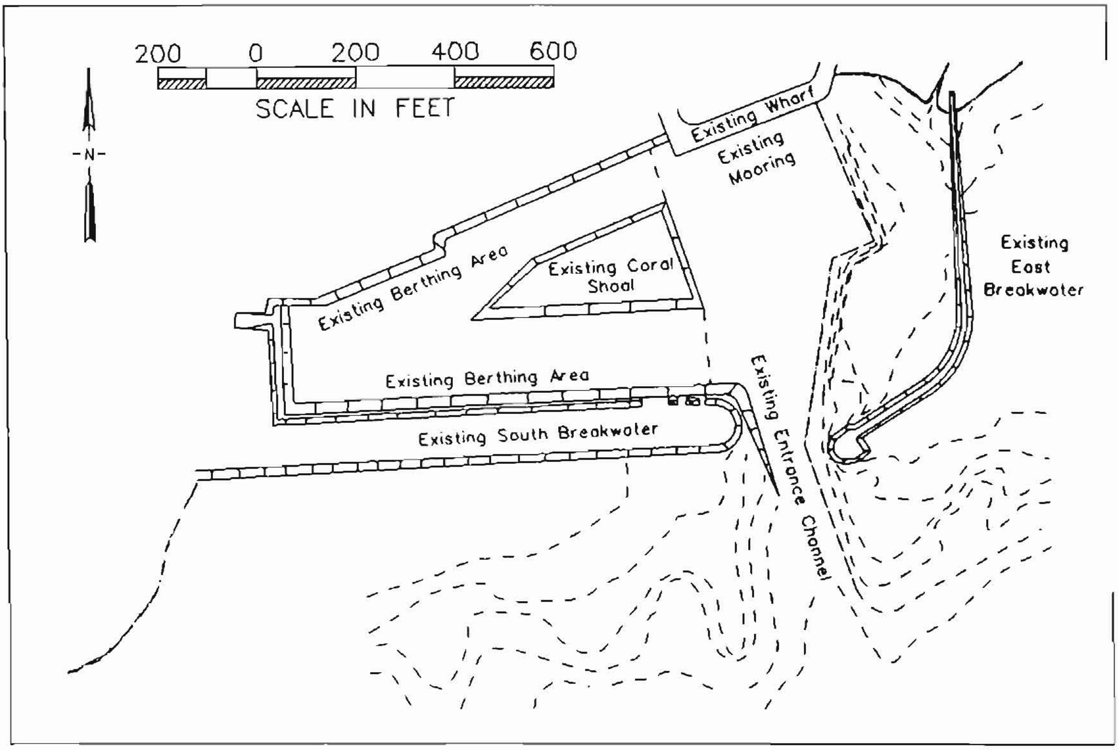

Figure 2. Existing layout of Maalaea Harbor.

of the incident wave. Another optional output is amplification factor averaged over pre-specified multi-node regions of special interest in the harbor. Since the model is basically linear, results from multiple incident wave triplets can be recombined to simulate a spectral response.

SHORT WAVE APPLICATIONS

Maalaea Harbor

A recent study of Maalaea Harbor, Maui, Hawaii, typifies the use of HARBD to evaluate harbor layout alternatives (Lillycrop *et al.*, 1993a). Maalaea Harbor is a small shallow draft harbor on the south side of the island of Maui. The harbor is protected from the west by land, from the south by a wide main breakwater, and from the east by a rubble breakwater (Figure 2). The objectives of any harbor modifications would be to provide increased protection from short waves and to increase the available berthing space. Additional considerations include preserving adequate flushing in the harbor and giving proper attention to favorable surfing areas in the vicinity of the harbor.

The grid developed for the existing harbor is shown in Figure 3. At this stage of the project, three modified plans and several variations were under consideration. Grids were devised to represent all of the alternative plans (*e.g.*, Figure 4). The plans include deepening the area adjacent to the east breakwater to create a new berthing area. Wave climate near the harbor entrance was developed by estimating the deep water climate and using a large scale numerical model to calculate the effects of shallow water and the offshore sheltering island of Kahoolawe.

Using the frequency of occurrence information for the wave conditions making up the local wave climate and the incident wave vs. harbor response relationships calculated with HARBD, wave climate was estimated in the harbor berthing areas and entrance channel. These results were then evaluated relative to the standard CE criteria, which specify that wave heights should exceed 0.3

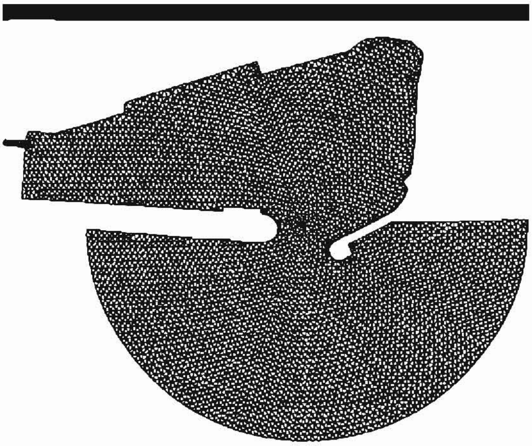

Figure 3. Numerical grid, Maalaea Harbor, existing configuration.

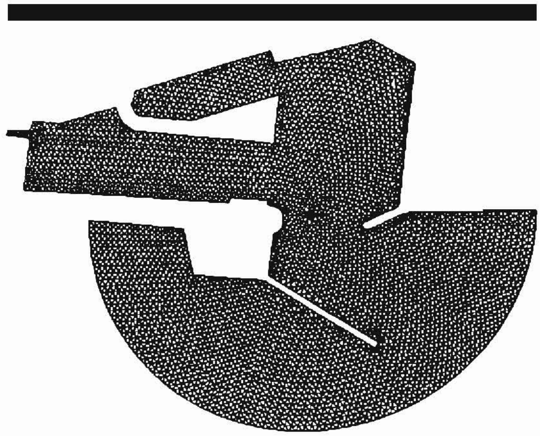

Figure 4. Numerical grid, Maalaea Harbor, Plan 1.

m (1 ft) in berthing areas and 0.6 m (2 ft) in entrance channels less than 10 percent of the time (Table 1). Model results indicate that the existing harbor berthing areas do not have sufficient protection. Plans 1, 1a, and 3 can be expected to remedy the problem, though Plan 1a may only marginally satisfy the berthing area criterion. Thus, the HARBD model was helpful in identifying the more promising alternative plans.

Port Allen Harbor

Another recent short wave application of the HARBD model was at Port Allen Harbor, Kauai, Hawaii (THOMPSON and HADLEY, 1994). The harbor lies at one end of an embayment and is protected by a single rubble mound breakwater (Figure 5). The seaward end of the breakwater suffered damage in several storms, most recently Hurricane Iniki in 1992. As a result, the effective breakwater length is about 20 m shorter than the original design. A small study was conducted to help assess the benefits of restoring the breakwater to its original length. The HARBD model was used to evaluate the relative difference in protection between the existing harbor and the original plan.

Table 1. *Evaluation of Maalaea Harbor plans against CE performance criteria.*

	Percent of Time Criterion is Exceeded						
Location	CE Criterion	Existing	Plan 1	Plan 2	Plan 3	Plan 1a	Plan 1b
Berthing areas							
(1 ft criterion)	<10.0	21.4	6.1	17.7	2.0	10.0	18.9
Entrance channel							
(2 ft criterion)	<10.0	9.6	2.0	11.3	2.0	5.0	4.9

LONG WAVE APPLICATIONS

Barbers Point Harbor

Barbers Point Harbor, Oahu, Hawaii, serves as a good example of the numerical model HARBD's ability to reproduce the geometry and bathymetry

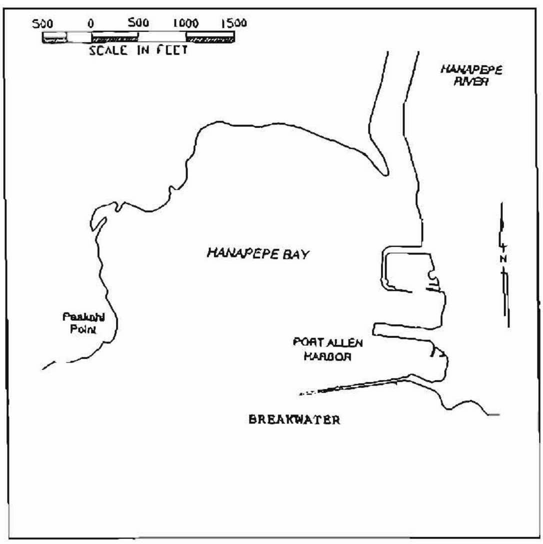

Figure 5. Layout of Port Allen Harbor.

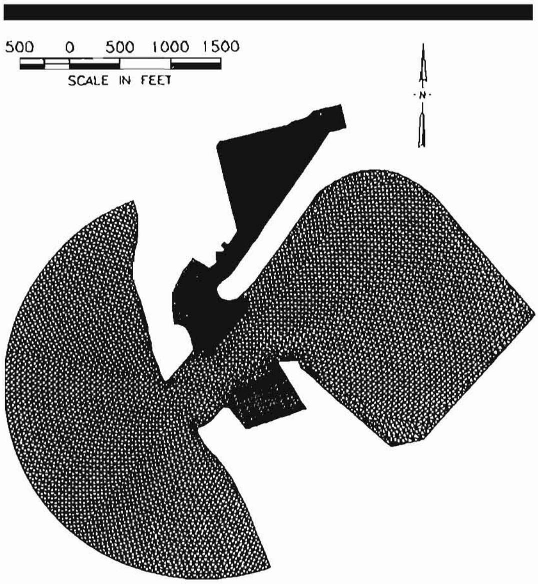

Figure 6. Numerical grid, Barbers Point Harbor, existing configuration.

of a harbor area and estimate harbor response to long waves. The State of Hawaii is considering plans for deepening and enlarging the harbor to accommodate larger vessels. At the same time, harbor and navigation safety must be maintained or improved. Numerical model tests were performed as part of a larger study which also involved physical modeling and field data collection (Briggs *et al.*, 1992, 1994; Briggs, 1993). The HARBD model was used to identify and visualize oscillation patterns in the existing and various planned harbor configurations.

An example numerical model grid is shown in Figure 6. This grid is finer than would normally be required for harbor oscillation studies because it was designed for both short and long waves. Grid size is further reduced in shallower basins branching off the entrance channel.

The numerical model was run for closely spaced frequencies (frequency is the reciprocal of wave period) over the full range of long wave frequencies to generate harbor response curves at various

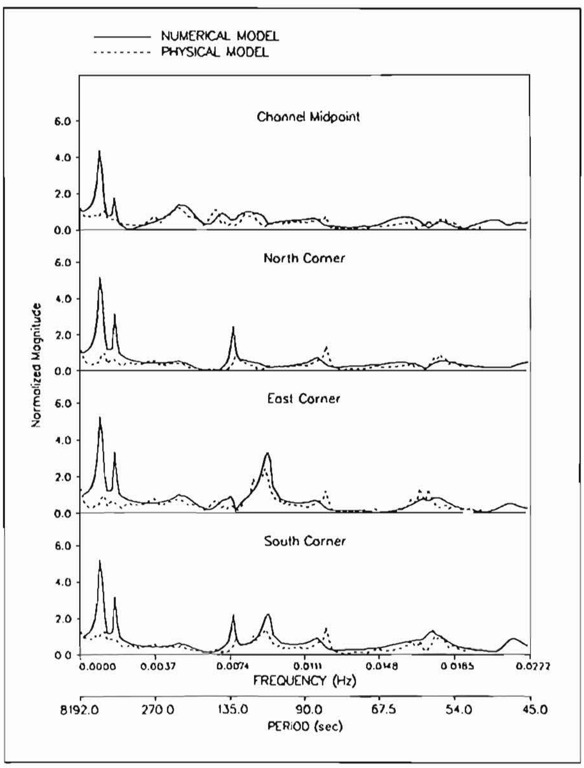

Figure 7. Frequency response curves, Barbers Point Harbor (from Lillycrop *et al.*, 1993b).

points in the harbor (Figure 7). The physical model performed similar tests, also shown in the figure. Harbor response at the north, east, and south corners of the main, nearly square basin is shown. The fourth response curve, labelled "channel midpoint," represents a point near the west (open) corner of the square basin geometry. All four corners show amplified response to the lowest frequency resonant cases. However, for resonant periods shorter than about 270 sec, the corners differ significantly in their responses, depending on the characteristics of the various resonant modes.

Numerical model results for resonance conditions of particular interest can be displayed over the whole harbor to show oscillation patterns. For example, amplification factors and phases calculated with the example grid are presented for the 132-sec wave period, corresponding to strong resonant peaks in the north and south corners of the main harbor basin (Figures 8 and 9). Phases are relative to the incident wave. Phase plots are useful because phases in a pure standing wave are constant up to a node and then change rapidly (180-deg shift) across the node. Thus, phase contour lines cluster together at node locations. Since regions of similar phase, plotted with similar gray shades (or colors on a computer screen) move up and down together, the resonant modes of oscillation can be much more easily visualized.

This information about node locations and behavior of resonant modes is quite useful in analyzing harbor oscillations. For example, Figure 9 shows that the 132-sec resonance is basically a simple standing wave oscillation between the north and south corners of the basin. The east corner and channel midpoint are near nodal zones, which explains why these locations showed only a weak response to 132-sec waves (Figure 7). The amplification factor and phase information can also be used to create animated displays and video footage of harbor response.

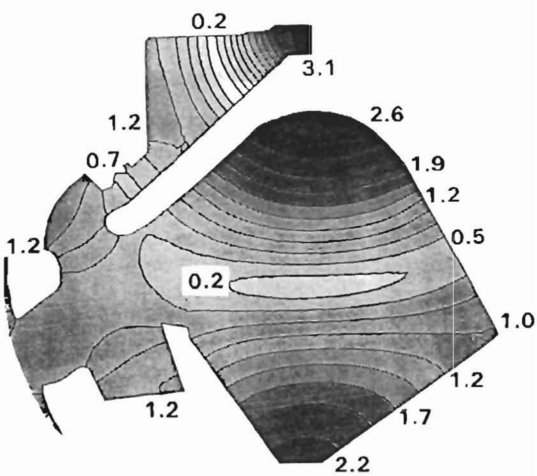

Figure 8. Amplification factor contours, Barbers Point Harbor, 132-sec period.

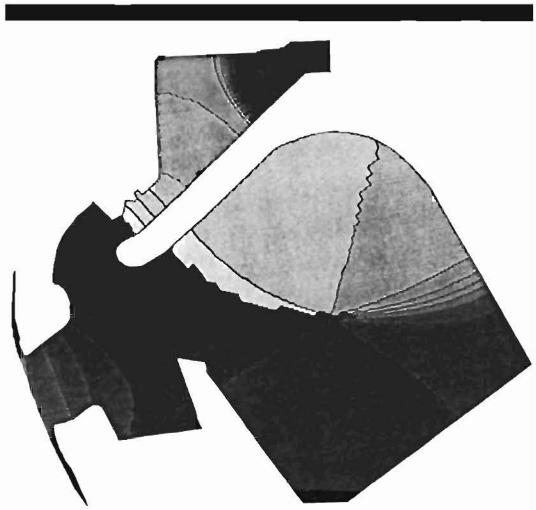

Figure 9. Phase contours, Barbers Point Harbor, 132-sec period.

Los Angeles and Long Beach Harbors

A similar study of long wave motion in Los Angeles and Long Beach, California, harbors was done with the HARBD model (SARGENT, 1989; HOUSTON, 1976). The study objective was to evaluate the performance of the existing, inter-connected harbors and proposed improvements.

The study by HOUSTON (1976) serves as a good illustration. Wave periods ranging from 1 min to 10 min were considered. The wave period range was divided into five intervals and a different grid was developed for each interval. Multiple grids were needed because of the trade-offs between need for coverage of the harbor domain, spatial resolution requirements (relative to wavelength) and computer processing demands. As the period increased, the grid element size and area of grid coverage increased. The grid for the longest periods (6–10 min) covered virtually the entire harbor complex (Figure 10). One interesting feature

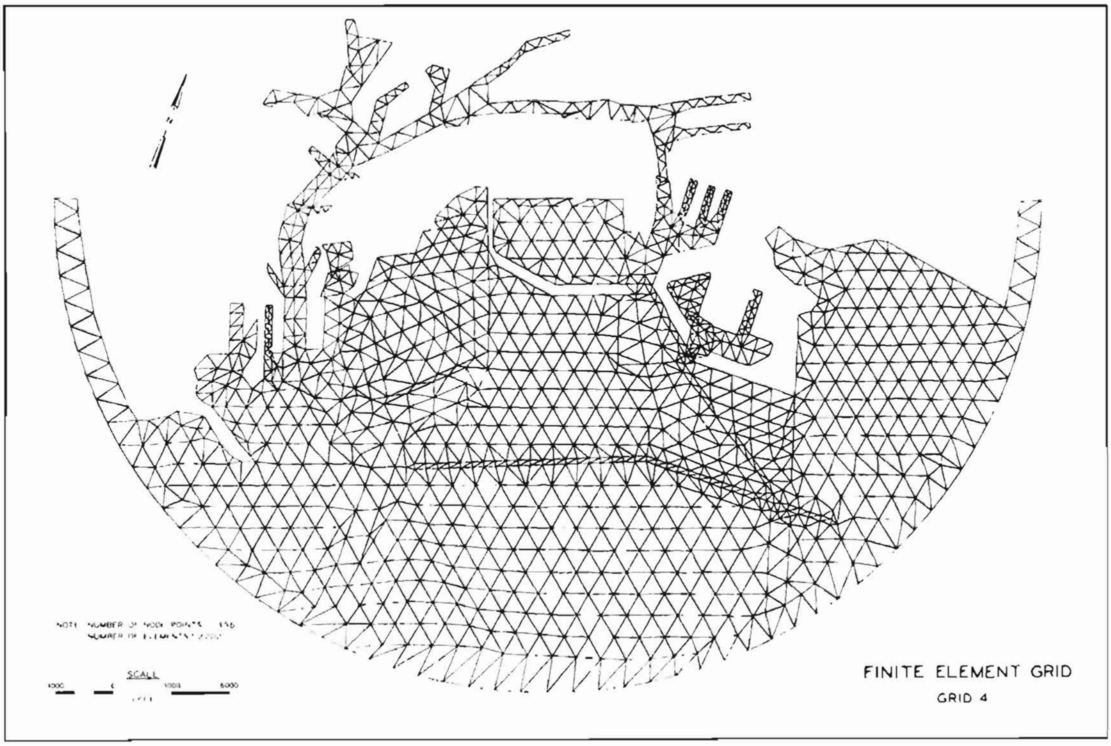

Figure 10. Numerical grid, Los Angeles and Long Beach harbors (from HOUSTON, 1976).

of the grid is the treatment of the three breakwaters protecting the outer harbor. Stone breakwaters are quite pervious to the long waves being considered. Accordingly, one breakwater was treated as completely pervious (no breakwater). The other two were modeled as submerged mounds with crest elevation matching the top of the impermeable breakwater cores.

SUMMARY

Both short and long waves can cause damaging conditions in harbors. Harbors of all sizes are affected, ranging from small recreational harbors to large commercial harbors. The CE has many years of experience with harbor wave concerns and has developed powerful and complementary numerical and physical modeling tools. The CE numerical model can be used effectively to answer many engineering questions about harbor wave response. Two examples are presented of numerical model studies to evaluate the relative level of short wave protection provided by different breakwater configurations. Two additional examples illustrate model applications to evaluate long wave-induced harbor oscillations.

ACKNOWLEDGEMENTS

This work was conducted at the Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, as part of a model documentation effort under the Numerical Model Maintenance Program. Permission was granted by the Office of the Chief of Engineers, U.S. Army Corps of Engineers, to publish this information.

LITERATURE CITED

BERKHOFF, J.C.W., 1972. Computation of combined refraction–diffraction. *Proceedings, 13th International Conference on Coastal Engineering* (ASCE, Vancouver, Canada), pp. 471–490.

BOWERS, E.C., 1992. Low frequency waves in intermediate water depths. *Proceedings, 23rd International Conference on Coastal Engineering* (ASCE, Venice, Italy), pp. 832–845.

BRIGGS, M.J., 1993. Making waves at CERC. *Journal of Coastal Research*, 9(2), 448–461.

BRIGGS, M.J.; LILLYCROP, L.S.; HARKINS, G.S.; THOMPSON, E.F., and GREEN, D.R., 1994. Physical and numerical model studies of Barbers Point Harbor, Oahu, Hawaii. *Technical Report CERC-94-xx* (in publication), Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

BRIGGS, M.J.; LILLYCROP, L.S., and MCGEHEE, D.D., 1992. Comparison of model and field results for Barbers Point Harbor. *Proceedings, Coastal Engineering Practice '92* (ASCE, Long Beach, California), pp. 387–399.

CHEN, H.S., 1986. Effects of bottom friction and boundary absorption on water wave scattering. *Applied Ocean Research,* 8(2), 99–104.

CHEN, H.S. and HOUSTON, J.R., 1987. Calculation of water oscillation in coastal harbors; HARBS and HARBD user's manual. *Instruction Report CERC-87-2,* Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

CHEN, H.S. and MEI, C.C., 1974. Oscillations and wave forces in an offshore harbor. *Report No. 190,* Massachusetts Institute of Technology, Cambridge, Massachusetts.

GILHOUSEN, D.B., 1993. Buoy wave extremes. *Mariners Weather Log,* 37(4), 33–34.

HOUSTON, J.R., 1976. Long Beach Harbor numerical analysis of harbor oscillations. *Miscellaneous Paper H-76-20,* Hydraulics Laboratory, USAE Waterways Experiment Station, Vicksburg, Mississippi.

HOUSTON, J.R., 1978. Interaction of tsunamis with the Hawaiian islands calculated by a finite-element numerical model. *Journal of Physical Oceanography,* 8(1), 93–101.

HOUSTON, J.R., 1981. Combined refraction and diffraction of short waves using the finite elements method. *Applied Ocean Research,* 3(4), 163–170.

LILLYCROP, L.S., 1993. Harbor wave oscillation model (HARBD), theory and program documentation. *In:* CIALONE, M.A.; MARK, D.J.; CHOU, L.C.; LEENKNECHT, D.A.; DAVIS, J.E.; LILLYCROP, L.S.; JENSEN, R.E.; THOMPSON, E.F.; GRAVENS, M.B.; ROSATI, J.D.; WISE, R.A.; KRAUS, N.C., and LARSON, P.M., Coastal Modeling System (CMS) users' manual. *Instructional Report CERC-91-1,* Chapter 9, Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

LILLYCROP, L.S. and BOC, S.J., 1992. Numerical modeling of proposed Kawaihae Harbor, HI. *Proceedings, Coastal Engineering Practice '92* (ASCE, Long Beach, California), pp. 412–424.

LILLYCROP, L.S.; BRATOS, S.M.; THOMPSON, E.F., and RIVERS, P., 1993a. Wave response of proposed improvements to the small boat harbor at Maalaea, Maui, Hawaii. *Miscellaneous Paper CERC-93-4,* Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

LILLYCROP, L.S.; BRIGGS, M.J.; HARKINS, G.S.; BOC, S.J., and OKIHIRO, M.S., 1993b. Barbers Point Harbor, Oahu, HI, monitoring study. *Technical Report CERC-93-18,* Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

OKIHIRO, M.; GUZA, R.T., and SEYMOUR, R.J., 1992. Bound infragravity waves. *Journal of Geophysical Research,* 97(C7), 11,453–11,469.

RAICHLEN, F. and LEE, J.J., 1992. Oscillation of bays, harbors and lakes. *In:* HERBICH, J.B. (ed.), *Handbook of Coastal and Ocean Engineering, Vol. 3,* Houston, Texas: Gulf Publishing Company.

SARGENT, F.E., 1989. Los Angeles–Long Beach harbor complex 2020 Plan harbor resonance analysis. *Technical Report CERC-89-16,* Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

THOMPSON, E.F.; CHEN, H.S., and HADLEY, L.L., 1993. Numerical modeling of waves in harbors. *Proceedings, WAVES 93,* pp. 590–601. ASCE, New Orleans, Louisiana.

THOMPSON, E.F. and HADLEY, L.L., 1994. Wave response of Port Allen Harbor, Kauai, Hawaii. *Miscellaneous Paper CERC-94-4,* Coastal Engineering Research Center, USAE Waterways Experiment Station, Vicksburg, Mississippi.

THOMPSON, E.F. and LEENKNECHT, D.A., 1994. Wind estimation for coastal modeling applications. *Journal of Coastal Research,* 10(3), 628–636.