Figure V-5-45. Dana Point Harbor, California (May 1969)

(a) The area is exposed to storm waves from directions ranging from southwest counterclockwise to south-southeast and to ocean swells from the south. Damaging wave energy may reach the berthing areas by passing through the outer navigation entrance and by overtopping and/or passing through the rubble-mound breakwaters.

(b) As part of the original design effort, a 1:100-scale hydraulic model investigation was conducted to determine the optimum breakwater plan and location and size of the navigation opening that would provide adequate protection for mooring areas during storms (Wilson 1966). Waves with periods ranging from 9 to 18 sec and heights ranging from 2.4 to 5.5 m (8 to 18 ft) were generated from eight deepwater directions using an swl of +2.0 m (+6.7 ft) mllw. A wave height acceptance criterion of 0.46 m (1.5 ft) was established in the harbor berthing areas by the sponsor and waves in the fairway were not to exceed 1.2 to 1.5 m (4 to 5 ft).

(c) Experiments were conducted for existing conditions and 13 plans. Results for existing conditions indicated rough and turbulent conditions in the area even for low-magnitude storm waves. The proposed improvement plan involved construction of outer breakwaters and inner-harbor development consisting of east and west basin berthing areas partially enclosed by the shoreline on the north and a mole section on the south, southeast, and southwest (Figure V-5-46).

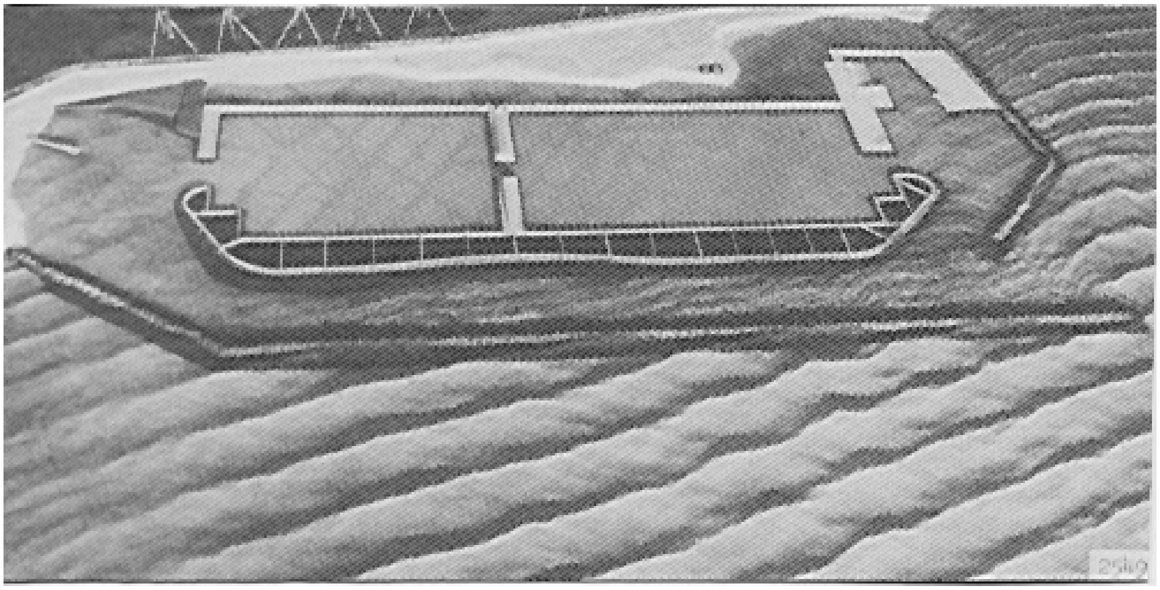


Figure V-5-46. Physical model view of Dana Point Harbor, California, under storm wave attack

(d) Experimental results indicated that wave conditions in the berthing areas were acceptable; however, wave heights in the fairway were about 2.0 m (6.5 ft) for severe storm wave conditions. It was noted that these conditions were due to a standing wave system caused by reflected waves from the mole slopes. Experimental results revealed that modifying the mole slope flanking the fairway, to include a berm, would reduce wave action considerably in the fairway.

(e) The harbor was constructed in accordance with recommendations from the physical model investigation. Post-construction monitoring has shown the harbor is performing as predicted. Mooring areas have experienced no wave problems. The outer west breakwater is overtopped by storm waves, which propagate across the interior channel to the outer revetted mole slope. Vessels in mooring areas behind the moles remain protected. The harbor has successfully endured intense storms, when other southern California small- craft harbor facilities have been severely damaged.

(3) Numerical modeling as a design tool. Numerical modeling requires computerized solution of equations that approximate harbor response to imposed natural forces. Numerical models and computer technology have evolved to the point where useful modeling of actual harbors can often be conveniently done on microcomputers. Numerical models are helpful in harbor studies, even for relatively simple harbor shapes. A combination of physical and numerical modeling is usually preferred for investigating the full range of conditions in a harbor. Numerical modeling related to harbors is best discussed in terms of the natural phenomenon to be modeled, such as waves, circulation, and shore response. Each model's equations and input/output forms are developed for application to particular phenomena. Model systems are now available that provide convenient access to a variety of modeling options under a single user-friendly interface (e.g. SMS 1994).

(a) Wind waves, swell, and harbor oscillations. Numerical wave models can be effectively applied to wave periods ranging from wind waves to long-period harbor oscillations. Numerical models have been 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 gauges (to achieve adequate exposure and avoid oscillation nodes) and to identify from many alternatives a few promising harbor modification plans for fine-tuning in physical model tests. Lillycrop et al. (1993) suggested that numerical modeling is preferable to physical modeling for oscillation periods longer than 400 sec. Both modeling tools can be used effectively for shorter period oscillations.

- Numerical wave modeling concerns are discussed in the following paragraphs, followed by an illustrative example. Additional information on numerical modeling of waves in harbors is available from a number of sources (e.g., Panchang, Xu, and Demirbilek (1998)).

- An initial step in modeling a harbor is to define the area to be covered and required horizontal resolution in the model grid. The coverage area should include the harbor and an area seaward encompassing bathymetry important for waves approaching the harbor. The seaward boundary should be a minimum of several wavelengths away from the harbor entrance, based on the longest wave periods to be modeled. Horizontal resolution is determined by the wavelength of the shortest wave period to be modeled. Typical resolution requirements are between $L/6$ and $L/15$ as the maximum grid element width. If grid elements are uniform in size over the entire grid, L should be based on the shallowest depths of interest. Depending on the particular study and grid-building software available, it may be preferable to build a grid with element sizes varying according to water depth, but still satisfying the wavelength-based maximum size criterion. Computer demands (memory, processing time, storage) in running a harbor model are directly linked to the total number of grid elements. Most harbor studies require a trade-off between coverage area and grid resolution to achieve a workable grid.

- Numerical models applied to harbors are usually based on a form of either the mild slope equation (MSE) or Boussinesq equations. Development of the equations is given by Dingemans (1997), Mei (1983), and others. MSE models are typically steady-state. The MSE model calculates an amplification factor (ratio of local wave height to incident wave height) and phase (relative to the incident wave) for every node in the grid. The MSE does not incorporate spectral processes. Typically, MSE models are run with a representative set of wave height, period, and direction combinations, based on knowledge of incident wave climate. If the MSE is linear, a single wave height for each period/direction combination will suffice. For wind wave and swell applications, regular wave results from the MSE model may be linearly combined, with appropriate weightings, to simulate harbor response to directional wave spectra.

- Boussinesq models are nonlinear and time-dependent. They are forced with an incident wave time series on the seaward boundary and produce a time series of wave response at each node in the grid. The time series may represent regular or irregular wave conditions. Boussinesq models are capable of more accurate representation of harbor wave response than MSE models, at the price of considerably greater computational demands. They are warranted in some practical studies and, with continuing intensive research and development, are likely to become a more workable option in the near future.

- Results from numerical harbor models are in the form of information at selected points or over the entire grid. Point information from Boussinesq models is comparable to time series from field or physical model wave gauges and may be analyzed in similar ways. Spatial information from Boussinesq models can provide animated displays of waves approaching, entering, and interacting with the harbor. Snapshots of waveforms over the harbor at selected times can easily be extracted for still displays. Spatial information from MSE models is in the form of snapshots of amplification factor and phase over the harbor area. Animated displays can be created by expanding amplification factor and phase information into sinusoidal wave time series, if desired.

(b) *Example: Kikiaola Harbor, Kauai, Hawaii*. Kikiaola Harbor is a small, shallow-draft harbor, located along the western part of the Kauai's south shore (Figure V-5-47). The original harbor consisted of west and east breakwaters. The harbor experienced excessive waves, resulting in the addition of inner and outer stub extensions to the east breakwater and a short inner breakwater. A wharf and boat ramp are located along the north boundary of the harbor, east of the inner breakwater.

- Prevailing northeast tradewinds result in a strong predominance of winds from the northeast, east, and southeast at the harbor. Typical wind speeds are 5 to 10 m/sec (10 to 20 mph). Winter storms can generate strong winds from the south. The harbor is exposed to waves approaching from a sector between the 134- and 278-deg azimuths, though the small island of Niihau creates some sheltering in the western exposure. Southern swell, generated by storms in the southern Pacific and Indian Oceans, is a significant part of the wave climate. Also, waves generated by storms in the North Pacific can wrap around the western side of Kauai and affect Kikiaola Harbor. Hurricanes can attack the harbor, which is important for structure design; but they are rare and do not impact operational concerns.

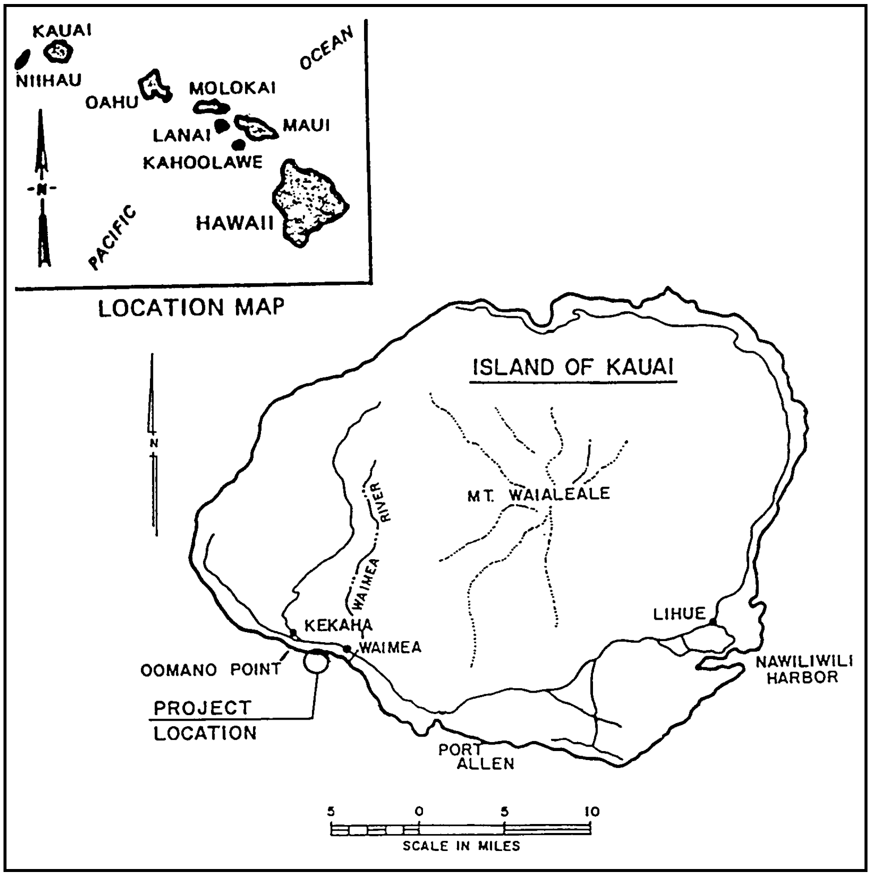
- Use of the existing harbor is limited by two primary factors. First, the harbor is quite shallow. Sediment movement along the local coast, predominantly from east to west, has resulted in shoaling of the entrance and inner harbor. Second, the existing entrance experiences breaking wave conditions that are hazardous to navigation. These two factors are interrelated. Breaking waves are more likely in the existing, shoaled entrance than they would be in a deeper, maintained entrance channel.

- Two plans for modifying the breakwater structures and navigation channels were defined, as follows (Figure V-5-48):

- *Plan 1*. Remove outer stub of east breakwater; remove and reconstruct inner stub of east breakwater a small distance further east; raise crest elevation of exposed portions of east breakwater by 1 m (3-4 ft) and flatten seaward slope to 1:2; widen outer 67 m (220 ft) of west breakwater; dredge 221-m- (725-ft-) long entrance channel with width varying from 32 to 62 m (105 to 205 ft) and maneuvering area to facilitate a 90-deg turn into access channel; dredge 98-m- (320-ft-) long access channel varying in width from 21 to 32 m (70 to 105 ft).

- *Plan 6*. Remove outer and inner stubs of east breakwater; raise crest elevation of exposed portions of east breakwater by 1 m (3-4 ft) and flatten seaward slope to 1:2; extend east breakwater further west to a distance of 33 m (100 ft) past the existing west breakwater location; shorten west breakwater to allow space for access channel; dredge entrance and access channels comparable to those in Plan 1.

- A numerical model study was initiated to investigate wave conditions in the proposed plans relative to the existing harbor and to USACE criteria for channels and berthing areas (Thompson et al. 1998b). An MSE-based numerical model was used to analyze the harbor area (Chen and Houston 1987). Because water depths are shallow (on the order of 1 m in the existing harbor) and the shortest wave period to be modeled was 6 sec, a dense grid was required. To maintain a workable grid size for the model being used, the offshore extent of the grid was significantly limited and could not reach deep water.



(a) Location map

(b) Photograph (1998)

Figure V-5-47. Kikiaola Harbor, Kauai, Hawaii

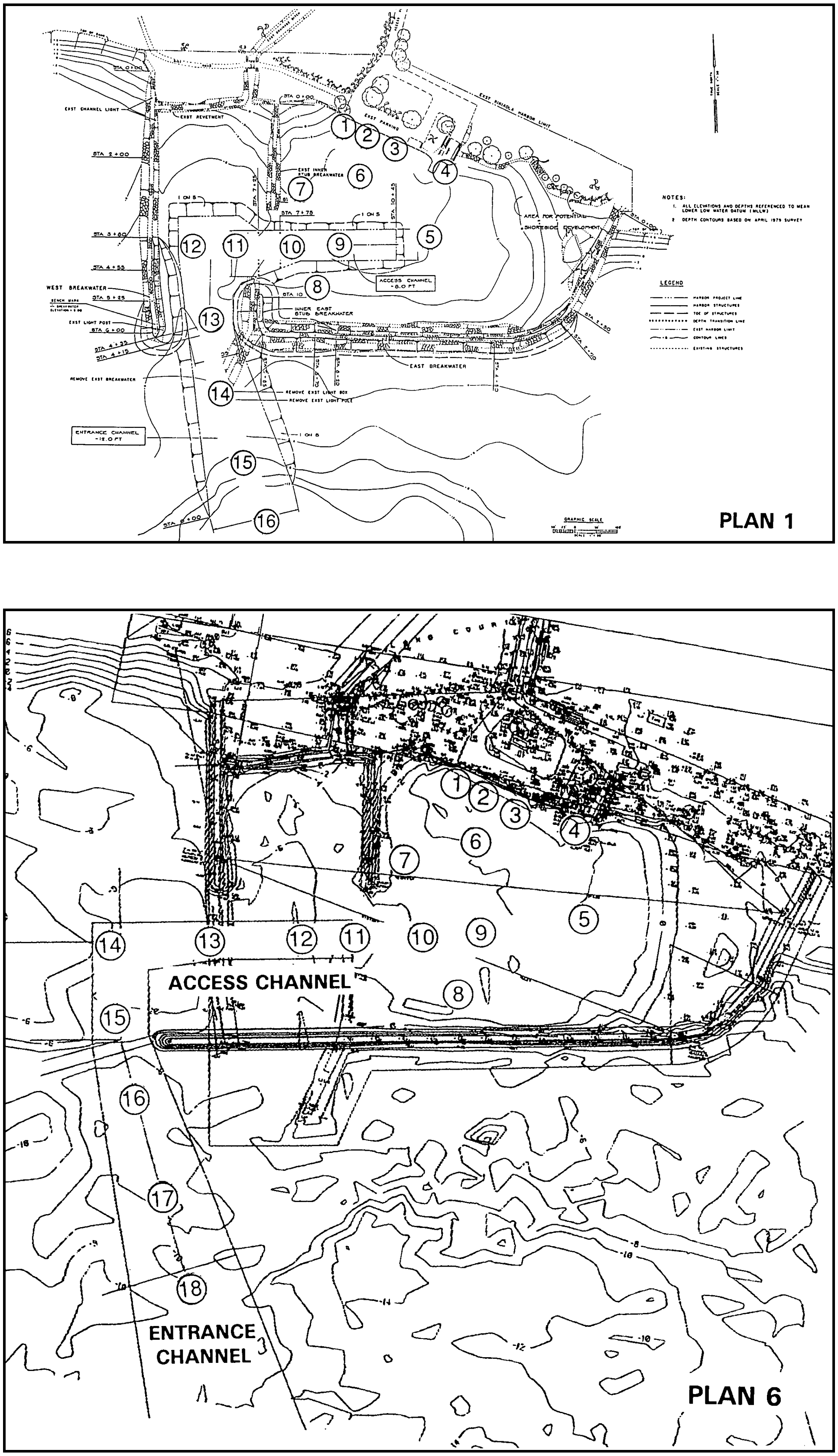


Figure V-5-48. Kikiaola Harbor alternative plans and model stations

- Wave climate at the seaward boundary of the harbor model grid was developed from updated WIS hindcasts in the Pacific OceanAugust 7, 2000. An additional modeling step accounted for sheltering by the islands of Kauai and Niihau as waves approach the harbor. Deepwater wave information was estimated at a point 1.6 km (1 mile) offshore from Kikiaola Harbor. Then, a shallow water transformation model was used to provide wave estimates at the seaward harbor model boundary, at about the 4-m (13-ft) water depth.

- The harbor model grid for the existing harbor consisted of 24,227 elements and 12,461 nodes. Model parameters, including boundary reflection coefficients and bottom friction, were set appropriate to the harbor configuration and model requirements. The tide range at Kikiaola Harbor is about 0.3 m (1 ft). Since harbor response is unlikely to vary much with water level over this small range, a water level of +0.3 m (+1 ft) mllw was used in all runs, representing a high tide condition.

- Wind wave and swell cases were periods ranging from 6 to 22 sec, in 1-sec increments, and approach directions of 164-, 184-, and 204-deg azimuths, representing the range of incident wave directions and entrance exposures. A linear form of the model was used (bottom friction set to zero), so a nominal 0.3-m (1-ft) wave height with each period/direction combination was sufficient. Thus, a total of (17 periods)x(3 directions) = 51 cases was run in the harbor model. Spectral results for each T_p and θ_p needed to represent the incident wave climate were simulated by linearly combining the 51 cases with appropriate weightings based on a JONSWAP spectrum with cos^{2s} directional spreading.

- Snapshots of amplification factor and phase for one incident wave condition illustrate harbor response (Figure V-5-49). A nonspectral condition is shown so that phases can be presented. The amplification factor increases over shoal areas just west of the entrance channel and then steadily decreases as the waves progress through the entrance and into the inner harbor. Plans 1 and 6 provide more shelter to the inner harbor than does the existing plan. Phase lines in the figure show the alignment of wave crests. They give a visual representation of diffraction and shoaling effects on wave direction and length as the 12-sec waves interact with harbor structures and bathymetry.

- Standard operational criteria used by USACE for wind waves and swell in small-craft harbors are:

- H_s in berthing areas will not exceed 0.3 m (1 ft) more than 10 percent of the time.

- H_s in access channels and turning basins will not exceed 0.6 m (2 ft) more than 10 percent of the time.

- To compare with USACE wave criteria, between 15 and 18 stations were selected in each plan, to include the wharf area, berthing area, access channel, and entrance channel (Figure V-5-48). Stations in the existing plan are identical to those shown for Plan 1 except the entrance channel stations are shifted appropriately. Spectral amplification factors were computed and applied to each incident H_s to give a wave climate at each station. The value of H_s exceeded 10 percent of the time was computed at each station. Results for Stations 1-9 are compared to the USACE berthing area criterion and the remaining stations to the USACE access channel criterion (Figure V-5-50). All plans, including the existing, satisfied the berthing criterion at all stations. The inner channel satisfies the channel criterion in all plans. The existing entrance channel does not meet the criterion; and the seaward portions of the Plan 1 and Plan 6 entrance channels slightly exceed the criterion. In conjunction with the increased width of the outer part of the plan entrance channels, the small exceedance of the USACE channel criterion is unlikely to interfere with safe navigation.

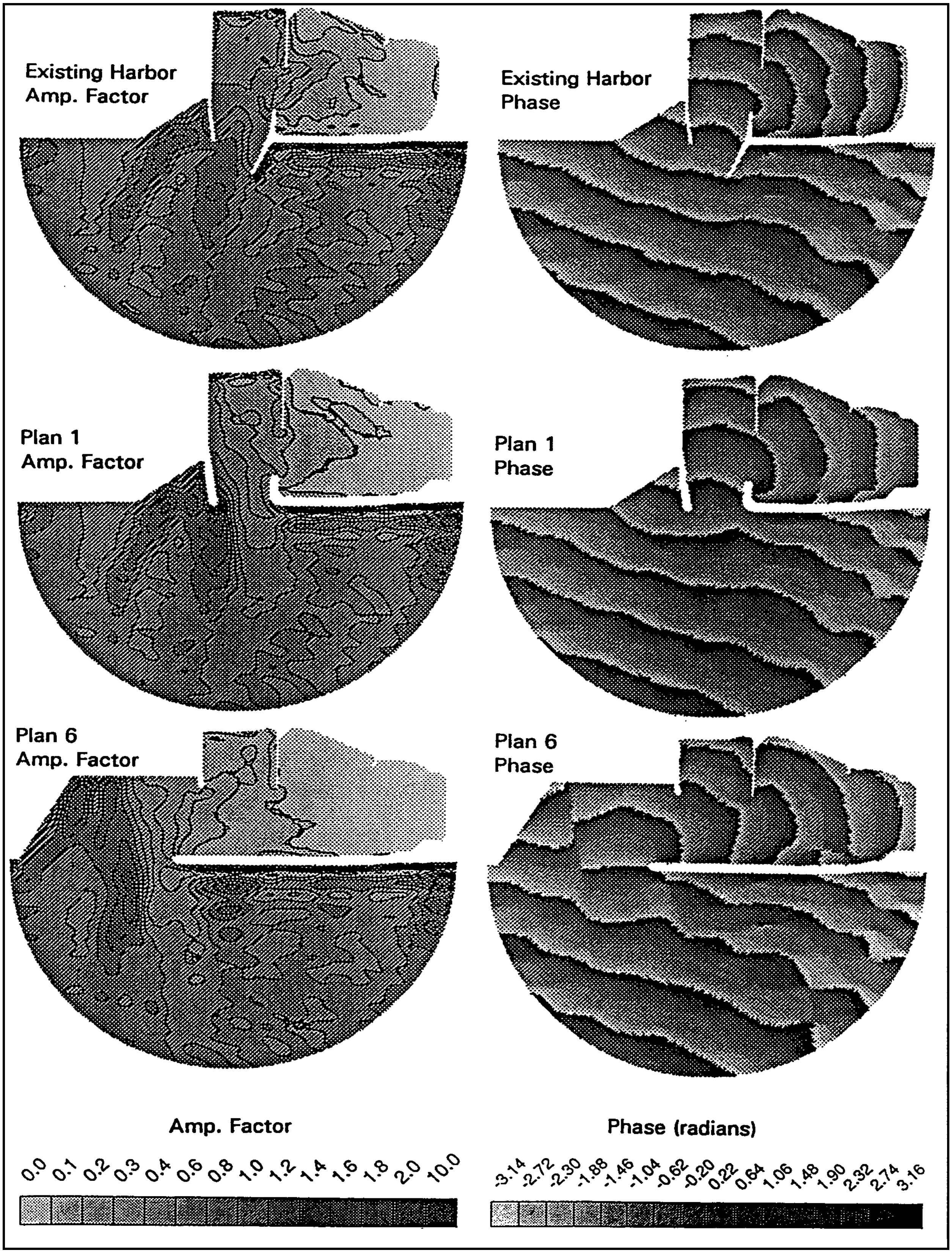


Figure V-5-49. Amplification factor and phase contours, 12-sec wave period, 200-deg azimuth approach direction, Kikiaola Harbor

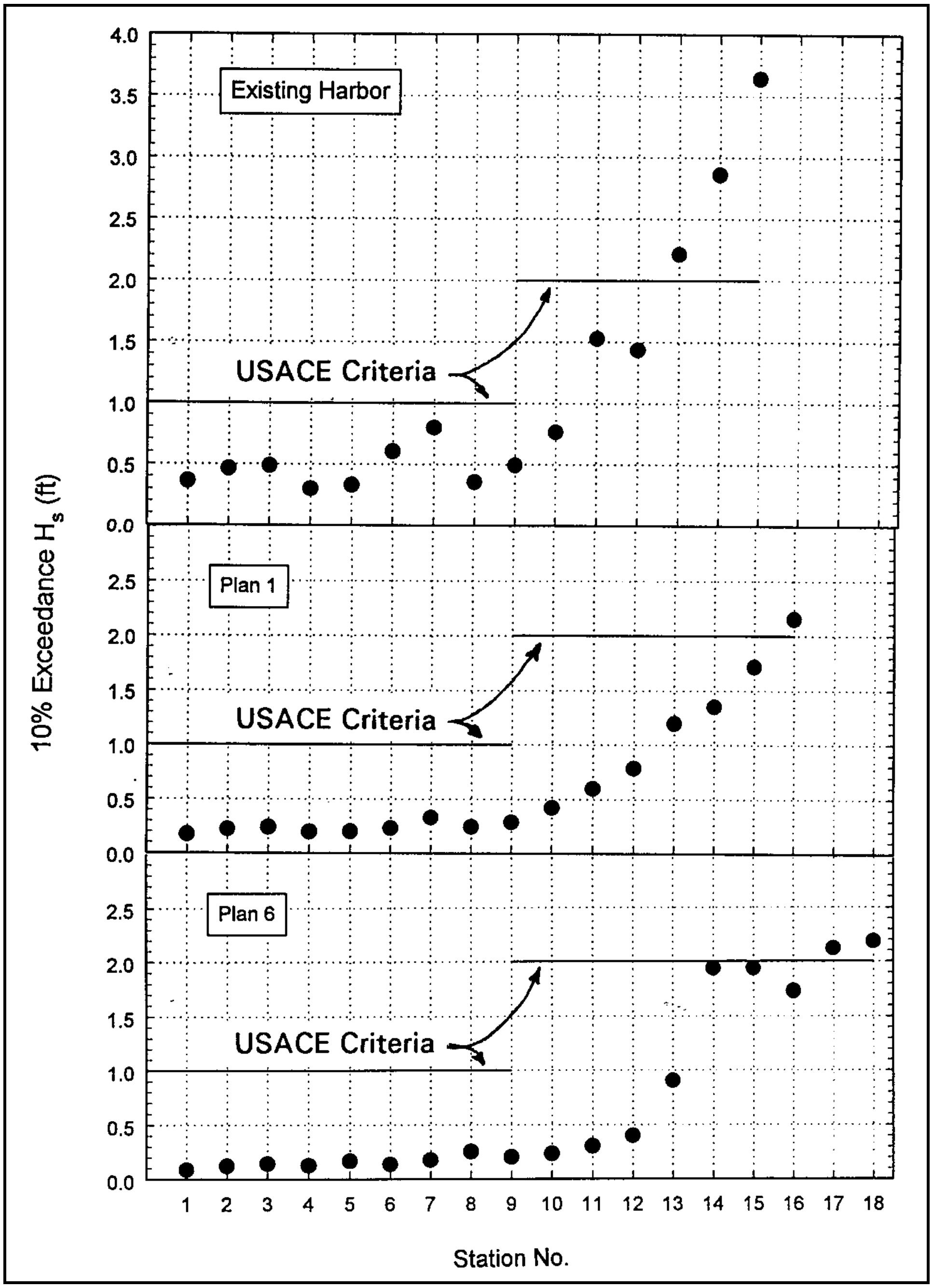


Figure V-5-50. Comparison of H_s exceeded 10 percent of the time, Kikiaola Harbor

- Harbor oscillation characteristics of the existing and plan harbors were also investigated to ensure the plans would not have operational problems due to oscillations. Model parameters were changed to give constant, nonzero bottom friction and full reflection from harbor boundaries. A total of 451 long-wave periods were run, ranging from 25 to 500 sec. The frequency increment between periods was 0.0001 Hz up to a period of 80 sec and 0.00006 Hz for longer periods. Fine resolution in frequency is needed to ensure that resonant peaks are captured. One long wave height is used, representing a moderately energetic long wave case, based on measurements at another Hawaiian harbor. One long wave direction, directly approaching the harbor entrance, is used, since past studies have indicated that harbor response is relatively insensitive to incident long wave direction.

- A snapshot of amplification factors in the existing harbor for a long-period resonance at a period of 150.6 sec represents a simple oscillation between the outer harbor and the east part of the inner harbor (Figure V-5-51). A node (indicated by very low amplification factor) is located a little east of the inner harbor entrance. Considering the most active areas of operational concern, amplification factors at the boat ramp (sta 4) and in the outer harbor (sta 12) were 2 and 3, respectively. A simple basis for judging the operational importance of harbor oscillation amplification factors is given in Table V-5-13 (Thompson, Boc, and Nunes 1998). Thus, the 150.6-sec resonance is not expected to be a problem in operational areas for boats. All amplification factors in all plans across the full range of long-wave periods were significantly less than 5, indicating that harbor oscillations are not a problem in the plan harbors. Additional information on numerical modeling of harbor oscillations is presented in Part II-7-5-f.

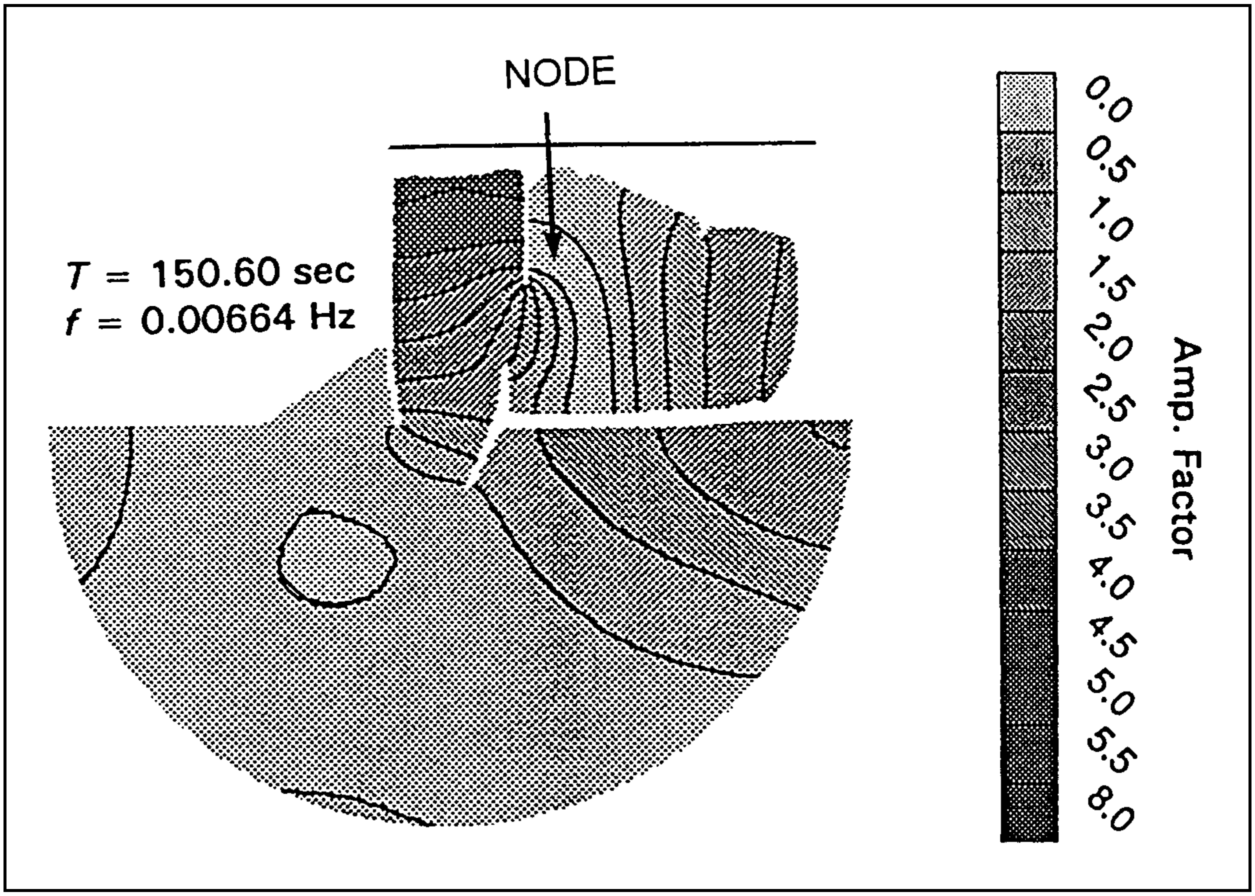


Figure V-5-51. Resonant long wave amplification factor contours, existing Kikiaola Harbor

Table V-5-13
Simple Criteria for Assessing Operational Impact of Harbor Oscillations

Amplification Factor	Operational Impact
> 5	Some problems
> 10	Major problems

(c) Flushing and circulation. Numerical models are effective for evaluating flushing and circulation in harbors and entrances due to forces such as tides and wind. This application is discussed in Part II-7. Numerical models also provide detailed currents along navigation channels needed in ship simulations.

(d) *Example: Maalaea Harbor, Maui, Hawaii.* Maalaea Harbor is a south-facing small-craft harbor located on the southwest coast of the Island of Maui (Figure V-5-52). The harbor facility consists of a 27-m- (90-ft-) wide, 3.7-m- (12-ft-) deep entrance channel and a 0.05-sq-km (11.3-acre) dredged basin. The harbor is protected by a 30-m- (100-ft-) long, 27-m- (90-ft-) wide breakwater on the south side and a 265-m- (870-ft-) long breakwater on the east side. A 91-m- (300-ft-) long paved wharf is located at the shore opposite the entrance. The west and central parts of the harbor are small-craft berthing areas.

Figure V-5-52. Maalaea Harbor, Maui, Harbor (from Air Survey Hawaii, March 1984)

- In response to needs for increased berthing space and better protection during severe wave conditions, the U.S. Army Engineer Division, Pacific Ocean, conducted studies to develop and evaluate harbor modification plans. To evaluate potential impacts on water quality in the harbor, a numerical model circulation and flushing study was conducted for the existing harbor and two proposed plans (Wang and Cialone 1995).

- Circulation in Maalaea Harbor is forced by tide and persistent, often strong winds from the north and northeast. Prototype data were collected over a 9-day period, including currents at two locations and tide. Concurrent wind measurements were available from a nearby airport.

- The numerical model used a curvilinear boundary-fitted coordinate system to generate a computational grid with two vertical layers. It provides current vectors over the harbor and a larger area outside the harbor (Figure V-5-53). The average horizontal grid cell size is 15 m (50 ft). The model is time-dependent, driven with time series of surface elevation along the seaward boundary and wind over the grid surface. Prototype data were used to calibrate the model. Parameters adjusted during calibration include friction, drag, and mixing coefficients.

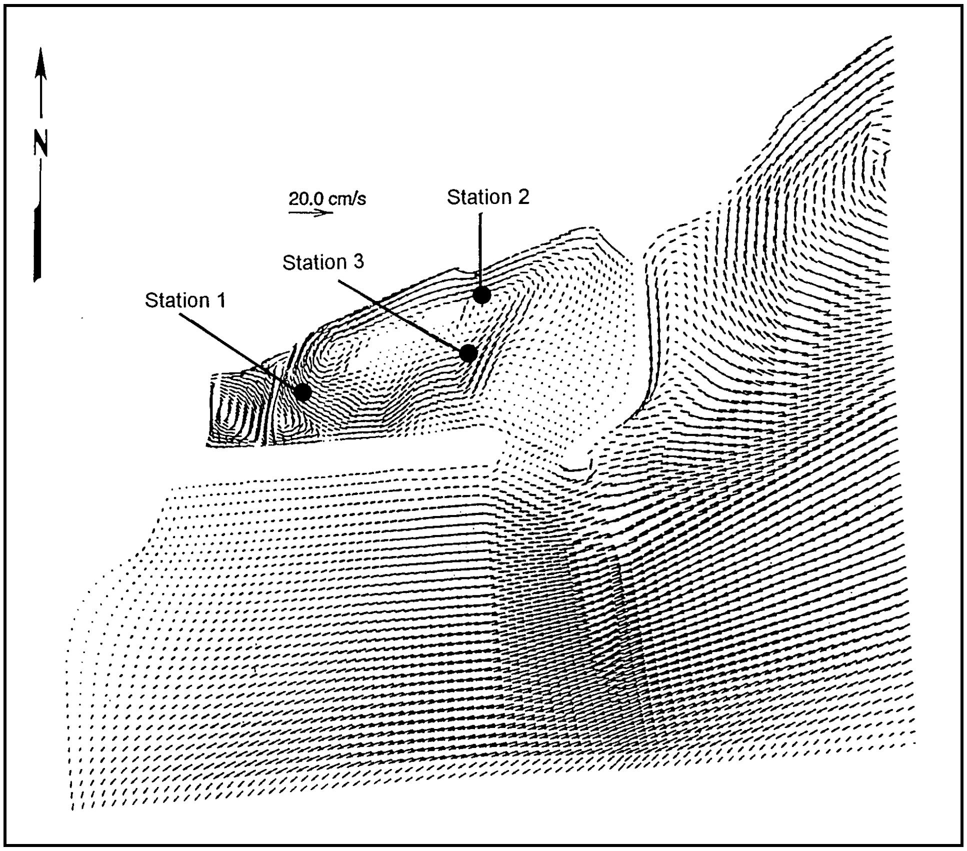


Figure V-5-53. Station locations and surface layer circulation snapshot at Day 3, Maalaea Harbor, existing plan

- Flushing time was defined as the time required for a conservative tracer to decrease to 36.8 percent (1/*e*, *e* = 2.71828) of its initial concentration. This time was evaluated in each plan by beginning a simulation with constant concentration of 100 ppt (parts per thousand) in the harbor and 0 ppt outside the harbor, running the simulation for multiple days, and extracting a concentration time series at three interior harbor stations (Figure V-5-53). Flushing time in the existing harbor was longest at sta 1, in the west part of the harbor and most distant from the entrance (Figure V-5-54). The 2.9-day flushing time was considered acceptable, based on flushing times of 2-4 days as acceptable for design, 4-10 days as marginal, and greater than 10 days as unacceptable (Clark 1983).

(e) Shore response. Possible changes in adjacent shoreline configuration and nearshore bathymetry in response to navigation structures and channel dredging are often a significant concern in navigation projects. Shoreline evolution with and without the project in place can be predicted and analyzed with numerical modeling tools. Guidance on sediment processes at inlets and harbors and numerical modeling options is given in Parts III-2 and V-6.

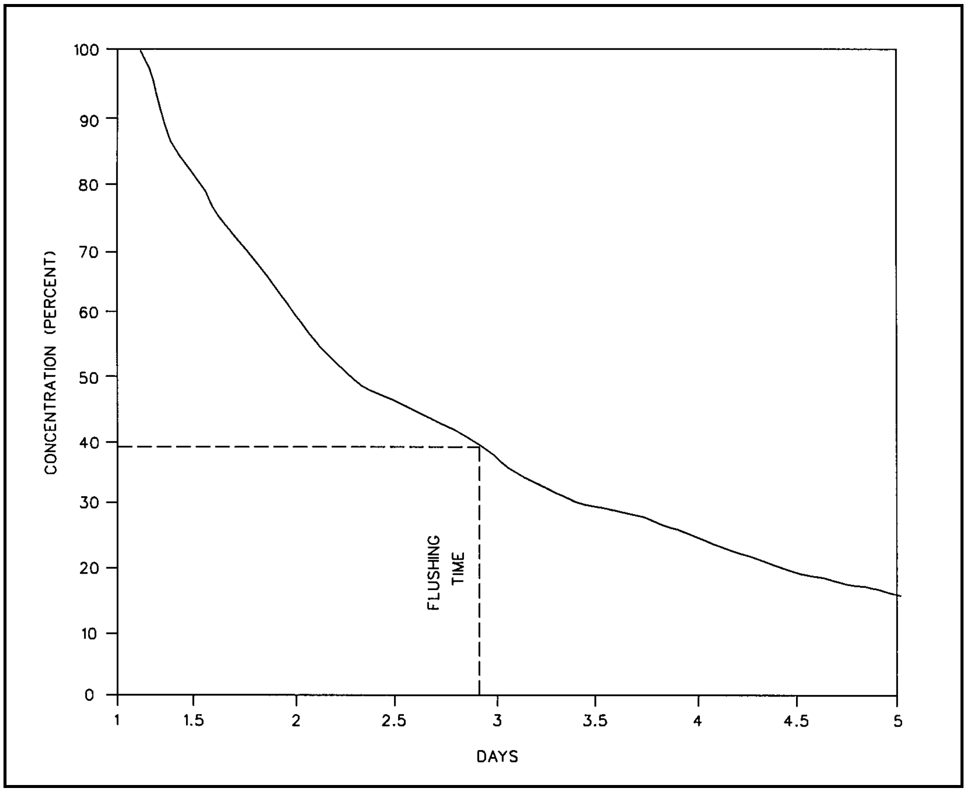


Figure V-5-54. Time series of conservative tracer concentration at sta 1, Maalaea Harbor, existing plan

b. Navigation modeling.

(1) Physical models. Physical models have been used for a variety of navigation studies, with vessel controls such as autopilot, human pilot steering, and free-running vessels with remote control. Physical models are particularly useful for evaluating the behavior of a vessel in the presence of intense, interacting forces, typically involving an entrance channel with ocean waves and possibly harbor or alongshore cross-currents. Waves and human control decisions are statistical processes. Free-running vessel motions in response to many samplings of those processes provide valuable design information about channel depth, width, layout, etc. Vessel position is tracked with high precision relative to channel boundaries in the model. The use of physical models for designing navigation projects is illustrated in the following example.

(a) *Example: Barbers Point Harbor, Oahu, Hawaii*. Barbers Point Harbor is a deep-draft commercial harbor located near the southwest corner of the Island of Oahu, Hawaii (Figures V-5-55 and V-5-56). The harbor was constructed along a previously uninterrupted coastline in 1982. The harbor complex includes a barge basin and small craft marina in addition to the deep-draft basin. The design ship was a general cargo vessel 219 m (720 ft) long with a beam of 29 m (95 ft) and a loaded draft of 10.4 m (34 ft). The entrance channel, designed for one-way traffic, is a constant 137 m (450 ft) in width and 12.8 m (42 ft) mllw in depth over its full length. Just past the coastline, channel depth transitions to 11.6 m (38 ft) mllw, the design depth of the inner channel and deep-draft harbor. The deep-draft basin is approximately 671 m x 610 m (2,200 ft x 2,000 ft) in size, covering an area of 0.37 sq km (92 acres).

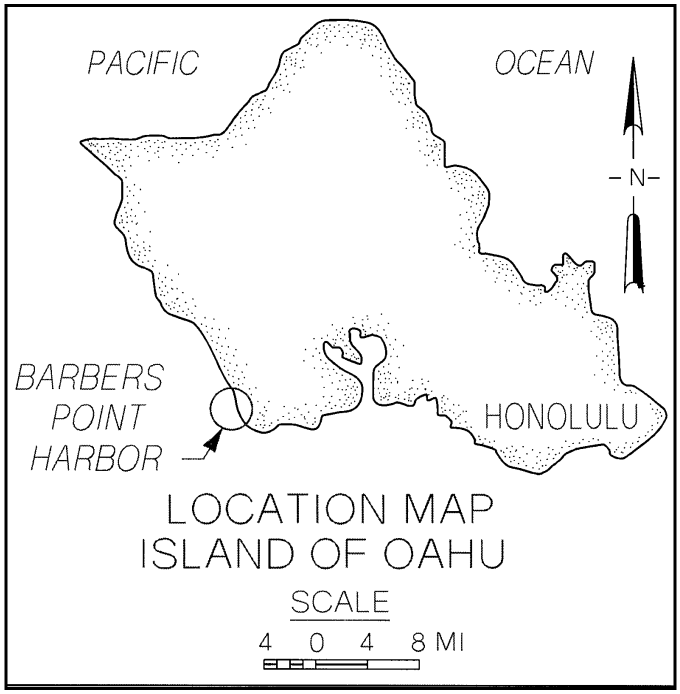


Figure V-5-55. Barbers Point Harbor, Oahu, Hawaii, location map

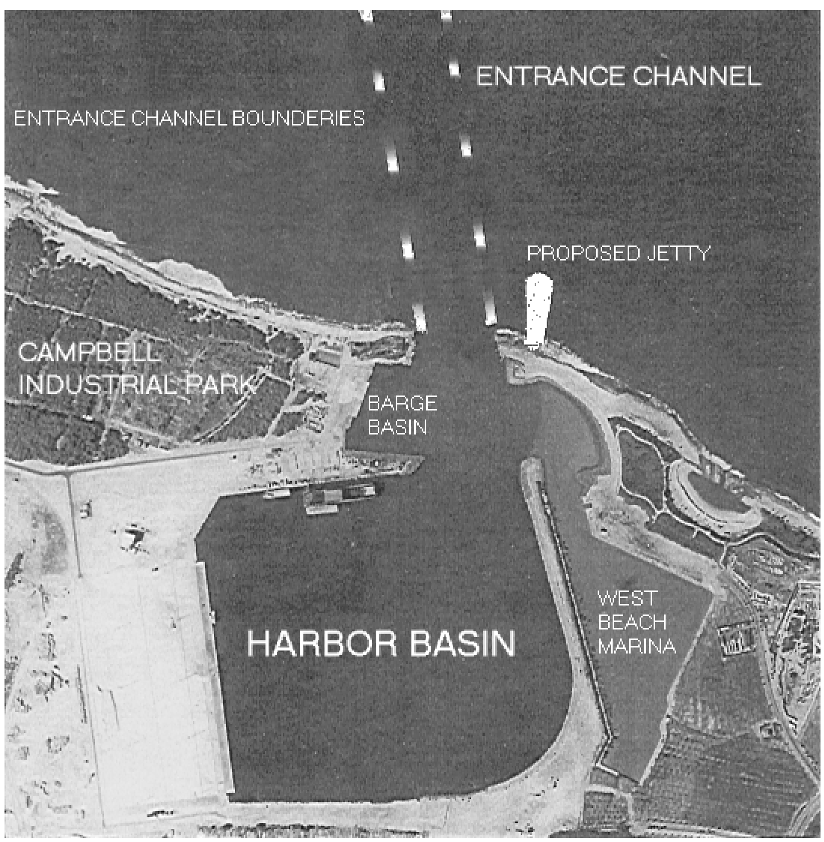


Figure V-5-56. Barbers Point Harbor, Oahu, Hawaii (August 1994)

- Changing economic conditions have created a need for the harbor to serve larger ships. In response to this need, the State of Hawaii and the U.S. Army Engineer Division, Pacific Ocean, sponsored physical and numerical model studies to assist in designing harbor modifications (Briggs et al. 1994, Harkins and Dorrell 1998). The primary study task was to evaluate the navigability of proposed channel and harbor configurations for a larger design ship unaided by tugs.

- A physical model of the harbor complex and adjacent coastal areas was constructed (Figure V-5-57). The model scale, 1:75 undistorted, was selected for proper reproduction of important harbor features, storm waves and longshore currents, and the design ship. Model bathymetry extended to the 30-m (100-ft) mllw bottom contour and a distance of about 1,067 m (3,500 ft) along the coast on either side of the entrance channel. Total area covered by the model was over 1,000 sq m (3,500 sq ft). A directional spectral wave maker was placed seaward of the modeled bathymetry. Longshore currents, which affect navigation in the existing harbor, were created in the model with a system of PVC pipe extending along each lateral boundary (with diffuser ports) and meeting at a pump station located behind the model, landward of the coastline. Pump controls allowed generation of longshore currents in either direction. Diffuser ports were open or plugged as needed to achieve desired current patterns.

Figure V-5-57. Physical model of Barbers Point Harbor

- Two design ships were identified, based on anticipated use of the harbor for container and bulk coal traffic. Existing ships were selected as representative of future harbor traffic, the *President Lincoln*, a C9 container ship with capacity of 2,900 TEU operated by American President Lines, and the *Bunga Saga Empat*, a bulk carrier (Figure V-5-58). The design bulk carrier was a modified version of the *Bunga Saga Empat*, with length increased by 30 m (100 ft). Design ship dimensions are summarized in Table V-5-14.

Figure V-5-58. Bulk carrier *Bunga Saga Empat*

Table V-5-14
Design Ship Dimensions for Barbers Point Harbor Studies

	Prototype Ship Dimensions	
	Container Ship	**Bulk Carrier**
Length Overall	262 m (860 ft)	259 m (850 ft)
Beam	32 m (106 ft)	32 m (106 ft)
Fully Loaded Draft	11.9 m (39 ft)	13.7 m (45 ft)

- Model ships were constructed to match the harbor model scale, 1:75 (Figures V-5-59 and V-5-60). Model ships were self-powered by onboard batteries. Forward and reverse speeds, rudder angle, and, for the container ship, bow thruster direction and speed were remote-controlled.

- A set of design transit conditions was selected for simulation. Prototype measurements of waves and currents near the harbor entrance were available. Wave data were collected over a period of approximately 4 years; currents were collected over a 65-day period. For harbor plan evaluation, the following conditions were used. The highest measured H_s values and a representative range of T_p and θ_p were selected, a total of eight wave conditions. The range of H_s and T_p values was 2.1 to 3.0 m (7.0 to 10.0 ft) and 6 to 18 sec, respectively. Longshore currents were selected to represent average, normal, and extreme conditions from both directions. Extreme currents were 0.41 m/sec (0.80 knot) from the north and 0.33 m/sec (0.65 knot) from the south. Based on data from a nearby airport, severe wind speeds of 10.3, 12.9, and 20.6 m/sec (20, 25, and 40 knots) were selected.

Figure V-5-59. Model bulk carrier

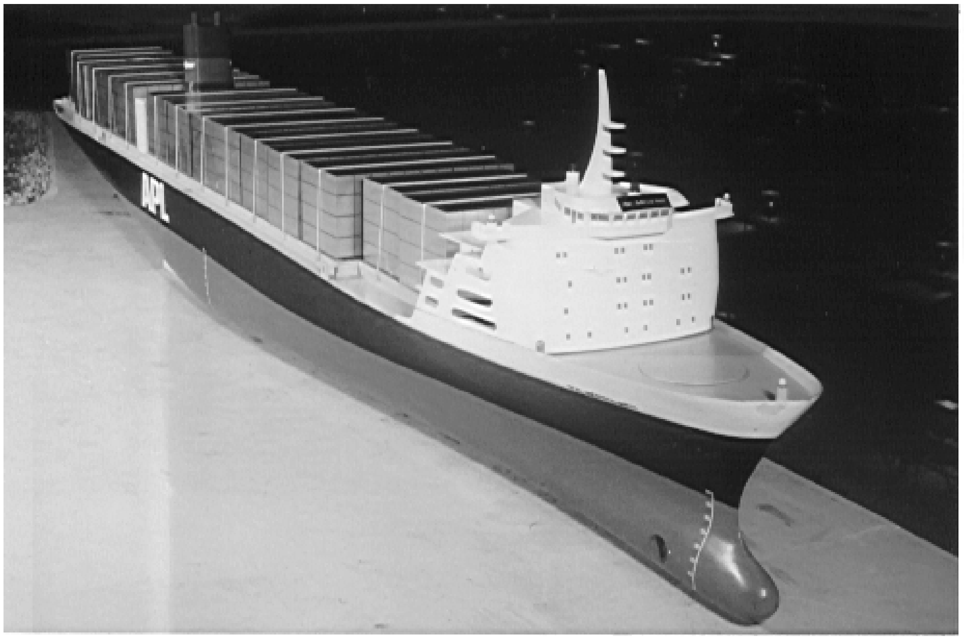


Figure V-5-60. Model container ship

- Six harbor plans were studied with varying combinations of the waves, current, and wind, as selected for design transit conditions. Wind forces were simulated with a ship-mounted fan. Model ships were guided by remote control between deep water and the protected harbor. Both inbound and outbound runs were made. Two experienced local pilots assisted in verifying the model setup and conducting some of the runs. Inbound runs were significantly more difficult than outbound runs. The ship must slow in approaching the entrance and it becomes more difficult to control. Typical inbound ship speeds are 13.0 km/hr (7 knots) at the seaward end of the entrance channel, 7.4-9.3 km/hr (4-5 knots) in the vicinity of the coastline, and 3.7-5.6 km/hr (2-3 knots) in the harbor. After a recommended harbor plan was identified, a number of channel/harbor depth variations were studied to optimize design depths. A total of nearly 2,000 runs were made, of which the majority were inbound.

- Navigability was evaluated by several methods during the course of the model studies. Ship operators recorded their observations after each run, with particular attention to any difficulties during the run. An overhead video camera recorded each run. A commercial motion analysis system was used to collect and analyze model ship motions. The system uses digital cameras and strobes to track reflecting balls. Six balls were mounted on the model ship (e.g., Figure V-5-59) and four were placed at fixed locations around the channel. After processing, the system provides a time series of clearance between ship hull and bottom.

- Physical model data on ship horizontal and vertical clearance in the channel were evaluated in a probabilistic assessment of channel design. The design then includes a consideration of the natural variability of wave, current, wind, ship track, and ship response, which is crucial in realistically assessing the probability of a momentary grounding event during ship transit. Thus risk of design ship contact with channel sides or bottom can be incorporated into the design process. The expected time interval between C9 container ship grounding events as a function of number of transits per year illustrates risk information available for design (Figure V-5-61). Since several different methods for estimating probabilities were applied to the physical model tests, the average from all methods is shown, bracketed by best and worst expected performance based on variability in the methods. Additional details are given by Briggs, Bratteland, and Borgman (2000).

- The recommended plan differs from the existing harbor in the following ways:

  - Entrance channel is deepened and flares out at the seaward end to allow ships more maneuvering space during initial approach.

  - Transition from entrance channel depth to harbor depth is moved from the coastline to the inner harbor basin opening. This change moves the transition to a lower wave energy environment and gives pilots more space to correct when vessel shear occurs at the depth discontinuity.

  - Harbor is deepened and expanded in size by excavation in the east part of the harbor.

(b) Additional information, based on numerical model studies of Barbers Point Harbor oscillation characteristics, is available in Part II-7.

(2) Ship simulations. Increasingly, deep-draft channels are being designed using ship simulators. For example, the USAERDC ship simulator is schematized in Figure V-5-62. Ship simulations typically have pilots operate the steering wheel and ship controls and navigate a realistic course in real time. Pilots give verbal commands for tug assistance as needed, and an assistant operates tug controls. Pilots are drawn from professional pilot associations serving the project area. Their experience and intuition aids in evaluating existing projects as well as refining and studying new alternatives for safe and optimum channels and/or

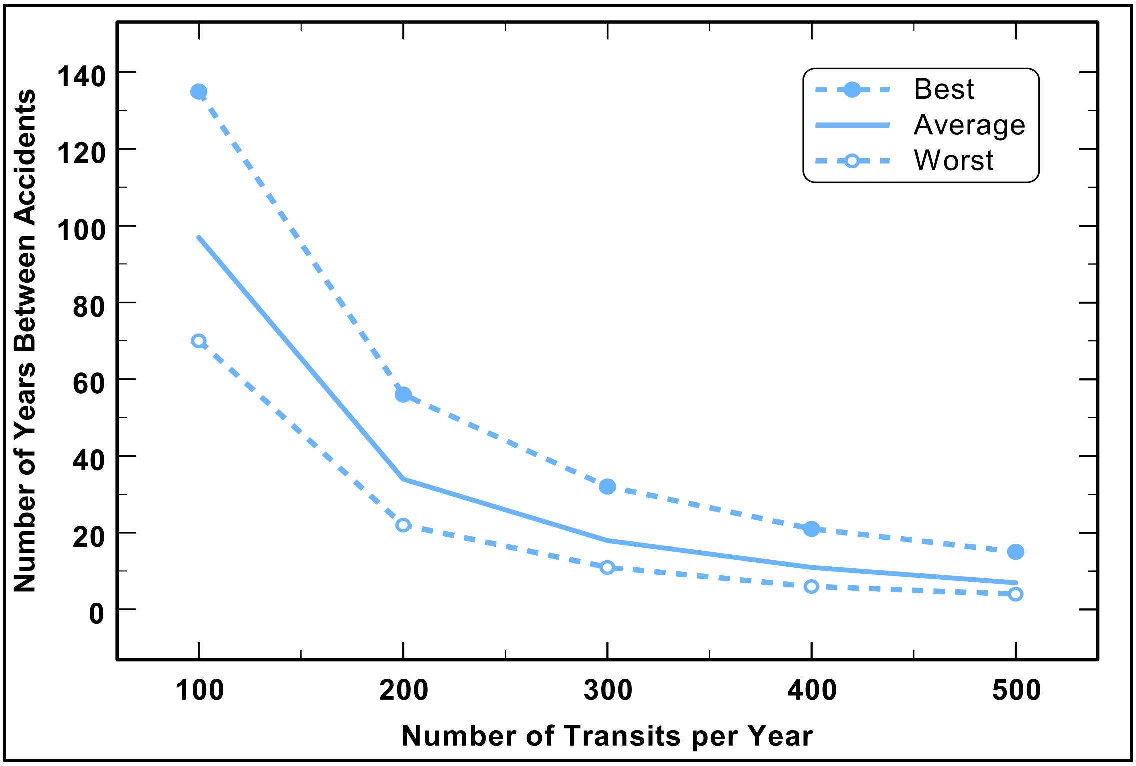


Figure V-5-61. Probability assessment for C9 container ship navigating recommended entrance channel, Barbers Point Harbor

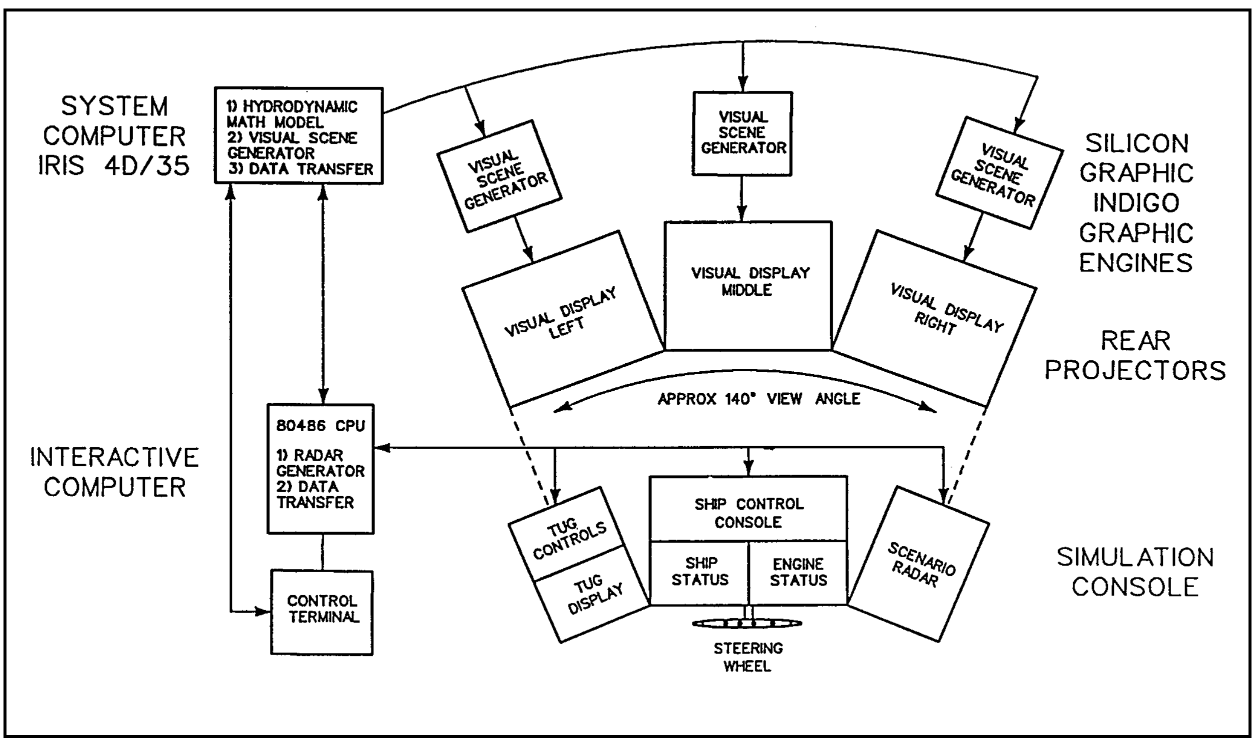


Figure V-5-62. USAERDC ship simulator system

turning basins. At some levels of project design, simulators may be used advantageously for fast-time runs with either autopilot or human control instead of a more comprehensive and costly real-time pilot evaluation program.

- Simulators are special numerical models involving representations of a ship, navigation channel, currents, wind, visual scene (including view over the ship, aids to navigation, bridges, docks, and other visual features needed for piloting cues and adequate realism), radar image, tugs and thrusters, ship bridge controls, and typical bridge instruments. Simulated forces and effects are depicted in Figure V-5-63. The ship model(s) experiences these forces and effects in ways similar to the prototype ship(s).

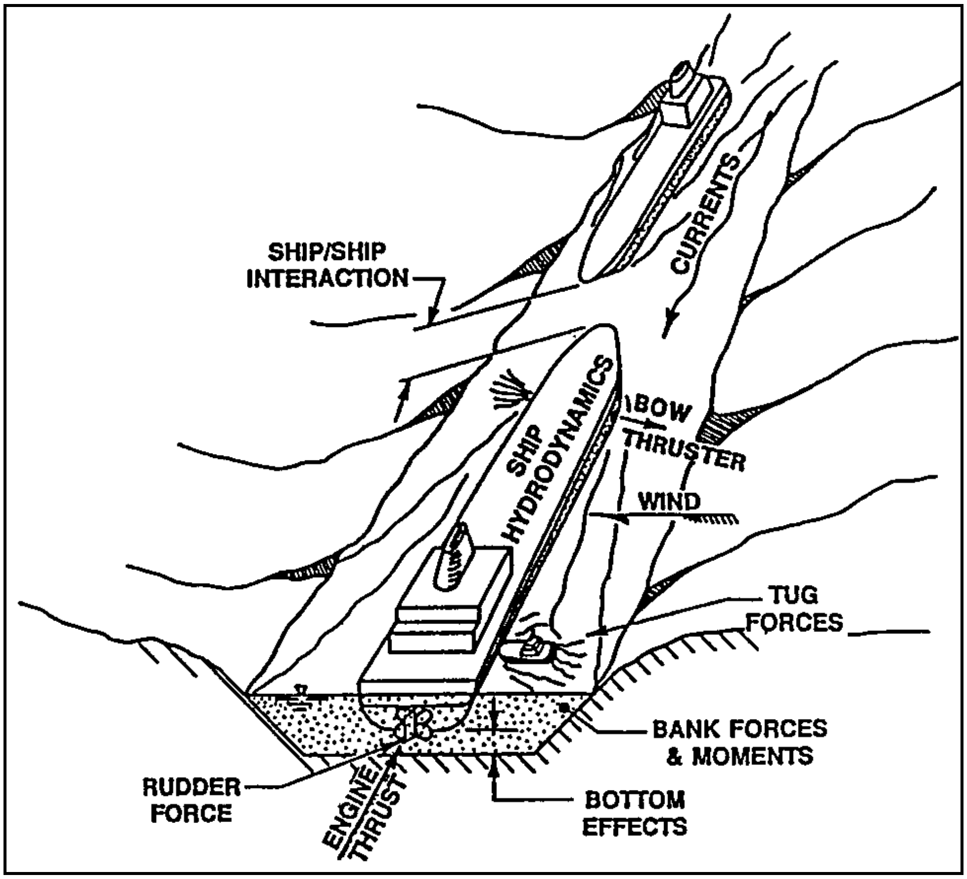


Figure V-5-63. Ship simulator forces and effects

- The key steps in a real-time simulation are shown in Figure V-5-64. Output information saved at selected short time intervals during a simulation includes ship position, engine and rudder settings, ship movement information (speed, heading, rate of turn, drift angle), and minimum clearance relative to channel boundaries. If tugs are used, information on tug forces imposed on the ship may also be saved.

- Two example ship simulator studies are discussed in the following paragraphs. More information on ship simulators is available from USACE (1998), Webb (1994), and PIANC (1997a).

(a) *Example: Alafia River Harbor, Florida*. The Alafia River Harbor is located along the eastern shore of Hillsborough Bay, about 13 km (8 miles) southeast of Tampa, Florida (Figure V-5-65). The

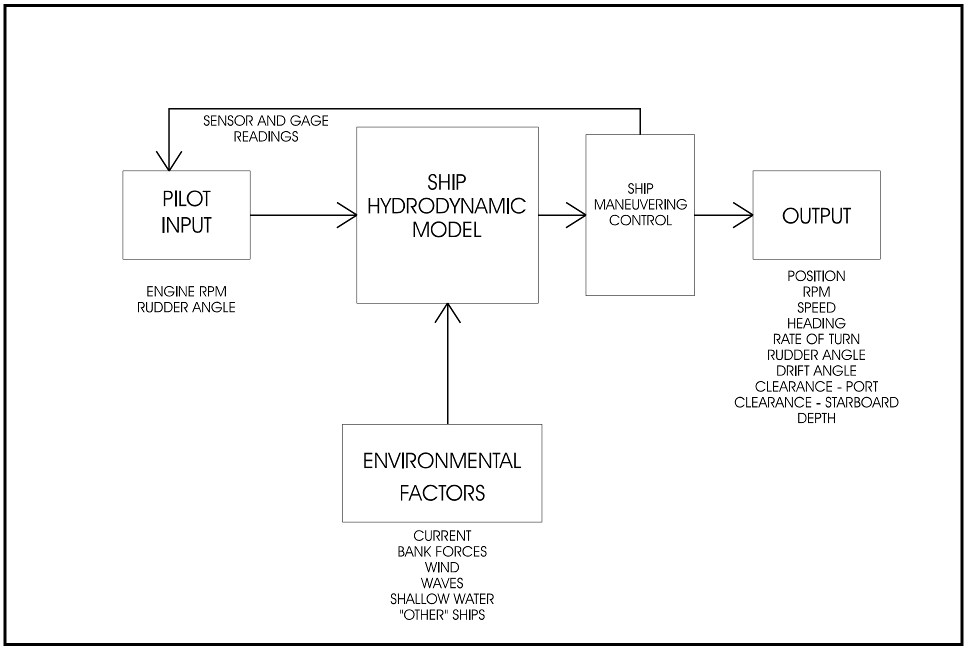


Figure V-5-64. Real-time simulation

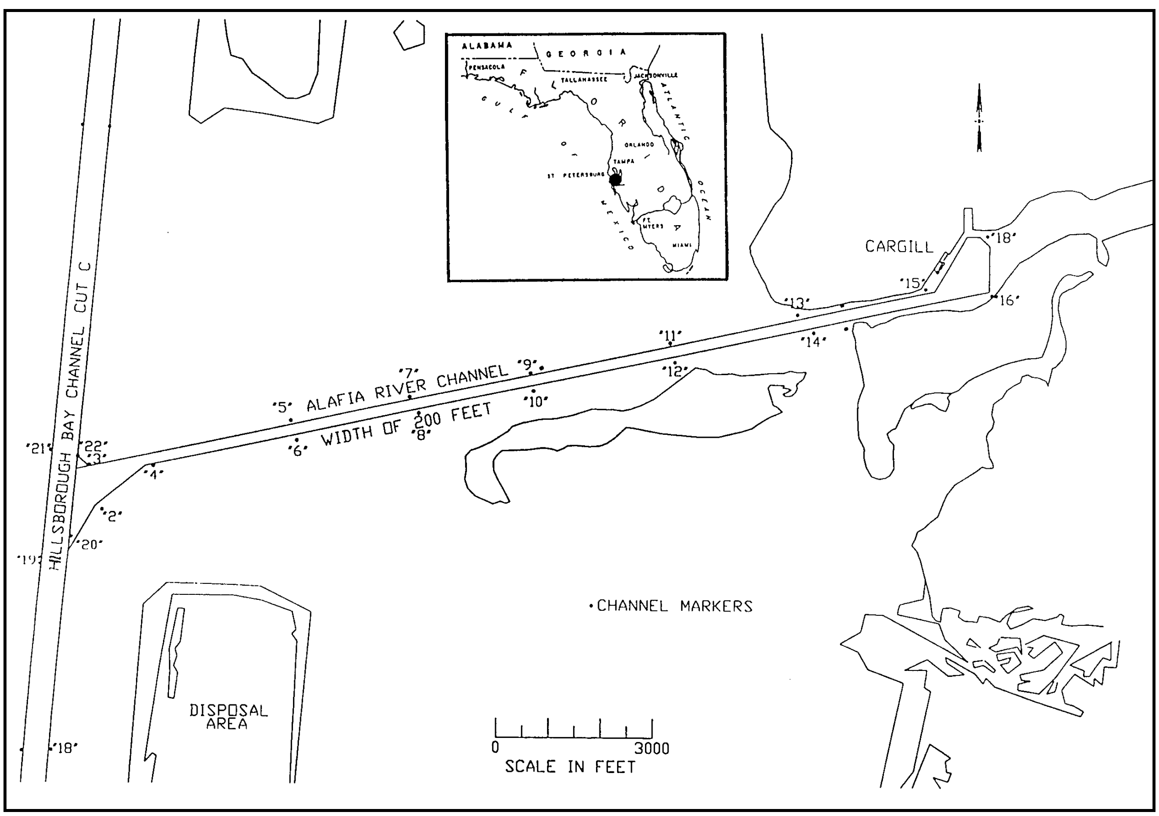


Figure V-5-65. Existing Alafia River Channel and turning basin

existing federally maintained project consists of a turning basin adjacent to the dock facilities and a channel connecting the turning basin to Hillsborough Bay Channel Cut C, the primary north-south shipping channel in Hillsborough Bay. Total length of the federal project is 5.8 km (3.6 miles). Channel depth is 9.1 m (30 ft) mllw. Channel width is 61 m (200 ft). The turning basin is 213 m (700 ft) wide and 366 m (1,200 ft) long.

- Alafia River Harbor is used mainly to ship phosphate rock and bulk phosphate products. Ships typically enter the harbor in ballast and load bulk materials until the ship draft reaches the limit allowed in Alafia River Channel or until the ship is fully loaded. Ships turn in the turning basin at the start of the outbound run, in a loaded condition.

- The U.S. Army Engineer District, Jacksonville, funded ERDC to conduct a ship navigation simulation study to investigate performance of two proposed plans for upgrading the Alafia River Channel and turning basin to accommodate larger ships. A notable part of the study is the detailed visual scene developed to provide pilots with realistic visual cues. The cues are a crucial part of slowing the ship on approach to the turning basin, approaching the dock, and turning the ship for the outbound run. Figure V-5-66 shows two pilots operating a bulk carrier. One pilot is guiding the ship, the other is operating tug controls on command. The ship has just entered the turning basin and turned toward the dock. The view direction (which is easily selected by the pilot) is to starboard, with the ship bow visible at the right side of the scene. The Alafia Channel heading out to Hillsborough Bay is visible at the left side, including a channel marker in the foreground. The dock and dock-side loading facilities are just to the left of the ship bow. Further left are numerous small trees and a line of rail cars. This scene adjusts continuously as ship position or pilot view direction change. Additional details of the study are given by Thompson et al. (1998a).

Figure V-5-66. Visual scene of Alfia River Harbor ship simulation study, inbound bulk carrier approaching dock

(b) *Example: San Juan Harbor, Commonwealth of Puerto Rico*. San Juan Harbor is located on the north coast of Puerto Rico, with open exposure to the Atlantic Ocean (Figure V-5-67). It is the largest port in Puerto Rico and a major container port. Noncontainerized cargo, such as petroleum products, lumber, grain, automobiles, and steel, is also imported to the island by sea. Rum, Puerto Rico's principal export, is shipped in containers. Cruise vessels frequently call on San Juan Harbor.

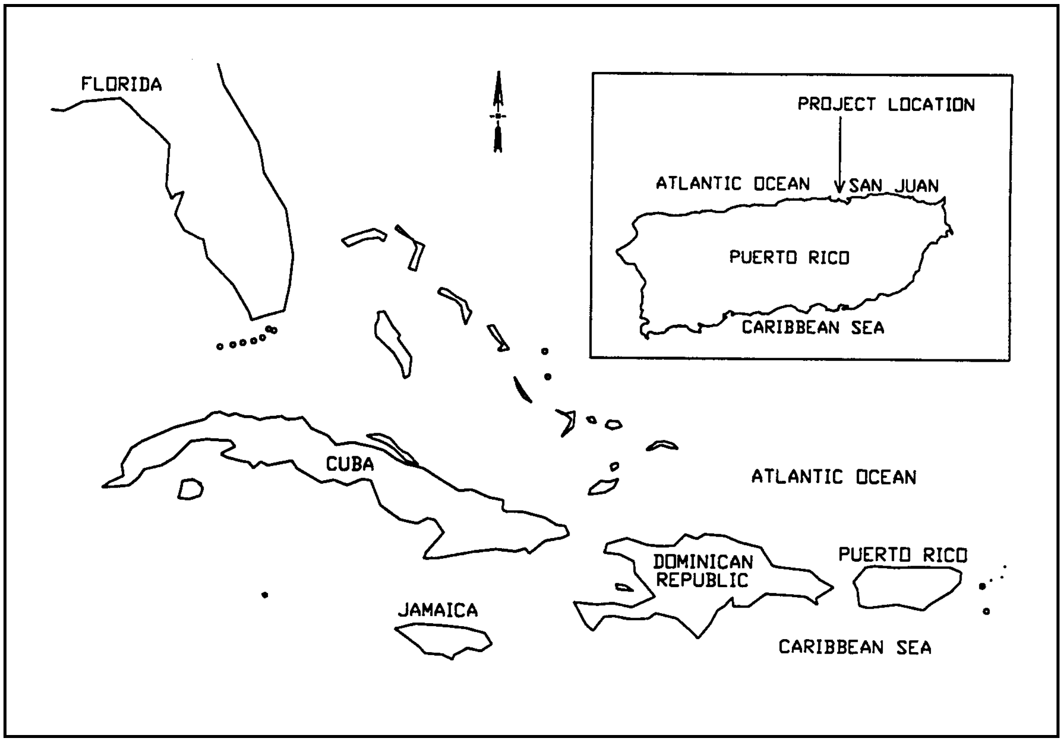


Figure V-5-67. San Juan Harbor, Commonwealth of Puerto Rico, location map

- Federally maintained channels include an entrance channel (Bar Channel), a main interior approach channel to the harbor complex (Anegado Channel), and three interior channels forming a triangular path accessing the principal dock areas (Army Terminal, Puerto Nuevo, and Graving Dock Channels) (Figure V-5-68). Design depth of the outer Bar Channel is 13.7 m (45 ft). The deepest approach to the harbor is the S-shaped path along Bar, Anegado, and Army Terminal Channels, with a controlling depth of 11.0 m (36 ft). Puerto Nuevo and Graving Dock Channels have design depths of 9.8 and 9.1 m (32 and 30 ft), respectively. Bar and Anegado Channel widths are 152 and 305-366 m (500 and 1,000-1,200 ft), respectively. The other three channels have design widths of between 91 and 122 m (300 and 400 ft).

- Wind and waves strongly affect the harbor entrance. Winds are usually steady and are described as being between 8 and 10 m/sec (15 and 20 knots) predominantly from the east and northeast. Waves typically approach the entrance from the north, northeast, and east, with significant heights up to 6-7 m (20-22 ft) during severe events.

- Pilots typically board inbound ships when they are 4.8 km (3 miles) from the harbor entrance. The entrance channel can be difficult to navigate in the presence of wind and wave conditions. Ships must maintain speed in the entrance channel for control, yet they must slow to make the relatively sharp turn into Anegado Channel. All documented accidents in recent years are groundings that have occurred on the south side of this turn. The turn is difficult for outbound ships, too, because of the

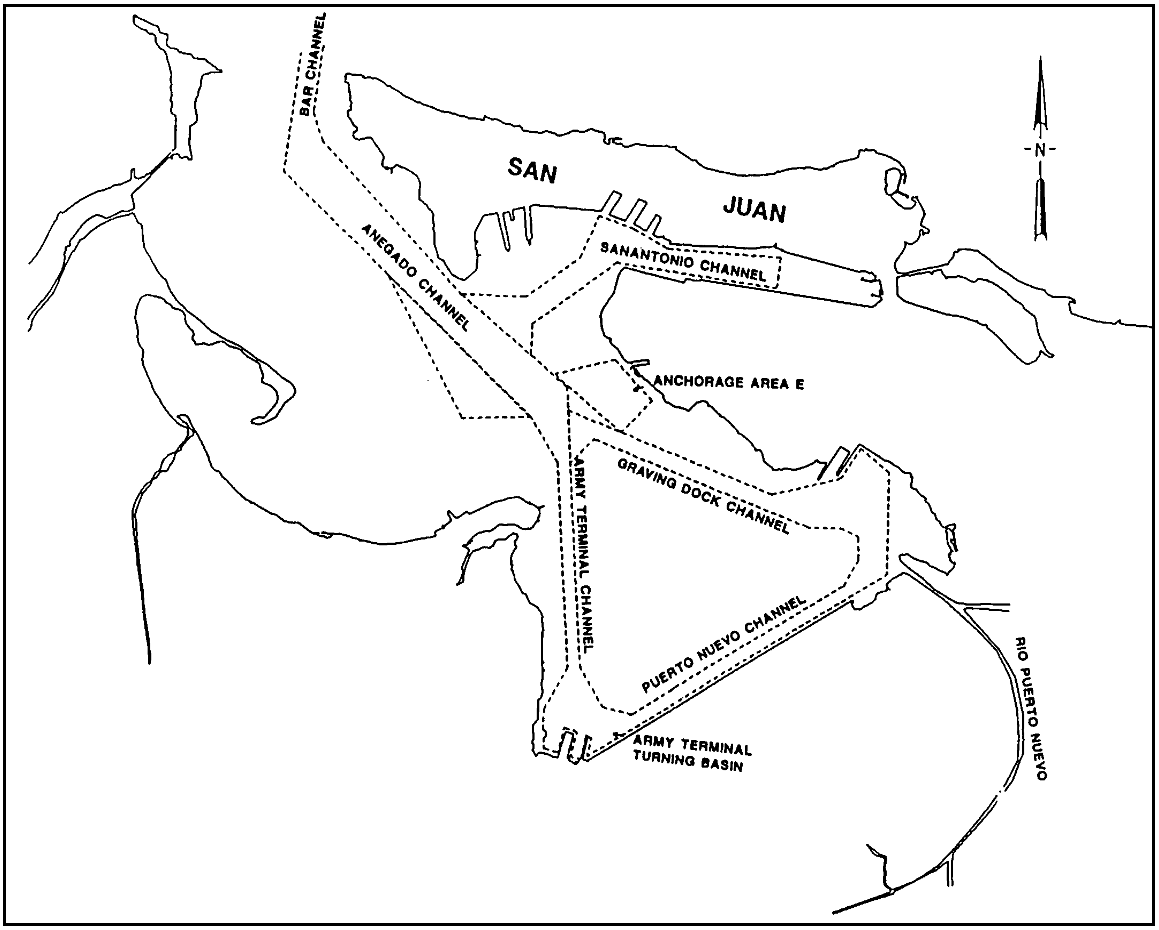


Figure V-5-68. San Juan Harbor channels

relatively narrow entrance channel. Sharp turns associated with the relatively narrow interior channels can also be difficult to navigate.

- The U.S. Army Engineer District, Jacksonville, funded a real-time ship simulator study of existing and two proposed alternative plans to address navigation concerns in San Juan Harbor channels and to allow access to deeper draft ships (Webb 1993). Controlling depth in the proposed plans is 11.9 m (39 ft) in Anegado, Army Terminal, and Puerto Nuevo Channels and 11.0 m (36 ft) in Graving Dock Channel. The purposes of the simulator study were to determine effects of the proposed improvements on navigation, to optimize channel width and alignment for safe and efficient navigation, and to determine necessary depths in Bar and Anegado Channel sections affected by waves.

- Design transit conditions were developed. A wind from the northeast was used with a speed of 10.3 m/sec (20 knots) in the outer entrance. Wind speed was decreased to between 0 and 7.7 m/sec (15 knots) in interior areas sheltered by bluffs and/or tall buildings. Wave information from a 20-year hindcast was used to define incident wave conditions for moderate and heavy seas. A numerical model transformed the selected incident wave conditions to the harbor and through the entrance, giving wave estimates along the channel. For simulation, incident H_s was 4.6 m (15 ft), coming from the northeast. This H_s is about the practical upper limit for ships to enter the harbor. The H_s progressively decreased along Bar Channel to 1.2 m (4 ft) and then to 0 after the turn into Anegado Channel. Tidal currents in the channels were determined with a numerical model of the harbor embayment. Currents are very small. Since flood tide tends to reduce control of ships entering the harbor, flood tide currents were used with all simulations. A wave-driven cross-current of 0.3 m/sec was added in the more exposed section of the Bar Channel, based on pilot comments.

- Two design ships were used, a tanker 232.6 m (763 ft) in length (LBP) with a 38.1-m (125-ft) beam and a container ship 246.9 m in length (LBP) with a 32.3-m (106-ft) beam. The inbound tanker draft (loaded) was 9.8 m (32 ft) for the existing channels and 11.0 m (36 ft) for proposed channels. The outbound tanker draft (in ballast) was 7.9 m (26 ft). For both inbound and outbound runs, the container ship draft was the same as the inbound loaded tanker draft.

- The simulation was validated with the assistance of two pilots from the San Juan Harbor Pilots Association. Simulations were conducted in three 1-week periods. A total of six licensed San Juan Harbor pilots conducted the simulations (two per week), giving a representative range of experience and piloting strategies. Pilots completed a written questionnaire immediately after each run, including a rating scale of key project features. Some desirable modifications to the proposed plans emerged after the first week of simulations. The plans were adjusted to improve navigation in localized areas with difficult clearance and/or to reduce dredging in areas not needed for navigation.

- Design depths for the wave-influenced Bar and outer Anegado Channels were developed in a separate study component. A range of wave conditions and ship speeds were considered. The sum of vertical ship motion and squat was used to define the required underkeel clearance to be added to the 11.0-m (36-ft) ship draft. Because wave height decreases along the Bar Channel, a stepped design depth was recommended, with depth of 16.8 m (55 ft) at the seaward end of Bar Channel progressively decreasing in three steps to 13.7 m (45 ft) through the turn into Anegado Channel.

- Results from the simulations were summarized to evaluate proposed plans. For example, average pilot ratings for inbound container ship runs indicate the plans will significantly improve harbor access, especially in Puerto Nuevo Channel and at the turn separating it from Army Terminal Channel (Figure V-5-69). The wider entrance channel in the plans gives a significant improvement. Ship track plots from all runs show how the increased width and gentler turn would be used in navigation (Figure V-5-70). An unused area on the outside of the proposed turn is defined by the envelope of ship tracks. Simulations indicated that a ship could not enter this area and still turn safely. Therefore, one study recommendation was that the unused area be deleted from the plan, reducing dredging requirements. Complete results, conclusions, and recommendations are given by Webb (1993).

c. *Specialized field studies*.

(1) Harbors. As field measurement and data collection techniques have advanced, field studies have become powerful and reliable for documenting the behavior of existing harbors. However, the cost for comprehensive field studies is significant, and such studies are generally practical only for large projects with high economic impact. Typically, field data are used for calibration and validation in physical and numerical model studies. Field data helpful for harbor studies include incident directional waves, water levels, waves and currents at several interior locations, and winds. The data provide valuable information about harbor response to wind waves and swell, entrance channel wave conditions, harbor oscillations, and circulation and flushing. A representative, but extensive, field data collection program in the massive Los Angeles and Long Beach, California, harbor complex is described by Seabergh, Vemulakonda, and Rosati (1992). The program was aimed at enhancing physical and numerical models used in harbor planning.

(a) *Example: Kahului Harbor, Maui, Hawaii*. Kahului Harbor, located on the north shore of the Island of Maui, is the island's only deep-draft harbor and the busiest port in Hawaii outside of the Island of Oahu

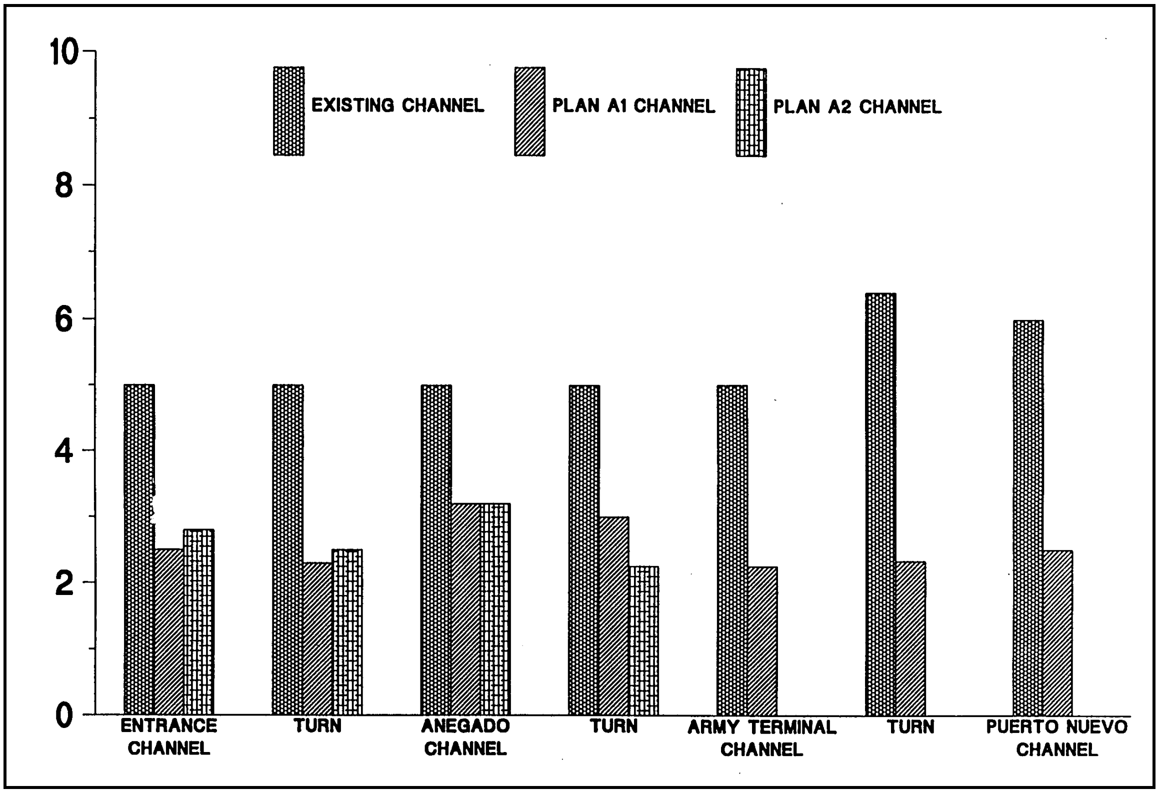


Figure V-5-69. Pilot degree of difficulty ratings, inbound container ship, San Juan Harbor

(Figure V-5-71). Commercial piers are presently on the east side of the harbor. In conjunction with long-term planning for expanded harbor usage, a field wave data collection program was established in the harbor. The program included an offshore directional array to measure incident waves and four pressure gauges in the harbor interior (Figure V-5-72). Interior gauge locations were determined with the assistance of a preliminary numerical model study of harbor wave response (Okihiro et al. 1994).

(b) Data from more than 1 year were collected and proved to be very helpful in subsequent harbor wave response, modeling, and planning studies (Thompson et al. 1996, Okihiro and Guza 1996).

(2) Ship tracking. The optimum depth and width of proposed navigation channel improvements may be determined with increased accuracy by measuring actual ship motions. The measurement program should encompass a significant number of transits of the route during adverse conditions. Availability of differential Global Positioning System (DGPS) apparatus for recording accurate ship fixes (±3 m) at a rapid rate (0.2 Hz or faster) makes this an affordable component of feasibility studies. Commercial software is available for data recording and display in formats applicable to channel design. These systems use standard DGPS receivers compatible with the U.S. Coast Guard network of DGPS radio beacons, as illustrated in Figure V-5-73. A time series of fixes is recorded with concurrent gyrocompass headings and other data, such as engine rpm, rudder angle, and relative wind speed and direction.

(a) Commercial gyrocompasses aboard seagoing cargo vessels usually provide heading accuracy of ±0.3 deg or better. Concurrent time series of position and heading define the swept path of the vessel. Comparison of ship tracks with tidal currents, winds, waves, water levels, visibility conditions, and other environmental conditions present at the time of recording, provide channel designers with realistic parameters for width computations.

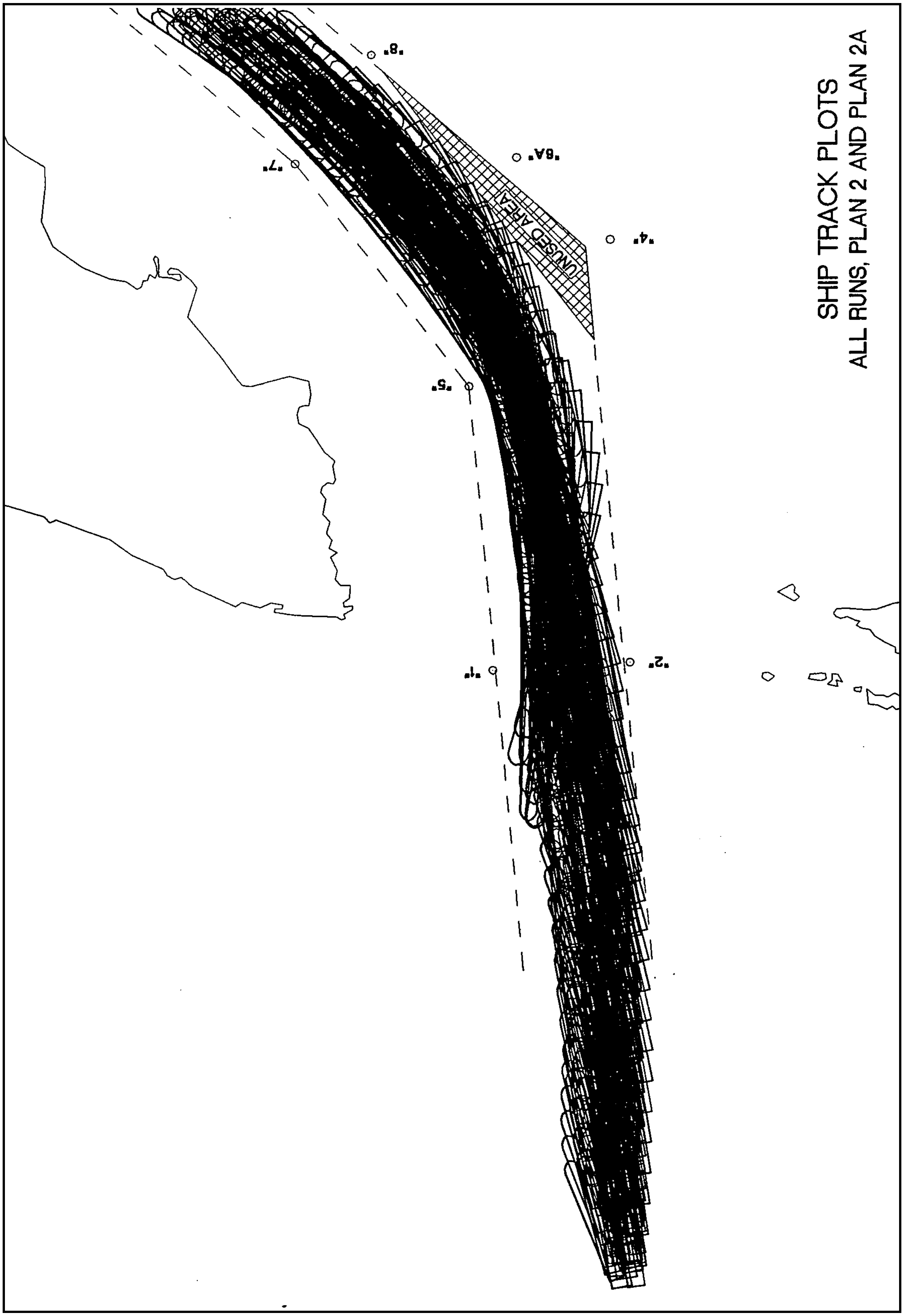


Figure V-5-70. Ship tracks, proposed Bar Channel and turn into Anegado Channel, San Juan Harbor

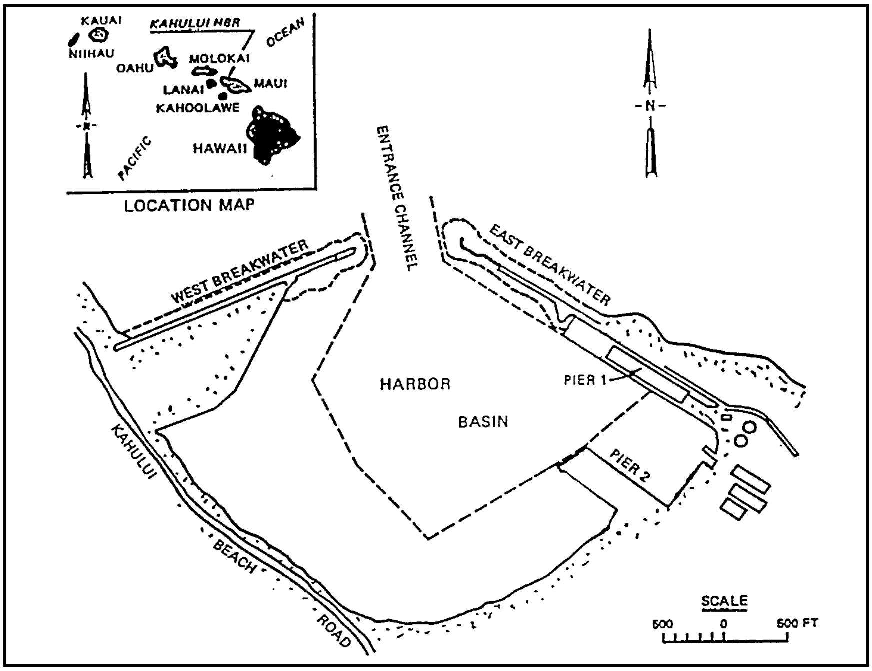


Figure V-5-71. Kahului Harbor, Maui, Hawaii, location map

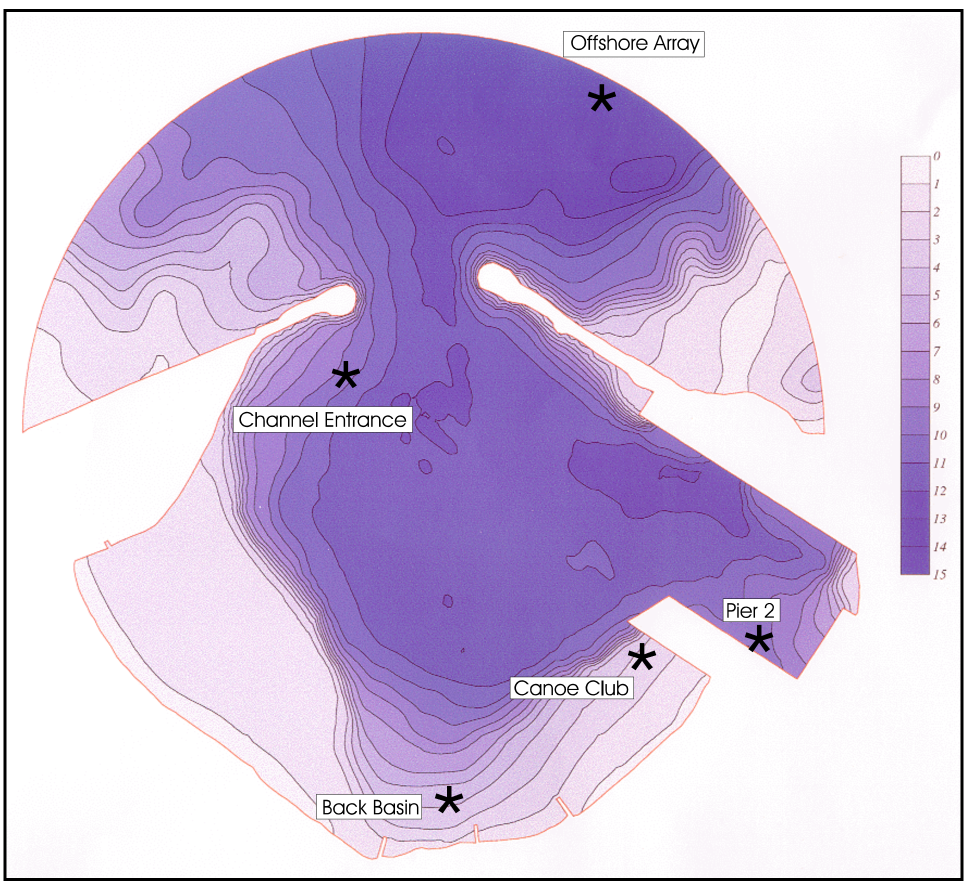


Figure V-5-72. Field gauge locations and bathymetry, Kahului Harbor

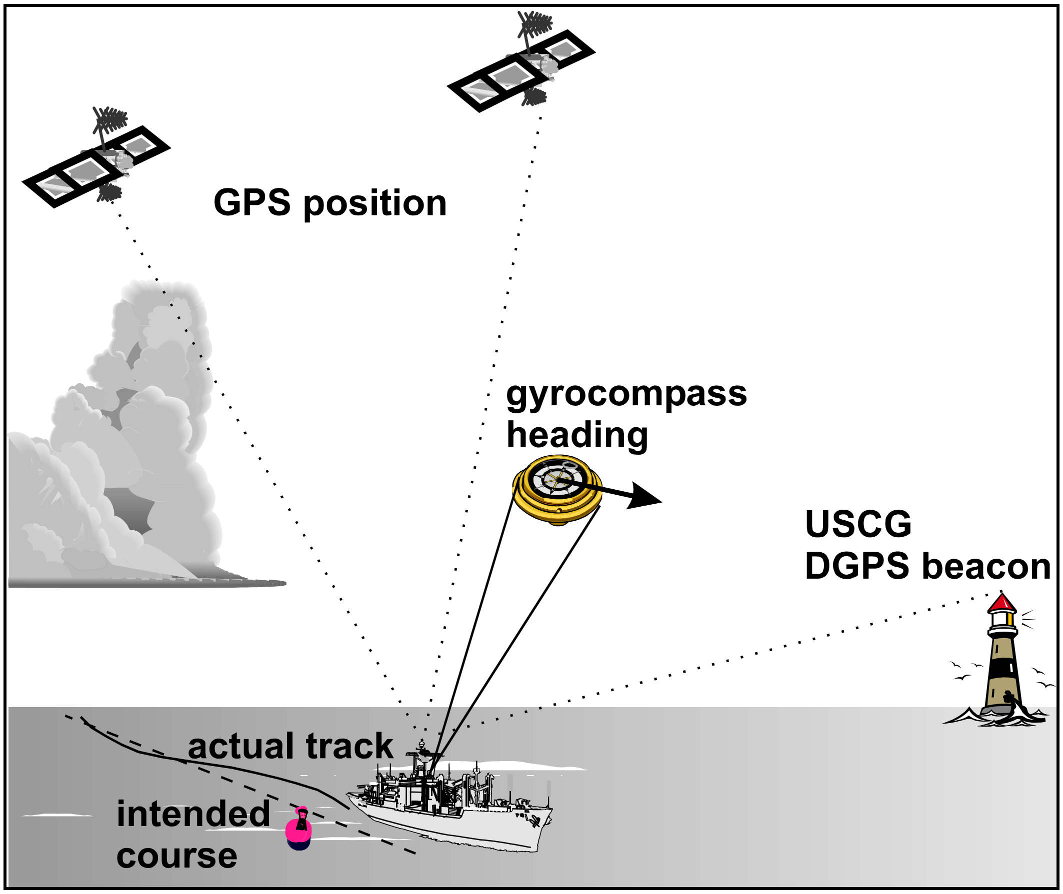


Figure V-5-73. Components of ship track measurements

(b) A dual-frequency DGPS system that measured horizontal and vertical location of ship bow and stern with 1 cm accuracy is described by Webb and Wooley (1998). The data, along with concurrent measurements of current and water level, provided direct calculation of ship squat. The data are useful for evaluating existing navigation conditions, designing modifications, and/or validating ship simulation models to study proposed conditions.

V-5-11. References

EM 1110-2-1615
EM 1110-2-1615, "Hydraulic Design of Small Boat Harbors"

EM 1110-8-1
EM 1110-8-1, "Winter Navigation on Inland Waterways"

EM 1110-2-1613
EM 1110-2-1613, "Hydraulic Design Guidance for Deep-Draft Navigation Projects"

ER 1105-2-100
ER 1105-2-100, "Guidance for Conducting Civil Works Planning Studies"

EP 1165-2-1
EP 1165-2-1, "Digest of Water Resources Policies and Authorities"

American Society of Civil Engineers 1994
American Society of Civil Engineers (ASCE). 1994. *Planning and Design Guidelines for Small Craft Harbors*, ASCE Manual and Reports on Engineering Practice No. 50, New York, NY.

Bottin 1976
Bottin, R. R., Jr. 1976. "Igloo Wave Absorber Tests for Port Washington Harbor, Wisconsin; Hydraulic Model Investigation," Miscellaneous Paper H-76-22, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bottin 1992
Bottin, R. R., Jr. 1992. "Physical Modeling of Small-Boat Harbors: Design Experience, Lessons Learned, and Modeling Guidelines," Technical Report CERC-92-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Briggs, Bratteland, and Borgman 2000
Briggs, M. J., Bratteland, E., and Borgman, L. E. 2000. "Probability Assessment of Deep Draft Navigation Channel Design," submitted to *Coastal Engineering Journal*, Elsevier Science, The Netherlands.

Briggs et al. 1994
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-94-14, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bruun 1990
Bruun, P. 1990. *Port Engineering*, Fourth Edition (2 Vols.), Gulf Publishing, Houston, TX.

Chen and Houston 1987
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, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Clark 1983
Clark, J. R. 1983. *Coastal Ecosystem Management: A Technical Manual for the Conservation of Coastal Zone Resources*, John Wiley & Sons, New York, NY.

Dingemans 1997
Dingemans, M. W. 1997. *Water Wave Propagation over Uneven Bottoms*, 2 vols., World Scientific, Singapore.

Dunham and Finn 1974
Dunham, J. W., and Finn, A. A. 1974. "Small-Craft Harbors: Design, Construction, and Operation," Special Report No. 2, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Ferguson 1991
Ferguson, A. 1991. "Navigation, Dredging and Environment in the Fraser River Estuary," Navigation and Dredging Workgroup Report, Fraser River Estuary Management Program, British Columbia, Canada.

Gaythwaite 1990
Gaythwaite, J. W. 1990. *Design of Marine Facilities for the Berthing, Mooring, and Repair of Vessels*, Van Nostrand Reinhold, New York, NY.

Harkins and Dorrell 2000
Harkins, G. S., and Dorrell, C. C. 2000. "Barbers Point Harbor Physical Model Navigation Study," Technical Report ERDC/CHL TR-00-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Harris 1981
Harris, D. L. 1981. "Tides and Tidal Datums in the United States," Special Report No. 7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Herbich 1992
Herbich, J. B. 1992. *Handbook of Coastal and Ocean Engineering, Vol. 3, Harbors, Navigational Channels, Estuaries, Environmental Effects*, Gulf Publishing, Houston, TX.

Hudson et al. 1979
Hudson, R. Y., Herrmann, F. A., Jr., Sager, R. A., Whalin, R. W., Keulegan, G. H., Chatham, C. E., Jr., and Hales, L. Z. 1979. "Coastal Hydraulic Models," Special Report SR-5, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Hughes and Fowler 1990
Hughes, S. A., and Fowler, J. E. 1990. "Midscale Physical Model Verification for Scour at Coastal Structures," Technical Report CERC-90-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huval 1980
Huval, C. J. 1980. "Lock Approach Canal Surge and Tow Squat at Lock and Dam 17, Arkansas River Project; Mathematical Model Investigation," Technical Report HL-80-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huval 1993
Huval, C. J., ed. 1993. "Planning, Design, and Maintenance of Deep Draft Navigation Channels," PROSPECT Training Course Notes, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huval and Lynch 1998
Huval, C. J., and Lynch, G. C. 1998. "Ship Navigation Simulation Study, Brunswick Harbor, Georgia," Technical Report CHL-98-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Irish 1997
Irish, J. L. 1997. "Sensitivity of Channel Sedimentation Prediction to Wave-field Characterization," Bulletin No. 95, PIANC, Brussels, Belgium, pp 5-19.

LeMéhauté 1965
LeMéhauté, B. 1965. "Wave Absorbers in Harbors," Contract Report No. 2-122, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, prepared for National Engineering Science Company, Pasadena, CA, under Contract No. DA-22-079-CIVENG-64-81.

Lillycrop et al. 1993
Lillycrop, L. S., Briggs, M. J., Harkins, G. S., Boc, S. J., and Okihiro, M. S. 1993. "Barbers Point Harbor, Oahu, Hawaii, Monitoring Study," Technical Report CERC-93-18, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

McBride, Smallman, and Huntington 1998
McBride, M. W., Smallman, J. V., and Huntington, S. W. 1998. "Guidelines for Design of Approach Channels," *Proceedings, PORTS '98*, ASCE, pp 1315-1324.

McCartney, Hermann, and Simmons 1991
McCartney, B. L., Hermann, F. A., Jr., and Simmons, H. B. 1991. "Estuary Waterway Projects - Lessons Learned," *Journal of Waterway, Port, Coastal, and Ocean Engineering* 117(4), American Society of Civil Engineers, pp 409-421.

Mei 1983
Mei, C. C. 1983. *The Applied Dynamics of Ocean Surface Waves*, John Wiley & Sons, New York, NY.

Melo and Guza 1991
Melo, E., and Guza, R. T. 1991. "Wave Propagation in Jettied Entrance Channels. II: Observations," *Journal of Waterway, Port, Coastal, and Ocean Engineering* 117(5), pp 493-510.

NOAA (Annual)
National Oceanic and Atmospheric Administration (NOAA). (Annual). *Tide Tables* and *Tidal Current Tables*, Rockville, MD.

Noda 1972
Noda, E. K. 1972. "Equilibrium Beach Profile Scale-Model Relationship," *Journal of the Waterways, Harbors, and Coastal Engineering Division* 98(WW4), ASCE, pp 511-528.

Norrbin 1986
Norrbin, N. H. 1986. "Fairway Design with Respect to Ship Dynamics and Operational Requirements," SSPA Research Report No. 102, SSPA Maritime Consulting, Gothenburg, Sweden.

Okihiro and Guza 1996
Okihiro, M. S., and Guza, R. T. 1996. "Observations of Seiche Forcing and Amplification in Three Small Harbors," *Journal of Waterway, Port, Coastal, and Ocean Engineering* 122(5), ASCE, 232-238.

Okihiro et al. 1994
Okihiro, M. S., Guza, R. T., O'Reilly, W. C., and McGehee, D. D. 1994. "Selecting Wave Gauge Sites for Monitoring Harbor Oscillations: A Case Study for Kahului Harbor, Hawaii," Miscellaneous Paper CERC-94-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Panchang, Xu, and Demirbilek 1998
Panchang, V. G., Xu, B., and Demirbilek, Z. 1998. "Wave Models for Coastal Applications," *Handbook of Coastal Engineering*, J. B. Herbich, ed., Vol. 4 (to be published).

PIANC 1984
PIANC. 1984. "Ice Navigation," Supplement to Bulletin No. 46, Permanent International Association of Navigation Congresses, Brussels.

PIANC 1995
PIANC. 1995. “Approach Channels, Preliminary Guidelines,” First Report of the Joint PIANC-IAPH Working Group II-30, Permanent International Association of Navigation Congresses, Brussels, Belgium.

PIANC 1997a
PIANC. 1997a. “Approach Channels, a Guide for Design,” Supplement to Bulletin No. 95, Permanent International Association of Navigation Congresses, Brussels, Belgium.

PIANC 1997b
PIANC. 1997b. “Guidelines for the Design of Armoured Slopes Under Open Piled Quay Walls,” Supplement to Bulletin No. 96, Permanent International Association of Navigation Congresses, Brussels, Belgium.

Quinn 1972
Quinn, A. D. 1972. *Design & Construction of Ports & Marine Structures*, McGraw-Hill.

Sager and Hollyfield 1974
Sager, R. A., and Hollyfield, N. W. 1974. “Navigation Channel Improvements, Barnegat Inlet, New Jersey,” Technical Report H-74-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Seabergh, Cialone, and Stauble 1996
Seabergh, W. C., Cialone, M. A., and Stauble, D. K. 1996. “Impacts of Inlet Structures on Channel Location,” *Proceedings, 25th International Conference on Coastal Engineering*, ASCE, pp 4531-4544.

Seabergh, Vemulakonda, and Rosati 1992
Seabergh, W. C., Vemulakonda, S. R., and Rosati, J., III. 1992. “Los Angeles-Long Beach Harbors Model Enhancement Program,” *Proceedings, PORTS ‘92*, ASCE, pp 884-897.

Silver 1992
Silver, A. L. 1992. “Environmental Monitoring and Operator Guidance System (EMOGS) for Shallow Water Ports,” *Proceedings, PORTS ‘92*, ASCE, pp 535-547.

Silver and Dalzell 1997
Silver, A. L., and Dalzell, J. F. 1997. “Risk Based Decisions for Entrance Channel Operation and Design,” *Proceedings, 7th International Offshore and Polar Engineering Conference*, International Society of Offshore and Polar Engineers, pp 815-822.

SMS 1994
SMS. 1994. “Surface-Water Modeling System,” developed by Brigham Young University and USACE, updated periodically.

State of California 1980
State of California. 1980. “Layout and Design Guidelines for Small Craft Berthing Facilities,” Department of Boating and Waterways.

Stevens et al. 1942
Stevens, J. C., Bardsley, C. E., Lane, E. W., Straub, L. G., Wright, C. A., Tiffany, J. A., and Warnock, J. E. 1942. *Hydraulic Models*, Manuals of Engineering Practice, No. 25, American Society of Civil Engineers, New York, NY.

Thompson, Boc, and Nunes 1998
Thompson, E. F., Boc, S. J., Jr., and Nunes, F. S. 1998. "Evaluating Operational Impact of Waves Along Proposed Harbor Piers," *Proceedings, PORTS '98*, ASCE, pp 860-869.

Thompson et al. 1996
Thompson, E. F., Hadley, L. L., Brandon, W. A., McGehee, D. D., and Hubertz, J. M. 1996. "Wave Response of Kahului Harbor, Maui, Hawaii," Technical Report CERC-96-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thompson et al. 1998a
Thompson, E. F., Fong, M. T., Van Norman, P. S., and Brown, B. 1998a. "Ship Navigation Simulation Study, Alafia River, Tampa Bay, Florida," Technical Report CHL-98-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thompson et al. 1998b
Thompson, E. F., Lin, L., Hadley, L. L., and Hubertz, J. M. 1998b. "Wave Response of Kikiaola Harbor, Kauai, Hawaii," Miscellaneous Paper CHL-98-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Tobiasson and Kollmeyer 1991
Tobiasson, B. O., and Kollmeyer, R. C. 1991. *Marinas and Small-Craft Harbors*, Van Nostrand Reinhold, New York, NY.

Tsinker 1997
Tsinker, G. P. 1997. *Handbook of Port and Harbor Engineering*, Chapman & Hall, New York, NY.

Turner 1984
Turner, H. O., Jr. 1984. "Dimensions for Safe and Efficient Deep-Draft Navigation Channels," Technical Report HL-84-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

USACE 1983
U.S. Army Corps of Engineers. 1983. "Engineering and Design of Military Ports," Technical Manual TM 5-850-1, Headquarters, Department of the Army, Washington, DC.

U.S. Coast Guard 1981
U.S. Coast Guard. 1981. "Aids to Navigation Manual - Administration," COMDTINST M16500.7, U.S. Coast Guard, Washington, DC.

U.S. Coast Guard 1988a
U.S. Coast Guard. 1988a. "Aids to Navigation Manual - Seamanship," CG-222.2, U.S. Coast Guard, Washington, DC.

U.S. Coast Guard 1988b
U.S. Coast Guard. 1988b. "Aids to Navigation Manual - Technical," COMDTINST M16500.3, U.S. Coast Guard, Washington, DC.

U.S. Navy 1981
U.S. Navy. 1981. "Harbors," Design Manual 26.1, Naval Facilities Engineering Command, Alexandria, VA.

U.S. Navy 1998
U.S. Navy. 1998. "Handbook for Mooring Design," MIL-HDBK 1026/4, Naval Facilities Engineering Command, Alexandria, VA.

Wang and Cialone 1995
Wang, H. V., and Cialone, A. 1995. "Numerical Hydrodynamic Modeling and Flushing Study at Maalaea Harbor, Maui, Hawaii," Miscellaneous Paper CERC-95-8, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wang et al. 1980
Wang, S., Butcher, C., Kimble, M., and Cox, G. D. 1980. "Columbia River Entrance Channel Deep-Draft Vessel Motion Study," Tetra Tech Report No. TC-3925, U.S. Army Engineer District, Portland, OR.

Webb 1993
Webb, D. W. 1993. "Ship Navigation Simulation Study, San Juan Harbor, San Juan, Puerto Rico," Technical Report HL-93-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Webb 1994
Webb, D. W. 1994. "Navigation Channel Design Using Real-Time Marine Simulator," *Proceedings, Dredging '94*, ASCE, pp 1081-1090.

Webb and Wooley 1998
Webb, D. W., and Wooley, R. T. 1998. "Using DGPS Ship Transit Data for Navigation Channel Design," *Proceedings, PORTS '98*, ASCE, pp 1325-1332.

Wilson 1966
Wilson, H. B. 1966. "Design for Optimum Wave Conditions, Dana Point Harbor, Dana Point, California; Hydraulic Model Investigation," Technical Report 2-724, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

WMO 1970
World Meteorological Organization (WMO). 1970. "WMO Sea-ice Nomenclature," WMO/OMM/BMO-No.259.TP.145, as amended, Geneva, Switzerland.

V-5-12. Definitions of Symbols

α_b	Breaking wave angle [deg]
A_C	Channel cross-section area [length^2]
B	Vessel beam at midships [length]
C_B	Block coefficient (Figure V-5-4) [dimensionless]
F_h	Channel depth Froude number [dimensionless]
F_L	Schijf limiting Froude number (Equation V-5-7) [dimensionless]
g	Gravitational acceleration [length/time^2]
h	Depth of channel [length]
h_1, h_2	Overbank depths [length]
L	Ship length [length]
N_B	Number of boats using the project
T	Vessel draft [length]
V	Vessel speed [length/time]
V_L	Schijf limiting ship speed in squat analysis [length/time]
W	Width of channel [length]
Z	Maximum ship squat [length]
Z_L	Maximum ship squat at Schijf limiting Froud number (Equation V-5-8) [length]
Z_T	Maximum squat in a trench channel (Equation V-5-9) [length]

V-5-13. Acknowledgments

Authors of Chapter V-5, "Navigation Projects:"

Edward F. Thompson, Ph.D., Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.
Carl J. Huval, CHL (retired)
Ray R. Bottin, CHL
Orson P. Smith, Ph.D., U.S. Army Engineer District, Alaska, Anchorage, Alaska, (retired)

Reviewers:

David Curfman, Naval Facilities Engineering Command, Norfolk, Virginia
Lee E. Harris, Ph.D., Department of Marine and Environmental Systems, Florida Institute of Technology, Melbourne, Florida
Mona King, U.S. Army Engineer District, Seattle, Seattle, Washington
John H. Lockhart, Headquarters, U.S. Army Corps of Engineers, Washington, DC, (retired)
J. Richard Weggel, Ph.D., Dept. of Civil and Architectural Engineering, Drexel University, Philadelphia, Pennsylvania