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**US Army Corps
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ENGINEERING AND DESIGN

Hydraulic Design of Deep-Draft Navigation Projects

ENGINEER MANUAL

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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Engineering and Design
HYDRAULIC DESIGN OF DEEP DRAFT NAVIGATION PROJECTS

1. Purpose. This manual provides design guidance for improving deep-draft navigation projects. The design goal applicable to project development is to provide a safe, efficient, environmentally sound, and cost-effective waterway for ships and other vessels. An economic objective is to provide for these goals while minimizing and balancing the initial construction costs and future maintenance costs. The general guidance presented in this manual is based on *average* navigation conditions and situations. The design engineer will adapt these guidelines to the local, site-specific conditions of the project. Usually, the final project design will be developed by application of a ship navigation study, incorporating real-time ship simulation tests with local professional pilots. Deviations from this guidance are acceptable if properly substantiated and approved by Headquarters, U.S. Army Corps of Engineers.

2. Applicability. This manual applies to all USACE commands having civil works responsibilities. The manual will be used in project planning, design, construction, operation, and maintenance as applicable.

3. Distribution Statement. This publication is approved for public release; distribution is unlimited.

FOR THE COMMANDER:

JOHN R. McMAHON
Colonel, Corps of Engineers
Chief of Staff

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Glossary

This manual supersedes EM 1110-2-1613, 8 April 1983.

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CHAPTER 1

Introduction

1-1. Purpose. This manual provides design guidance for improving deep-draft navigation projects. The design goal applicable to project development is to provide a safe, efficient, environmentally sound, and cost-effective waterway for ships and other vessels. An economic objective is to provide for these goals while minimizing and balancing the initial construction costs and future maintenance costs. The general guidance presented in this manual is based on *average* navigation conditions and situations. The design engineer will adapt these guidelines to the local, site-specific conditions of the project. Usually, the final project design will be developed by application of a ship navigation study, incorporating real-time ship simulation tests with local professional pilots. Deviations from this guidance are acceptable if properly substantiated and approved by Headquarters, U.S. Army Corps of Engineers (HQUSACE).

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1-4. References. See Appendix A for the complete list of references.

1-5. Scope. Deep-draft navigation projects involve development or improvement of channel systems to provide access to the Nation’s ports and harbors. Deep-draft navigation refers to channel depths greater than 15 feet (ft) (4.57 meters (m)) and applies to commercial seagoing vessels and Great Lakes freighters. Generally, the project involves larger, more heavily laden ship traffic that takes advantage of the project improvements. The projects also include, where appropriate, ship turning basins, maneuvering areas, anchorage areas, and other ancillary facilities such as dikes and jetties to improve navigation conditions.

1-6. Background. The navigation mission of the U.S. Army Corps of Engineers (USACE) is one of the oldest activities authorized by the Congress. Waterway and harbor maintenance and improvement to provide ship access to ports has been a major Federal development activity all over the country. Deep-draft navigation projects involve practically all commercial coastal ports, the lower portions of the Mississippi and Columbia Rivers, and a majority of harbors in the Great Lakes and St. Lawrence River system. There is increased emphasis on expanding the capacity of these projects by deepening to accommodate increased draft and larger capacity ships.

1-7. Manual Development. This manual summarizes the results of research, development, and project studies conducted at the U.S. Army Engineer Research and Development Center (ERDC)/(U.S. Army Engineer Waterways Experiment Station (WES)), Vicksburg, MS. The ERDC/WES Ship Simulator, as well as other simulator study results throughout the world, played a significant role in guidance upgrading. The experience of many Corps personnel involved in deep-draft navigation studies and projects is also reflected in the manual.

1-8. Training. The U.S. Army Engineer Division, Huntsville, offers a 1-week training course entitled “Planning, Design, and Maintenance of Deep Draft Navigation Channels,” which is held at ERDC/WES. The course covers the latest planning and engineering design considerations for the development and improvement of Corps navigation projects. The course notes offer major updating of design concerns and expand the information presented in this manual. If interested, Corps employees should check with their Training Officer for details. Non-Corps personnel may request participation in this training course by contacting CECW-EH. Course information may be obtained from the Corps web site.

1-9. Appendices. Required and related publications cited in this manual are listed alphabetically in Appendix A. Appendix B provides frequently needed units and conversion factors between systems of units. A summary report on recent ERDC/WES Ship Simulator research results is presented in Appendix C. Appendix D provides an example study and a checklist that may be used during study development. Symbols used in this manual are listed in the Notation section of the Glossary. An explanation of terminology frequently encountered by navigation project users of this manual is also provided in the Glossary.

CHAPTER 2

Project Study Formulation

2-1. Project Design. Design of a navigation project requires an understanding of the port and waterway needs, assembly and evaluation of all pertinent information, and development of a rational improvement plan. The planner/design engineer is responsible for developing and formulating several project design alternatives. This will allow the economically optimum plan to be clearly evident and readily substantiated. Project safety and efficiency should receive primary consideration before the cost-effectiveness of the project is determined. Planning for the project will require the anticipation of any possible development and operational problems and evaluation of alternative solutions. The cost of each proposed project must be considered in the development or improvement of the alternative deep-draft channel designs. A navigation project study plan should also be developed that will provide guidance during project formulation at all stages of project planning and design.

2-2. Typical Project Elements. Figure 2-1 presents an example generic harbor defining many of the typical project elements discussed below. The following project features are normally the responsibility of the Corps:

a. *Entrance channel*. A navigable channel connecting the ocean or lake to an enclosed water body such as a bay, estuary, river, or mouth of a navigable stream.

b. *Jetties*. Structural features that provide obstructions to littoral drift, control entrance currents, prevent or reduce shoaling in the entrance channel, maintain channel alignment, and provide protection from waves for navigation.

c. *Breakwaters*. Structures designed to provide shelter from waves and improve navigation conditions. Such structures may be combined with jetties where required (EM 1110-2-2904).

d. *Interior channel*. The access channel system inside a water body that connects the entrance channel (inlet or bar) to a port or harbor with appropriate ship facilities. Interior channels are usually located to provide some protection from waves and weather and are located in bays, estuaries, or rivers.

e. *Turning basin*. An area that provides for the turning of a ship (bow to stern). Turning basins are usually located at or near the upper end of the interior channel and possibly at one or more intermediate points along long channels.

f. *Anchorage area*. An area inside a water body providing the ships some protection from the weather while lying at anchor to stand by, load or unload cargo, await repairs, etc.

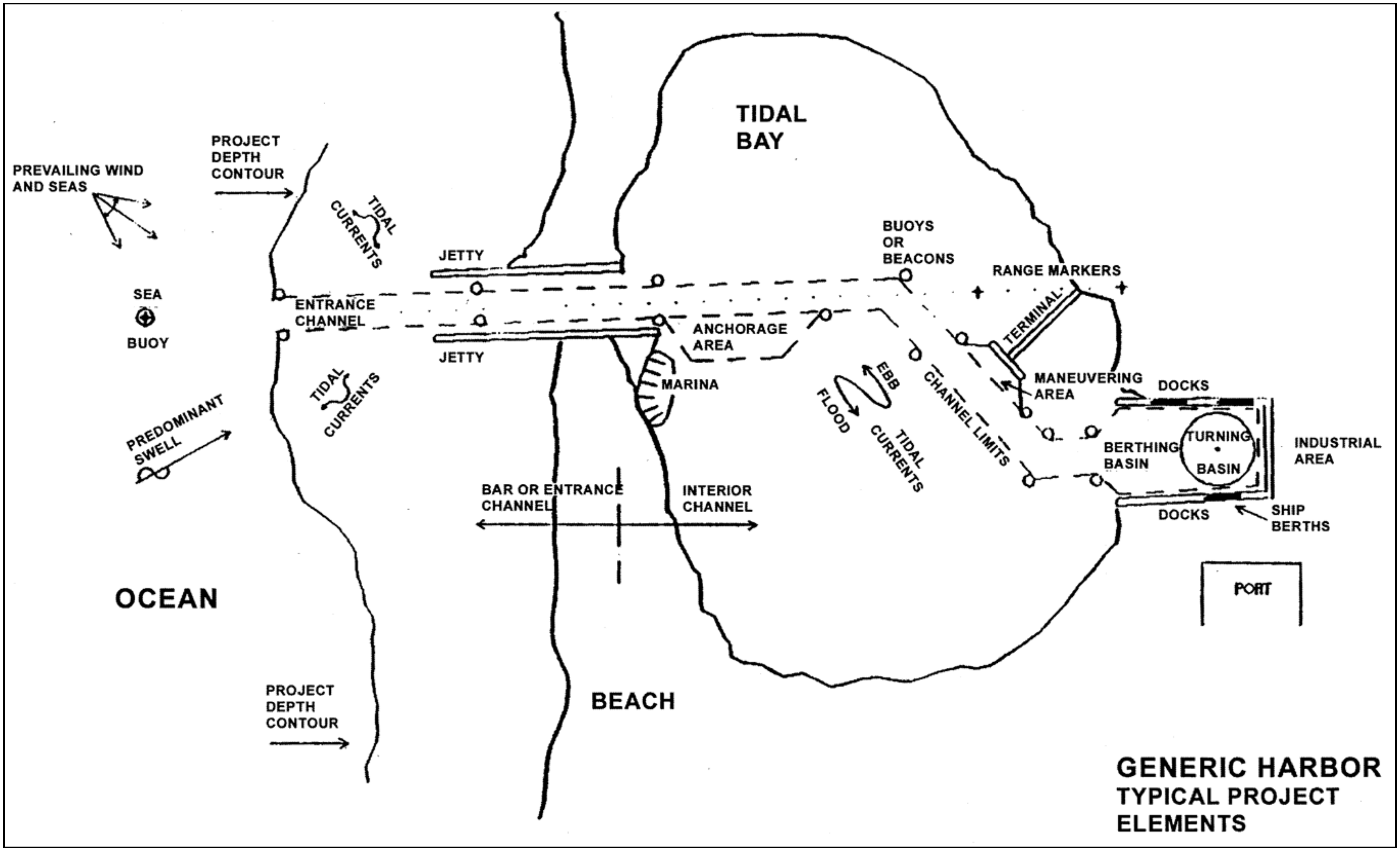

Figure 2-1. Generic harbor with typical project

g. *Special features*. Specifically designed structural elements that provide for special project design requirements, such as salinity control barriers, ship locks, ice control booms, bridge pier protection (fendering systems), hurricane barriers, sediment traps, and other similar control works.

2-3. Planning Procedure. The following checklist should be used during preliminary project planning:

a. Review appropriate HQUSACE Engineer Regulations (ER's), Engineer Manuals (EM's), and Engineer Technical Letters (ETL's).

b. Consult with local port authority, pilot associations, and harbor terminal users.

c. Collect and analyze pertinent physical and environmental data.

d. Review appropriate local pilot or captain ship maneuvering strategy and evaluate existing project navigation conditions.

e. Determine volume and type of ship traffic and largest ships to be accommodated.

f. Determine volume and type of commodity that will be moved.

g. Determine amount, type, and frequency of hazardous cargo (liquified natural gas (LNG), ammunition, oil, radioactive, etc.) movement and evaluate special requirements.

h. Select and list the required project design operational conditions.

i. Select channel layout and alternative dimensions to be considered and determine advantages and disadvantages with annual costs.

j. Assess any adverse environmental and other impacts.

k. Define environmental mitigation needs and enhancement opportunities, especially beneficial uses for dredged material.

2-4. Design Considerations. The amount and type of ship traffic that will use the navigation channel are very important in project planning and design. The project economic considerations will require information on commodities moved by the ship traffic. The designer will use information on the type of traffic to select the design ship, which is usually the largest ship of the major commodity movers expected to use the project improvements on a frequent and continuing basis. The amount of ship traffic and the length of access channel will determine the mode of navigation traffic to be provided, whether one-way or two-way. Consideration should also be given to providing one-way traffic for large ships and two-way traffic for smaller vessels, and providing channel segments with passing lanes. The designer should consider a stepped channel with different depths for loaded ballasted ships. Project layouts should be prepared using various channel alignments and dimensions and each alternative evaluated on the basis of economic efficiency involving commodity tonnage moved, ship transit time, safety, environmental and social impacts, and construction and maintenance costs.

2-5. Project Safety. The designer must consider and include aspects of project safety, efficiency of ship operations, and reliability of the proposed project. Safety of the project will depend on the size and maneuverability of the ships using the waterway, size and type of channel, aids to navigation provided, magnitude and direction of currents in the waterway, wind and wave effects, and experience and judgment of the local pilots. Since human factors (pilot skill and diligence) are involved in navigation channel safety and are difficult to evaluate, potentially hazardous conditions should be eliminated in the project design insofar as practicable. Therefore, optimum design of a specific waterway will require an evaluation of the physical environmental conditions, especially the currents and weather conditions and judgment of safety factors based on local pilot information.

2-6. U.S. Coast Guard. Consultations should be conducted with the local Coast Guard office in both the preliminary and final design processes. Their views on navigation channel and bridge safety, ship maneuverability, navigation traffic management, navigation operational restrictions, and optimum placement of aids to navigation should be incorporated into the design and presented in appropriate reports and design memoranda.

2-7. Physical Data. The design of a navigation project will require the collection, analysis, and evaluation of information on many aspects that impact project design. The following data are required:[1]

a. Design ship.

(1) Type, *size*, and dimensions (length, beam, draft).

(2) Maneuverability and normal operational speed.

(3) Engine type and power rating.

(4) Bow and/or stern thrusters—power and thrust.

(5) Number and frequency of transits.

(6) Type of cargo handled.

(7) Cargo load condition (trim and draft).

(8) Number and size of screws and rudders.

(9) Definitive maneuvering trial or computed data.

(10) Ballasted operation condition (trim and draft).

b. Waterway traffic.

(1) Ship size variation for present and future channel.

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[1] Many of the design factors may be seasonal, including the ship traffic volume and size mix. Seasonal variations in traffic mix and other parameters, e.g., wind, waves, fresh water inflows, etc., should be identified in the data gathered.

(2) Smaller vessel use and congestion.

(3) Navigation cross-traffic condition.

(4) Ship meeting, passing, and overtaking.

(5) High number of small craft (sailing ships, fishing vessels).

c. Weather.

(1) Visibility, day or night transits.

(2) Frequency of fog, smog, snow, storms.

(3) Ice conditions (thickness, duration, extent).

(4) Rainfall and temperature.

d. Currents.

(1) Speed, direction, and duration--flood and ebb.

(2) Astronomical tide and/or river flow.

(3) Tide height/current relation.

(4) Wind tide--induced currents.

(5) Current variation with depth.

e. Wind and waves.

(1) Wind force, direction, and duration.

(2) Wind generated waves--heights, period, length, direction, duration, and frequency.

(3) Wind variability or gustiness.

(4) Swell waves--heights, period, length, direction, duration, and frequency.

(5) Waves from passing vessels.

(6) Surges and seiching in berthing areas, particularly where containerships are loaded and unloaded.

f. Navigation constraints.

(1) Obstructions--sunken vessels, abandoned structures.

(2) Overhead bridges and power line crossings--location, type, and clearances.

(3) Dredging operations--location and frequency.

(4) Visible obstructions--high banks, headlands.

(5) Turns and curves with crosscurrents.

(6) Strong changes in banks and currents--ends of jetties, side channels, and anchorages.

(7) Shipyards, terminals, and other moored ships.

(8) Small-craft harbors and marinas.

(9) Underground pipelines and cables--location, type, and clearances.

g. Water level.

(1) Tidal variation--range, type of tide (diurnal, semidiurnal, or mixed).

(2) Tide datum plane--average high and low water.

(3) Upland river inflow--frequency and duration of effect.

(4) Abnormal high and low hurricane, storm surge, and wind tide.

h. Channel data.

(1) Channel and overbank hydrography.

(2) Channel cross section (canal, trench, shallow water).

(3) Alignment and configuration--turns and curves.

(4) Channel depth, width, and side slopes.

(5) Navigation traffic pattern (one-way, two-way).

(6) Dock and pier configuration--open (piles) or closed (solid, filled construction), finger piers, parallel to channel berthing.

(7) Length of channel.

(8) Intersecting lanes, one-way sections in two-way channels, passing areas in one-way channels.

(9) Approach fairways

i. Operational factors.

(1) Limits for ship transit operations--wind, daylight/night, tide height, current window.

(2) Limits for ship sizes.

(3) Bar closure--waves, fog, and wind.

(4) Required underkeel ship clearance.

(5) Ship traffic daily variation.

(6) Speed reduction to increase safety.

(7) Tidal advantage--riding high tide for larger draft.

(8) Ship lightering--offloading to smaller ships, boats, barges.

(9) Required spacing between ships in tandem.

j. *Geotechnical*.

(1) Stability of side slopes.

(2) Dredging conditions--hazardous, toxic, and radioactive waste (HTRW), and other polluted material.

(3) Subsurface bedrock.

(4) Soil properties--bed and bank material (soft, fluid “mud,” or hard).

k. *Sedimentation*.

(1) Rate of and tendency for siltation.

(2) Sediment sizes and distribution.

(3) Movement--scour and shoal areas.

(4) Source of sediments--upland or littoral.

(5) Sediment management facilities and techniques.

l. *Water quality*.

(1) Salinity distribution and variability.

(2) Dredge disposal areas.

(3) Biological population--type, density, and distribution.

(4) Environmentally sensitive areas.

m. Special concerns.

(1) Large change in channel alignment.

(2) Substantial increase in ship size or load or change in type.

(3) Major increase in port or terminal ship traffic.

(4) New port with new pilots.

(5) Effectiveness of proposed plans to deliver benefits.

(6) Known safety problems.

n. Design opportunities.

(1) Channel curves--changing to straight segments.

(2) Channel width--review for possible reduction or need, for local wideners.

(3) Duplicate channels--ensure absolute requirement.

(4) Multiple turning basins--possible reduction of number.

(5) Anchorage areas--determine usage and possibly abandon some.

o. Support services.

(1) Licensed pilotage.

(2) Tug availability--power, number, and bollard pull.

(3) Aids to navigation--buoys, channel markers, and range markers.

(4) Vessel traffic service--advisory or control.

(5) Information availability (hydrological and hydrometeorological data).

(6) Dredging and charting services--frequency, accuracy.

2-8. Typical Engineering Studies. The following list gives some examples of topics that require detailed coverage in normal navigation project design. More information on some of these topics is presented in subsequent portions of this manual.

a. Design ship.

b. Water level.

c. Currents.

d. *Waves*.

e. *Sedimentation.*

f. *Channel depth.*

g. *Channel width.*

h. *Channel alignment.*

i. *Dredging and disposal.*

j. *Turning basins.*

k. *Entrance channel.*

l. *Jetties and breakwaters.*

m. *Environmental impacts.*

n. *Accident record.*

o. *Pilot interviews.*

p. *Aids to navigation.*

q. *Model testing.*

(1) Hydraulic/tidal.

(2) Sedimenation.

(3) Salinity.

(4) Water quality.

(5) Ice.

r. *Ship simulation study.*

s. *Operation and maintenance plan.*

CHAPTER 3

Deep-Draft Ships

3-1. Introduction. Merchant ships used in worldwide and domestic commerce vary in size, hull design, and maneuverability, depending on commodities handled, ocean trading region, ports being served, and channels and waterways used. Investments by shipowners to build new and larger ships are heavily influenced by anticipated profit margins from future shipping revenues. Several worldwide economic factors have a direct bearing on ship investment decisions, including:

a. *Anticipated increase in shipping demand.*

b. *Competition among the various nations in world trade.*

c. *Potential for increased efficiency.*

d. *Need to replace obsolete ships.*

e. *Outlook for world oil production.*

Considerable effort is expended by shipowners and their naval architect designers in optimizing ship characteristics to account for economic parameters, port limitations, and operating costs that will provide adequate revenue from anticipated freight rates. Ships are designed for open- water, deep-sea conditions at full sea speed; this type of normal operation determines ship profit-making capabilities. Thus, ship maneuverability at slow, harbor speeds is a secondary attribute.

3-2. Ship Characteristics.

a. The general trend toward increased economic advantage of larger ship sizes continues and is especially important for bulk cargo ships and containerships. Many tankers in the world petroleum fleet cannot be accommodated in U.S. ports, which in most cases have controlling depths of 12.2 m (40 ft). Other bulk carriers with coal, ore, or grain cargoes include many ships with design drafts greater than 12.2 m. Containerships up to 14.3 m (47 ft) design draft are in service. Most general cargo ships, on the other hand, are usually designed for maximum draft of 12.2 m (40 ft), and do not normally play an important role in the design depths of many navigation projects. Bulk carriers and containerships have been the usual project design ship for increased navigation channel depths. Most studies concerned with development or improvement of deep-draft channels involve the economic analysis of larger ships or greater loads in ships using the existing project.

b. The largest ships in service are Ultra Large Crude Carrier (ULCC) tankers up to about 550,000 deadweight tons (dwt); this size ship is usually used in dedicated trade routes, such as from the Persian Gulf, around the Cape of Good Hope, and to offshore ports to serve Europe. Ships of this size have drafts approaching 30.5 m (100 ft) and can enter none of the major world ports. Indications are that maximum bulk carrier ship sizes will get no larger, but the average ship capacity will gradually increase as older ships are retired from service. Bulk carriers and tankers up to about 55,000 dwt can call at ports with 12.2-m (40-ft) channel depths; deepening to 15.2 m

(50 ft) will provide access to 105,000-dwt ships. Lightering operations and light-loaded tankers of this size do use existing 12.2-m (40-ft) channels.

3-3. Ship Dimensions.

a. Ships are complex three-dimensional (3-D) bodies whose sizes are described by several geometric parameters that are important to channel design and port operations. The navigation designer should be aware of the main ship geometry parameters and the important dimensions normally used, especially as they relate to commodity loading capacity and design ship parameters. The three principal ship dimensions are length, beam, and draft. The definitions of the various ship lengths used are presented in Figure 3-1; a similar drawing describing ship beam and draft appears in Figure 3-2. The ship depth and freeboard are two additional dimensions important in design and cargo capacity. Definitions of the more important geometric parameters are given in the Glossary.

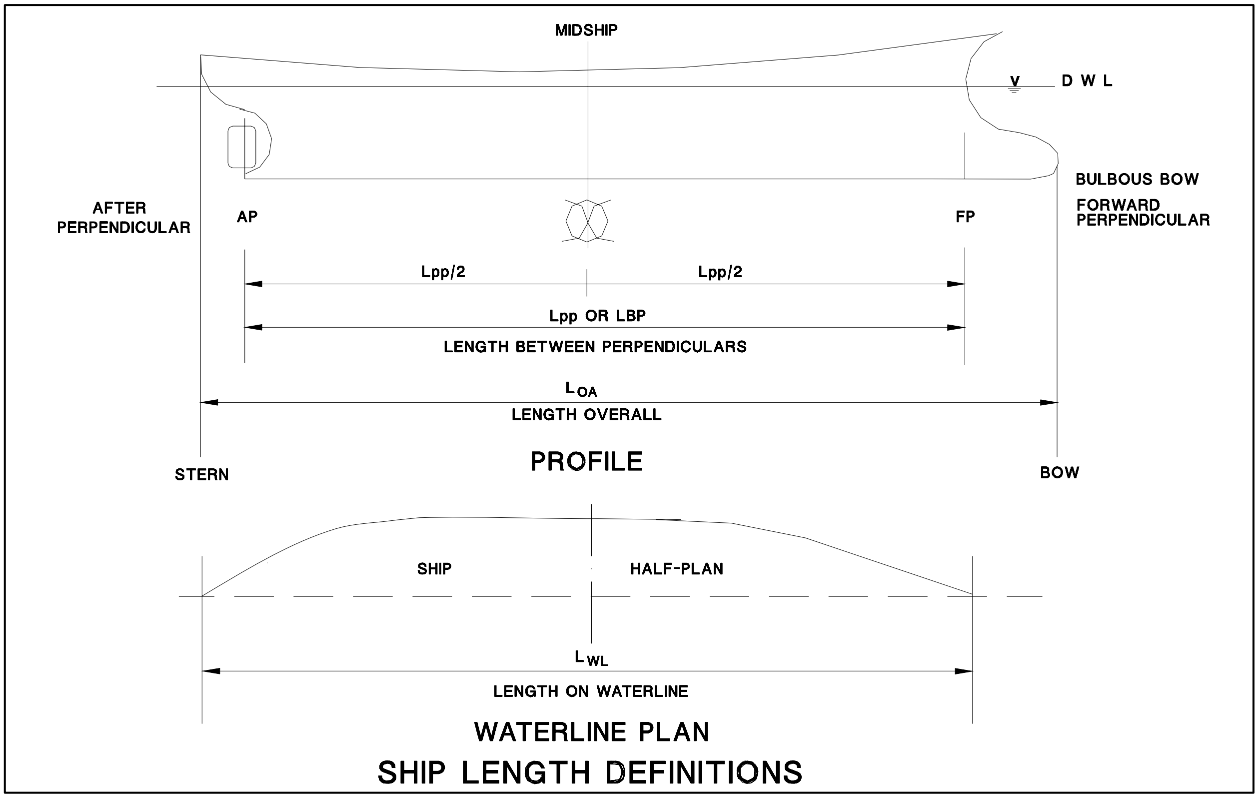


Figure 3-1. Ship length definitions

b. The most important length is the length between perpendiculars (Figure 3-1) since this governs ship cargo capacity and hydrodynamics. The length overall is the distance from the extremity of the bow structure to the stern structure. Another length on the ship design waterline may also be listed. The ship molded beam is the maximum ship width to the outer edges of the ship hull structural members at the maximum ship cross section, which is usually at the ship waterline, amidships. The maximum ship hull width is equal to the molded beam plus the hull plating thickness on each side of the ship. The beam at the design waterline may also be less than the maximum (Figure 3-2).

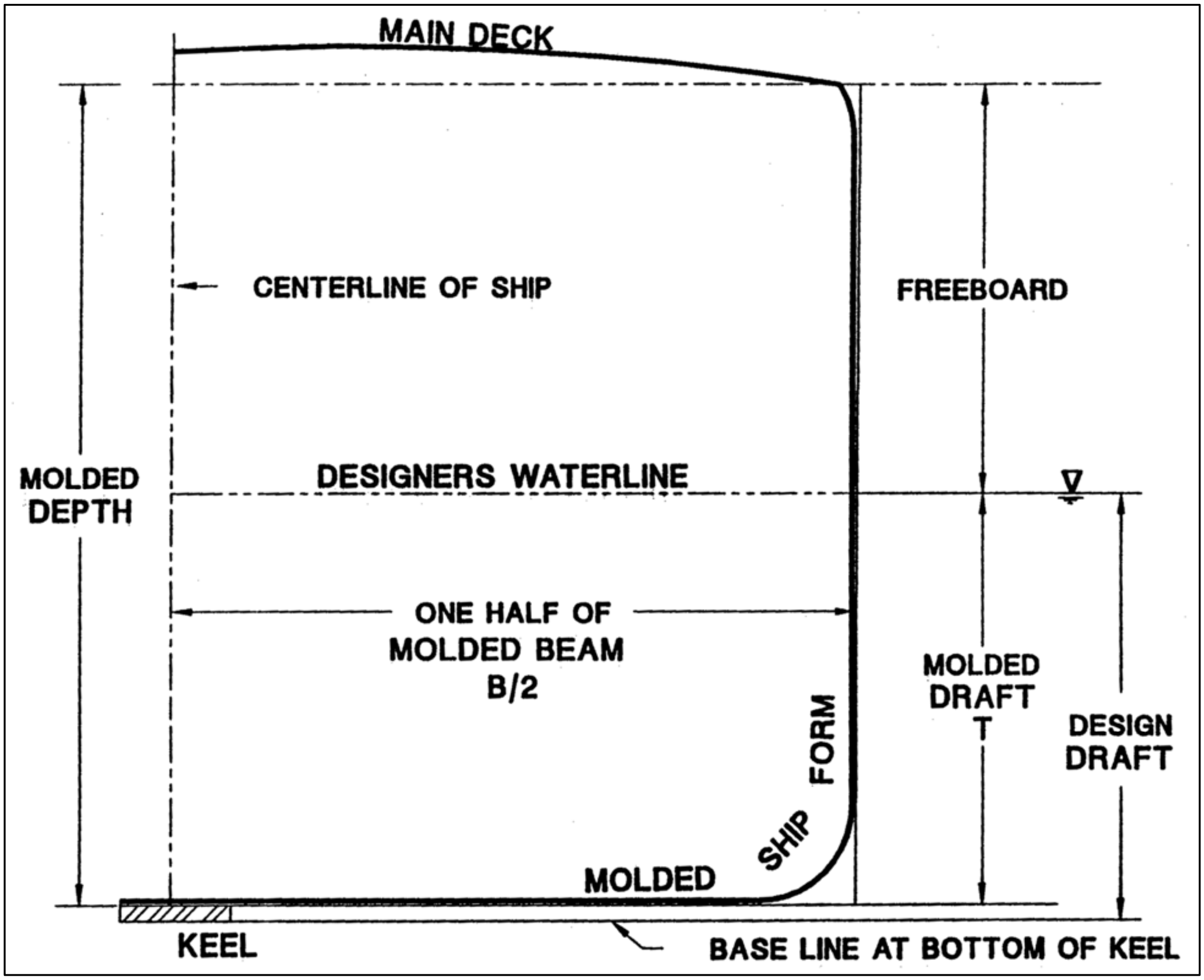


Figure 3-2. Midship-section molded-form definitions

c. The ship draft is the molded design or service ship draft and is the vertical height from the waterline to the inside edge of the hull structural members. The design waterline draft adds the keel thickness to the molded draft; usually, this is equal to the summer load line assignment draft certified by international convention and as authorized by the local rating society. The markings on the ship sides conform to the load line assignment. Ships in service are often loaded to less than the maximum draft, referred to as partially laden draft. A ship in ballast is loaded to ballasted draft. The forward draft and after draft are the ship drafts at the bow and stern, respectively; the average is the mean draft. Another ship dimension often provided in ship data lists is given as the ship depth; care must taken that this dimension not be confused with the ship draft. The freeboard is the difference between the ship depth and the draft and is usually an amount mandated by the load line assigning authority.

3-4. Cargo Capacity. The cargo-carrying capacity of a ship by weight is the dwt. However, this value also includes the weight of fuel, oil, fresh water, stores, crew, and baggage. The dwt is a reliable commodity capacity measure for tankers and most bulk carriers. Containerships are rated by Total Equivalent Units (TEU's), which are based on the number of 6.1-m (20-ft) boxes the ship can carry. The standard size box is 6.1 m long and 2.4 m (8 ft) wide by 8 ft deep. Containership box lengths may also include dimensions of 3.0, 6.1, 9.1 or 12.2 m (10, 20, 30, or 40 ft). Some bulk carriers with light cargo at high stowage factors (termed high cubic by the trade), such as grain or wood chips, may be more appropriately rated in volume. The standard naval architect's seawater specific or unit volume (reciprocal weight density) of 0.000976 m^3/kg @ 20 °C (35 ft^3/long ton) may be used to convert from weight to volume capacity. The capacity of LNG ships is also given in volume: cubic meters. Some ships may carry cargo with material density less than water's (e.g., wood chips), resulting in full volume loads with drafts less than design draft. The latter circumstances would impact channel design if the economic justification of channel depth were based on the design draft.

a. The loaded weight displacement of a ship is the total weight of the floating ship at its greatest allowable (fully loaded or design) draft. The difference in weight displacement between the loaded and unloaded ship condition is the dead weight; thus, the dead weight is equal to the loaded displacement minus the light displacement. The density of water can be used to convert weight displacement, Δ, to volume displacement, ∇. In this conversion, care must be given to the proper density value with respect to fluid salinity and temperature.

b. Ship so-called tonnage characteristics may sometimes be encountered during navigation channel planning and design. These are often given as gross and net tonnage and are only poorly related to ship cargo-carrying capacity. The tonnage of these ship characteristics is not really in tons at all, but the units are in 3.121 cu m per ton (100 cu ft per "ton") and to be used strictly for the purpose of setting canal tolls and port fees.

3-5. Form Coefficients.

a. A multitude of ratios and dimensionless coefficients are used by naval architects to describe ship hull form proportions and often used in ship design. The following discussion focuses on the two most useful form coefficients that the navigation analyst may need. One of the most commonly used is the block coefficient (C_B) which is used to describe the ship "fullness" or "fineness." It is the ratio of the volume of displacement to the volume of the rectangular block having the appropriate main ship dimensions, as shown in Figure 3-3.

$$C_B = \frac{\nabla}{LBT} \tag{3-1}$$

where

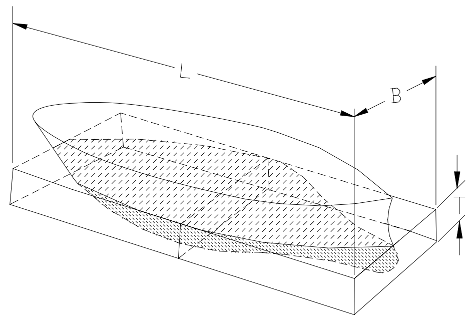
∇ = volume of displacement at molded draft T in cubic meters (cubic feet)

L = ship length between perpendiculars in meters (feet)

B = ship molded beam at the maximum section area in meters (feet)

T = ship full load molded draft in meters (feet)

The block coefficient for commercial ships varies from about 0.50 for fine form ships such as cargo liners and containerships up to about 0.90 for very full tankers and bulk carriers.



Block coefficient definition

Block coefficient (C_B) = Ratio of the volume of displacement to the volume of a rectangular block having a length, beam, and draft equal to that of the ship.

$$C_B = \frac{\nabla}{LBT}$$

L = Length between perpendiculars
T = Draft to the designed waterline, or molded ship draft
B = Beam amidships at the designed waterline, or molded beam
∇ = Volume of displacement of molded ship form at draft T

Figure 3-3. Block coefficient definition

b. Another coefficient used to describe ship performance is called the slenderness ratio. The one-third power is used to keep the ratio dimensionless.

$$C_s = \frac{L}{\nabla^{1/3}} \tag{3-2}$$

Values of this ratio vary from about 4.0 to 10.0 with increasing ship fineness. Figure 3-4 graphically indicates the empirical relationship between the block coefficient and the ship length Froude number for typical commercial vessels. A fitted curve is shown through the data points. This figure shows that ships with higher speeds tend to be “fine lined” or less “blocky,” i.e., have a lower block coefficient.

c. Ship dimension ratios are also very important in describing ship behavior, such as maneuverability. The length-to-beam, length-to-draft, length-to-depth, and beam-to-draft ratios are the most commonly used. Common values for these ratios for various ships and smaller vessels are shown in Table 3-1, which summarizes typical data.

3-6. Restrictions. Canal and lock sizes have an important effect on ship design, and the navigation analyst should be aware of those limitations. The Panama Canal has the following size limits because of the locks, which define Panamax ships allowed to transit the canal

a. Draft of 12.0 m (39.5 ft) fresh water, less in the dry season.

b. Beam of 32.2 m (105.75 ft).

c. Length of 289.6 m (950.0 ft).

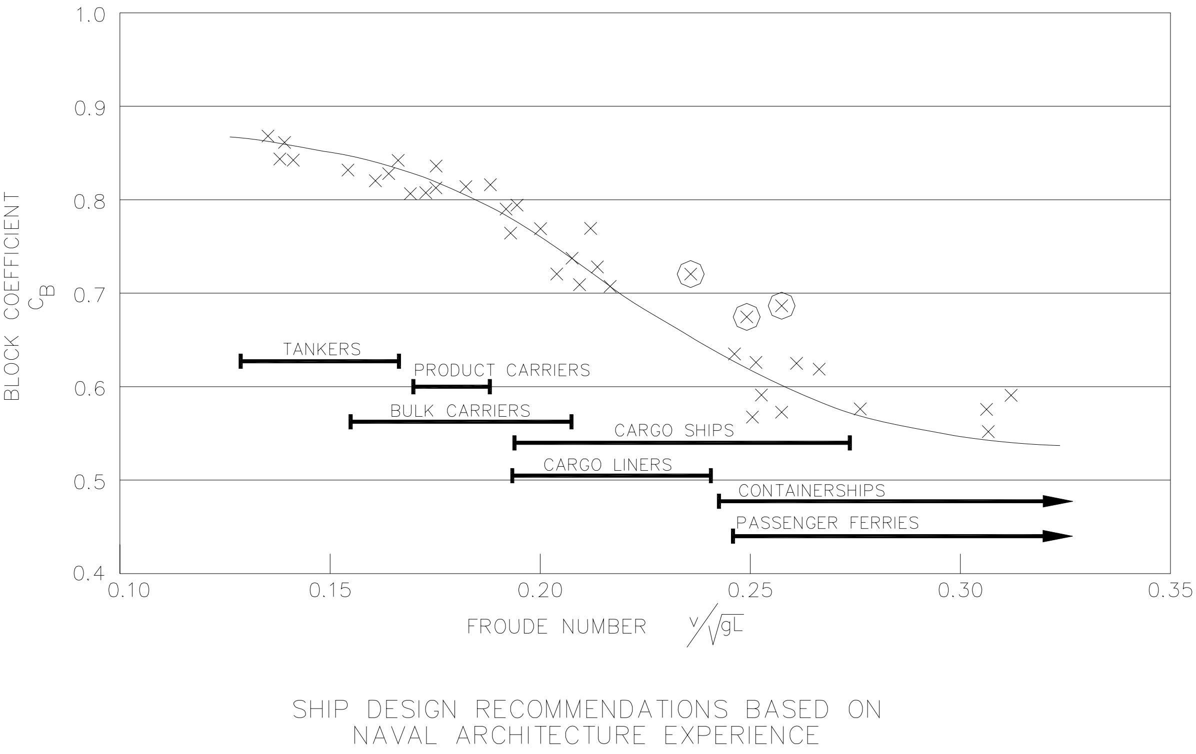


Figure 3-4. Ship design recommendations

The Suez Canal has no locks, but ships are limited to 16.2 m (53.0 ft) in draft and 64.0 m (210 ft) in beam; there are no limits on ship length. Large bulk carriers use the canal in ballast.

3-7. Ship Speed. The speed at which the design ship will be operated in the proposed channel should be selected carefully. The engine setting is changed from sea speed to maneuvering speed when a ship approaches a harbor area. This usually limits the maximum engine revolutions per minute (rpm) to less than the service speed available in the open ocean. Operational considerations also limit ship speeds because of the need to reduce ship squat (Chapter 6, paragraphs 6-6 to 6-13), increased ship resistance (Chapter 4, paragraph 4-4), and vessel wake and wave effects on waterways (Chapter 4, paragraphs 4-5 and 4-6). Ship speeds are also governed by ship control needs where wind, currents, and waves would tend to reduce the control margins. There is no doubt that there is also some economic incentive to keep vessel speeds at the highest prudent level, especially for projects with long transit distances or where tidal advantage is being exploited. An important consideration is the minimum ship speed necessary to maintain adequate ship steerage; this is normally 4 or more knots above the water current. Transit speeds from 5 to 10 knots are the most common ship speed in typical harbor channels as observed on a number of projects.

Table 3-1
General Typical Ship Hull Form Coefficients

Type	C_B	L/B	B/T	Speed V, knots, ft/sec	Length Froude No.[1] $F_l = \frac{V}{\sqrt{gL}}$	Number of Propellers/ Rudders	Rudder Area Ratio[2]
Harbor tug	0.50	3.3	2.1	10 (16.8)	0.25	1/1	0.025
Tuna seiner	0.50	5.5	2.4	16 (26.9)	0.31	1/1	0.025
Car ferry	0.55	5.1	4.5	20 (33.6)	0.34	2/2	0.020
Container high speed	0.55	8.3	3.0	28.5 (47.9)	0.53	2/2	0.015
						2/1	0.025
Cargo liners	0.58	6.9	2.4	21 (35.3)	0.29	1/1	0.015
RO/RO[3]	0.59	6.9	3.0	22 (37.0)	0.26	1/1	0.015
Barge carrier	0.64	7.5	2.9	19 (31.9)	0.20	1/1	0.015
Container med. speed	0.70	7.1	2.8	22 (37.0)	0.25	1/1	0.015
Offshore supply	0.71	4.7	2.75	13 (21.8)	0.28	2/2	0.016
General cargo low speed	0.73	6.7	2.4	15 (25.2)	0.20	1/1	0.015
Lumber low speed	0.77	6.7	2.6	15 (25.2)	0.20	1/1	0.025
LNG (125,000 m^3)	0.78	6.8	3.7	20 (33.6)	0.20	1/1	0.015
OBO[4] (Panamax)	0.82	7.5	2.4	16 (26.9)	0.17	1/1	0.01
OBO (150,000 dwt)	0.85	6.4	2.4	15 (25.2)	0.15	1/1	0.017
OBO (300,000 dwt)	0.84	6.0	2.5	15 (25.2)	0.14	1/1	0.015
Tanker (Panamax)	0.83	7.1	2.4	15 (25.2)	0.16	1/1	0.015
Tanker (100,000 to 350,000 dwt)	0.84	6.2	2.4	16 (26.9)	0.15	1/1	0.015
Tanker (350,000 dwt)	0.86	5.7	2.8	16 (26.9)	0.13	1/1	0.015
U.S. river towboat	0.65	3.5	4.5	10 (16.8)	0.25	2/2	...

[1] $\frac{V}{\sqrt{gL}}$ where V = ship speed, ft/sec ; g = acceleration due to gravity, ft/sec^2; and L = ship length, ft. To convert feet to meters, multiply by 0.3048.

[2] RUDDER AREA/SHIP LENGTH * DRAFT

[3] Roll-on, roll-off type ships

[4] Oil-, Bulk-, Ore-type ships

3-8. Conventions. A number of international rules have been developed by the seafaring nations to govern ship design in the interest of safety. Toll and service charges in ports and through canals also have an impact on ship design. Insurance companies are very influential by their rate-setting formulas. All ships are required by the U.S. Coast Guard to obtain load line certificates, which satisfy minimum static stability standards and attest to the seaworthiness of the ship. The main effect of the conventions and rules is in devising minimum freeboard allowances for ships in various trade route services. This has a direct impact on cargo loading limitations by the ship owners. The load line markings on the sides of the ship are an embodiment of the ship loading limitation and provide a visual guide on allowable ship drafts. These are called the Plimsoll markings, as shown in Figure 3-5, and depict different ship operational conditions, including freshwater draft, summer seawater draft, etc.

3-9. Maneuverability.

a. The maneuverability of ships depends on many factors, some of which are controllable by the naval architect in the ship design process. Usually, however, the economics of ship operational costs in the open ocean dominate the design, which often results in poor-handling ships. The navigation channel designer should understand the main ship characteristics that determine maneuverability for proper assessment of required channel dimensions.

b. Ships underway with normal self-powered operations in harbors are controlled by propellers and rudders located at or near the ship stern. The engine size that turns the propeller(s) and rudder area are the two most important parameters determining maneuverability. Handling characteristics of ships with twin propellers and a single rudder not located in the propeller slipstreams are usually poor compared with twin propellers and twin rudders located in the slipstreams. Single-propeller, single-rudder designs with adequate size rudders in the slipstream can provide adequate maneuverability. The availability of bow and stern thrusters increases the maneuverability of ships, especially at low speeds. Generally, maneuvering ships through navigation channels tends to be more difficult as the size of ship increases. The design of tankers and bulk carriers often makes the vessel directionally unstable, inhibiting the turning ability and causing difficulties in halting the turning of the vessel (called yaw checking). Pilots frequently use bursts of power and rudder action to start a ship in a turning maneuver; thus, the kick-turn ability of a ship is an important factor in ship control. Care must be taken to control this operation so that the ship does not gain too much speed.

c. Control of a ship becomes especially crucial when speed is being reduced while stopping or approaching a position to attach tugs for maneuvering assistance. Most ships tend to lose rudder control when the ship speed approaches 4 knots. Because of engine design, some ships are very difficult to steer at 6 knots or less and thus are difficult to control. Prudent mariners usually reduce engine speed when approaching a channel turn or other anticipated situations requiring major maneuvers. Reversing ship engines will frequently cause reduction or possibly loss of ship control.

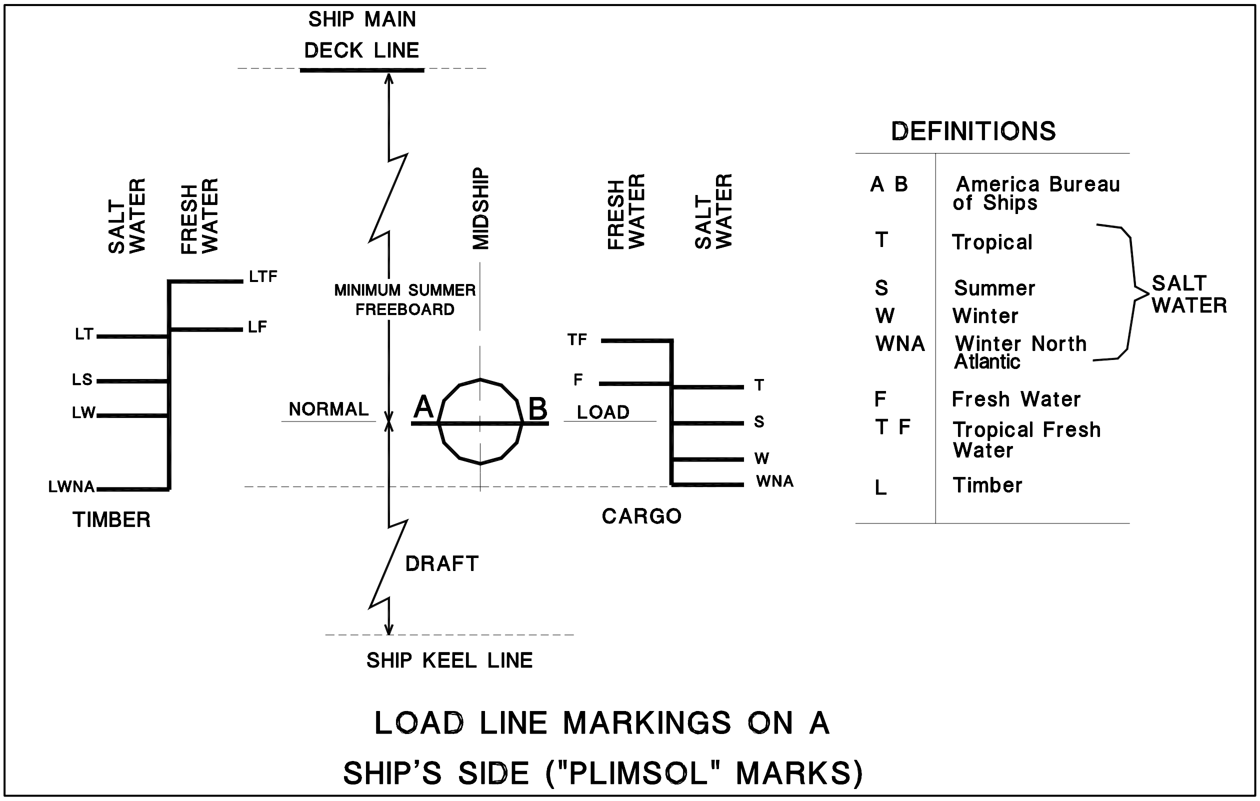


Figure 3-5. Load line markings on a ship

3-10. Environmental Factors.

a. The maneuverability of ships in a given navigation situation is influenced to a great degree by the environmental forces and resulting movements caused by the speed and direction of river and tidal currents, wind, waves, and channel banks. Studies have shown that ice at the surface and “fluff” on the channel bottom can also result in modified ship maneuverability. General rules to account for environmental factors are very difficult and usually are strongly site-specific.

b. Current and wind effects for normal operational levels are often not crucial, provided adequate ship speed can be maintained. Conversely, wave effects and bank suction forces will increase in severity with increasing ship speed. Bank suction is the term used to denote the forces and moments as a result of unequal pressure on a ship’s hull. The force on the hull is created when a ship transits off the channel centerline or when the banks are not symmetrical, thereby changing the flow pattern area between the hull and the submerged bank, accelerating the water and decreasing the dynamic pressure. Bank suction normally rotates the ship away from the bank because of the unsymmetrical pressure forces along the longitudinal axis of the hull. Current effects are much more important than wind effects, especially when currents have significant components perpendicular to navigation channels. In general, constant winds and currents pose less difficulty than time-varying or space-changing effects, which induce transient ship forces. Wind effects on ships are much more important for ballasted rather than loaded tankers because of the high above-water “sail area.” Car carriers and containerships with loaded boxes have substantial wind effects in many operations, especially at reduced speeds.

3-11. Design Ship.

a. The design ship or ships are selected on the basis of economic studies of the types and sizes of the ship fleet expected to use the proposed navigation channel over the project life. For project improvement studies, a thorough review and analysis of ships presently using the project should be included as a part of the study. Projections of ship fleet data, usually needed, account for expected ship construction trends. An example tabulation of merchant ships segregated into different categories by ship draft and cargo capacity in deadweight tons is presented in Table 3-2. This table shows that tankers and bulk carriers comprise the main ship types above Panamax draft of about 12.2 m (40 ft).

Table 3-2
Liquid Bulk Merchant Fleet of the World Categorized According to Draft Class
(To convert feet to meters, multiply by 0.3048)

Draft Class (ft)	Total Count	Total dwt	Total DWT Cumulative Percentage	Tankers		Product Tankers		LPG[1] Carriers		LNG[2] Carriers		Crude Oil Tankers		Chemical/Oil Tankers		Chemical Tankers	
				Count	Avg dwt	Count	Avg dwt	Count	Avg dwt	Count	Avg dwt	Count	Avg dwt	Count	Avg dwt	Count	Avg dwt
<10	295	1,612,207	0.5	166	3410	43	16,253	30	3902					13	6224	43	3472
10	140	319,473	0.6	58	1484	46	3649	8	1338					5	1212	23	2121
11	116	306,738	0.7	62	2678	28	3719	11	1038	1	463			3	1725	11	1774
12	147	286,470	0.8	93	2321	17	1995	19	720					6	1053	12	1392
13	279	419,481	0.9	134	1696	23	2415	69	971	3	992			9	1320	41	1337
14	333	542,653	1.1	170	1900	29	1545	66	1257					6	1571	62	1330
15	345	747,974	1.4	221	2247	27	2481	53	1839					11	2317	33	1862
16	303	727,593	1.6	190	2345	35	2896	38	2295			1	2000	7	2631	32	2283
17	312	910,151	1.9	159	2891	37	3064	62	3122					6	3165	48	2595
18	306	1,117,165	2.2	138	3582	31	4774	40	3452					16	3193	81	3527
19	268	1,009,730	2.6	154	3572	38	4012	46	4274			1	3395	9	3703	20	3693
20	231	1,048,847	2.9	95	4492	29	5408	24	5481	21	2692	1	4999	10	4270	51	4500
21	270	1,407,631	3.4	115	5092	38	5454	29	4954	1	9090	1	4999	27	4944	59	5484
22	277	1,639,346	3.9	112	5691	56	6446	29	4807			1	4986	22	6506	57	6201
23	250	1,982,690	4.5	67	6353	44	12,972	14	5881	2	10,979	2	17,500	21	6999	100	7000
24	137	1,095,598	4.9	39	7524	29	9897	17	5994			1	12,615	13	8100	38	7772
25	123	1,128,899	5.2	15	9998	21	10,825	21	6586	2	12,839			27	9096	37	9244
26	130	1,387,620	5.7	21	9900	40	13,387	8	7115					19	10,084	42	9422
27	87	990,191	6.0	11	11,542	13	12,198	20	11,062	1	21,301			16	11,740	26	10,549
28	101	1,507,759	6.5	17	16,629	23	16,390	19	8448	3	41,131			14	14,894	25	14,227
29	134	2,095,506	7.2	17	15,402	19	18,116	6	11,560			30	18,946	24	13,360	38	13,976
30	125	2,303,890	7.9	19	16,559	48	21,020	16	13,748	3	28,412			16	17,482	23	17,191
31	123	2,894,830	8.8	24	21,948	56	22,421	11	15,218	12	41,738	1	59,543	4	16,875	15	21,147
32	84	1,965,446	9.5	6	23,702	30	27,829	25	17,472					9	21,710	14	25,441
33	98	2,813,581	10.4	2	23,979	46	31,084	7	24,588	2	34,887	1	35,679	10	24,399	30	27,140
34	92	2,839,038	11.3	22	30,044	50	31,803	7	24,483	1	27,235			4	31,026	8	33,150
35	153	5,188,065	13.0	18	33,300	80	32,190	12	31,773	3	61,632	7	40,156	10	36,288	23	34,927
36	321	11,921,363	16.8	26	35,755	188	33,922	40	43,367	16	65,018	14	45,991	9	40,931	28	29,542
37	215	8,625,276	19.6	6	44,531	146	36,210	9	41,550	20	69,953	3	70,726	8	32,378	23	35,966
38	98	4,818,287	21.1	11	38,933	35	39,548	11	35,114	25	71,158	8	63,891	4	41,869	4	40,509
39	139	7,172,298	23.4	10	47,201	58	47,928	18	45,957	13	71,161	25	61,834	11	41,521	4	41,391
40	219	12,682,801	27.5	27	50,604	99	52,276	2	50,786	4	73,145	56	77,375	27	45,783	4	44,469
41	104	5,899,624	29.4	3	58,941	56	53,405	23	49,821	1	80,239	19	75,819	2	32,719		
42	126	8,520,599	32.1	10	76,452	49	56,472	6	50,191			58	78,395	3	46,965		
43	97	7,383,320	34.5	3	94,995	26	62,172	12	50,091			55	87,858			1	48,581
44	90	7,224,193	36.8	11	94,506	21	63,828	5	57,533	1	83,020	49	88,587	2	44,983	1	42,825
45	94	7,946,303	39.4	18	75,507	12	82,965	5	57,110			59	89,933				
46	60	5,529,881	41.2	8	87,285	7	77,664	1	43,386			43	97,152	1	67,031		
47	55	5,234,185	42.9	5	98,373	5	84,851					45	95,957				
48	51	5,422,759	44.6	3	95,193	5	106,634					43	107,070				
49	61	6,508,458	46.7	3	117,460	2	105,251					56	106,171				
50	35	4,301,177	48.1	1	141,861	3	99,515					31	124,541				
51	41	5,119,042	49.7	5	131,648	3	117,148					33	124,526				
52	5	562,011	49.9	2	156,522	2	82,658									1	83,651

(Continued)

Table 3-2 (Concluded)

Draft Class (ft)	Total Count	Total dwt	Total DWT Cumulative Percentage	Tankers		Product Tankers		LPG[1] Carriers		LNG[2] Carriers		Crude Oil Tankers		Chemical/Oil Tankers		Chemical Tankers	
				Count	Avg dwt	Count	Avg dwt	Count	Avg dwt	Count					Count	Avg dwt	Count
53	43	5,437,336	51.7	2	132,578	12	83,885					29	143,640				
54	20	2,832,840	52.6									20	141,642				
55	79	10,810,995	56.0	3	140,193							76	136,716				
56	50	7,407,504	58.4	1	159,718							49	147,914				
57	21	3,125,661	59.4									21	148,841				
58	1	127,002	59.5									1	127,002				
59	6	824,153	59.7							1	70,593	5	150,712				
60	1	238,898	59.8									1	238,898				
61	5	735,225	60.0									5	147,045				
62	21	5,154,030	61.7									21	245,430				
63	27	6,932,061	63.9									27	256,743				
64	36	9,187,452	66.9									36	255,207				
65	28	6,935,824	69.1									28	247,708				
66	12	3,093,732	70.1									12	257,811				
67	34	9,535,606	73.2									34	280,459				
68	40	10,953,284	76.7			2	294,772					38	272,730				
69	38	10,665,992	80.1									38	280,684				
70	15	4,198,560	81.5									15	279,904				
71	25	7,200,575	83.8									25	288,023				
72	45	13,522,320	88.1									45	300,496				
73	52	16,894,280	93.6									52	324,890				
74	22	7,067,312	95.9	1	392,798							21	317,834				
75	17	6,261,321	97.9									17	368,313				
76	3	1,124,334	98.2									3	374,778				
77	1	409,400	98.4									1	409,400				
78	1	132,960	98.4									1	132,960				
79	1	491,120	98.6									1	491,120				
81	1	564,650	98.7									1	564,650				
82	4	1,830,252	99.3									4	457,563				
83	2	1,033,318	99.7									2	516,659				
93	1	484,276	99.8									1	484,276				
94	1	555,051	100.0									1	555,051				
TOTAL	7723	310,927,473		2304		1707		839		136		1275		404		1058	

[1] Liquid petroleum gas.
[2] Liquid natural gas.

b. Additional information on tankers is presented in Figure 3-6. Tankers up to about 200,000 dwt at design drafts of about 18.3 m (60 ft) are being brought into the deeper 15.2-m (50-ft) U.S. harbors at partial load in some cases.

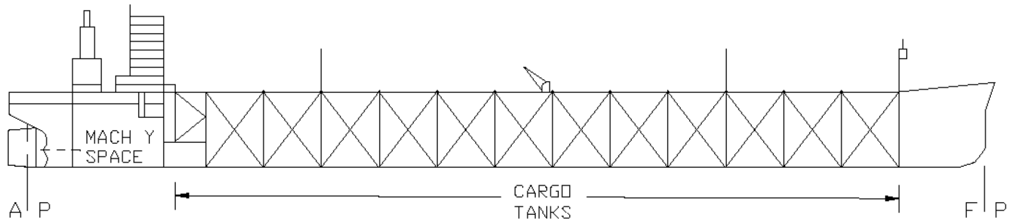
c. The design ship is chosen as the maximum or near-maximum-size ship in the range of ship sizes from the vessel fleet. The design dimensions of the channel will be determined to accommodate the design ship(s) representative of the project forecasted user fleet. The channel width and depth need not be constant throughout the project but may vary as necessary so that the design ship will be able to make a safe, efficient, and cost-effective transit of the channel under the set of operational conditions chosen. Upon project authorization, the design dimensions are considered, nominally, to be the authorized dimensions. This should not preclude minor adjustments in width and depth during continued design, construction, and operation as circumstances warrant and delegated authorities permit.

3-12. Design Transit Conditions. The selection of the operational design conditions for the project is of major importance. The design ship should be able to make a safe transit while sailing through the proposed navigation channel under these design conditions. Extremes of weather, rare tidal or discharge events, and other limiting (though seldom encountered) conditions are not normally part of the design conditions. Some of the operational factors that have to be specified are:

- *a.* Suitable current conditions.
- *b.* Specified wind and wave conditions.
- *c.* Visibility (day, night, fog, and haze).
- *d.* Use of tidal advantage for additional water depth.
- *e.* Traffic conditions (one- or two-way, pushtows, cross traffic).
- *f.* Speed restrictions.
- *g.* Tugboat assistance.
- *h.* Underkeel clearance.

The use of tidal advantage may establish ship transit periods during the tidal cycle, thus controlling tidal currents encountered by the ship. Normally, the design transit conditions should not consider extreme events that would limit or halt navigation traffic, such as hurricane winds or severe high tidal or flow currents. The inclusion of possible emergency events, such as engine failures, etc., should also be avoided, unless the channel is specifically to be designed to accommodate such operational circumstances. Normal operational conditions are strongly influenced by individual, local pilot, and pilot association rules and practices. Pilots will not usually move a ship through access channels to a terminal or dock for berthing if conditions and circumstances will not allow adequate tug assistance. There may be operational wind, wave, or current limitations on the ability to safely moor a ship at a terminal or berth, thus requiring a delay in ship transit. Turning operations and maneuvering into a side finger slip may set limitations on certain tidal height or current conditions. An important parameter is the wave height at a harbor entrance, which could prohibit a pilot boat from safely transferring the pilot onboard the ship.

Typical VLCC (Very Large Crude Carrier) Tanker



Length Overall	362.0 m (1187.5 ft)
Length Between Perpendiculars	348.4 m (1143.0 ft)
Length On Design Waterline	356.9 m (1171.0 ft)
Beam, Maximum Molded	69.5 m (228.0 ft)
Depth To Upper Deck At Side Molded	29.0 m (95.0 ft)
Draft, FUll Load Molded (Approx)	22.6 m (74.0 ft)
Displacement At Full Load Draft	450,910 Tons
Lightship	60,140 Tons
Total Deadweight	390,770 Tons
Shaft Horsepower	45,000
Sea Speed, Knots	15.9
Propeller 6 Blades, diam.	9.6 m (31.5 ft)

Ship Particulars
For Example Tankers

	Amanda Miller	Sea Spirit	Jade	Nisseke Maru	Esso Atlantic
Length B.P., m (ft)	228.0 (748.0)	251.0 (843.2)	329.2 (1080.0)	330.0 (1082.7)	406.6 (1334.0)
Beam, m (ft)	32.2 (105.7)	40.8 (134.0)	51.8 (170.0)	54.5 (178.8)	71.0 (232.9)
Depth, m (ft)	17.5 (57.5)	21.3 (70.0)	25.6 (84.0)	35.0 (114.8)	31.2 (102.4)
Draft, m (ft)	13.2 (43.2)	16.0 (52.4)	20.1 (65.8)	27.0 (88.7)	25.0 (82.0)
VS, Knots	15.0	16.95	15.70	15.0	16.0
C_B	0.828	0.803	0.836	0.862	–
Froude Number	0.163	0.174	0.142	0.136	0.130
SHP	20,000	28,000	32,000 (M)	40,000	45,000
Propulsion	Diesel	steam	Steam	Steam	Steam
Light Ship, tons	15,060	19,700	33,150	52,150	–
Deadweight, tons	65,740	116,250	255,374	370,812	508,731
Displacement, tons	80,800	135,950	288,524	422,962	–
Length/Depth	13.009	12.046	12.858	9.428	13.032
Length/Beam	7.079	6.293	6.352	6.055	5.727

TANKER PARTICULARS

Figure 3-6. Tanker particulars (To convert tons to metric tons, multiply by 0.9072)

CHAPTER 4

Ship Operations

4-1. Introduction. Deep-draft navigation projects are built or improved to enhance the safety, efficiency, and productivity of waterborne commerce in U.S. ports and harbors. To properly assess navigation traffic in the waterway channels, the planner and designer must understand ship behavior in ports and harbors and the main operational factors having an impact on navigation. This chapter presents the necessary ship operation information required by the analyst and highlights important impacts on channel design.

4-2. Navigation System. The proper design of navigation channels requires an understanding of port and harbor operations viewed as a system. Generally, at least three components or viewpoints are relevant as listed below with a brief outline of each:

a. *Waterway engineering subsystem.*

(1) Navigation channels design and maintenance.

(2) Environmental factors wind, waves, tides, and currents.

(3) Dredging and mapping services.

(4) Shore docking facilities.

b. *Marine traffic subsystem.*

(1) Operational rules and regulations.

(2) Aids to navigation.

(3) Pilot and tug service.

(4) Information and data sources.

(5) Communications and vessel traffic services (VTS).

c. *Vessel hydrodynamic subsystem.*

(1) Ship design.

(2) Maneuverability and controllability.

(3) Human factors.

(4) Navigation equipment.

The important point is that each of the three subsystems cannot be considered without information from the other two subsystems. Therefore, the channel designer is required to analyze the total system in an integrated fashion, taking into account the ship factors and the traffic factors to produce an adequate design. It should also be clear that tradeoffs between investments for the three subsystems are not only possible but are normal procedure. Thus, the channel dimensions often dictate ship design and placement of aids to navigation; the converse of this is also true, i.e., that the channel design is heavily influenced by the ship sizes and the available accuracy of aids to navigation.

4-3. Typical Operations.

a. The methods used during typical ship transits into and out of ports are of major concern to the navigation designer since they guide the design process. Ships at sea will give notice to the local port authority and pilot group several days out upon approaching the port entrance. A local shipping agent or firm is usually also involved as the commercial chartering entity acting in the business transaction between the cargo shipping entity, the ship owners offering transportation services, and the destination company ordering or requesting the commodity. Upon arrival at the entrance, the ship will be met while underway or at anchor by one or more locally licensed pilots who provide the navigation service guiding the ship safely to the proper berth or terminal. The boat meeting and pilot transfer to the ship take place at a designated anchorage area located near the ocean end of the entrance channel marked by a sea buoy. Local tug services are also usually contacted and plans finalized for the ship transit. Many tug companies also provide a tug pilot who will also board the ship to help guide the ship during the final phase of the transit and the actual docking and mooring at the ship berth. At some ports, the local pilot also acts as the tug docking pilot.

b. Upon reaching the ship bridge, the pilot confers with the ship master or watch officer on the ship particulars: namely, engine power, rudder, navigation equipment, and loading condition (draft and trim). Legally, the pilot is only an advisor, so that the ship captain still has responsibility for the ship. In practice, the pilot takes control of the ship, issuing rudder and engine commands as well as course orders.

c. The process of steering and controlling the ship in a channel is typical of a feedback control system as depicted in Figure 4-1. The transit into a port follows a series of straight segments of the navigation channel centerline by a process of course keeping where the pilot gives course settings, and the steersman monitors and changes the rudder setting to maintain the ship heading. If currents or wind effects are important, the pilot will carefully keep an eye on the course, changing the heading to correct for any set by those forces. The engine rpm may be constant or may be changed during the straight legs but often is reduced to “slow” or “dead slow” for speed reduction. Ships are usually maintained at high maneuvering speeds, if possible, which are less than sea speeds. For most ships, transit speeds in the straight channel segments may be up to 12 knots (6.1 m/sec (20.2 ft /sec)) if traffic is light and without any particular hazards.

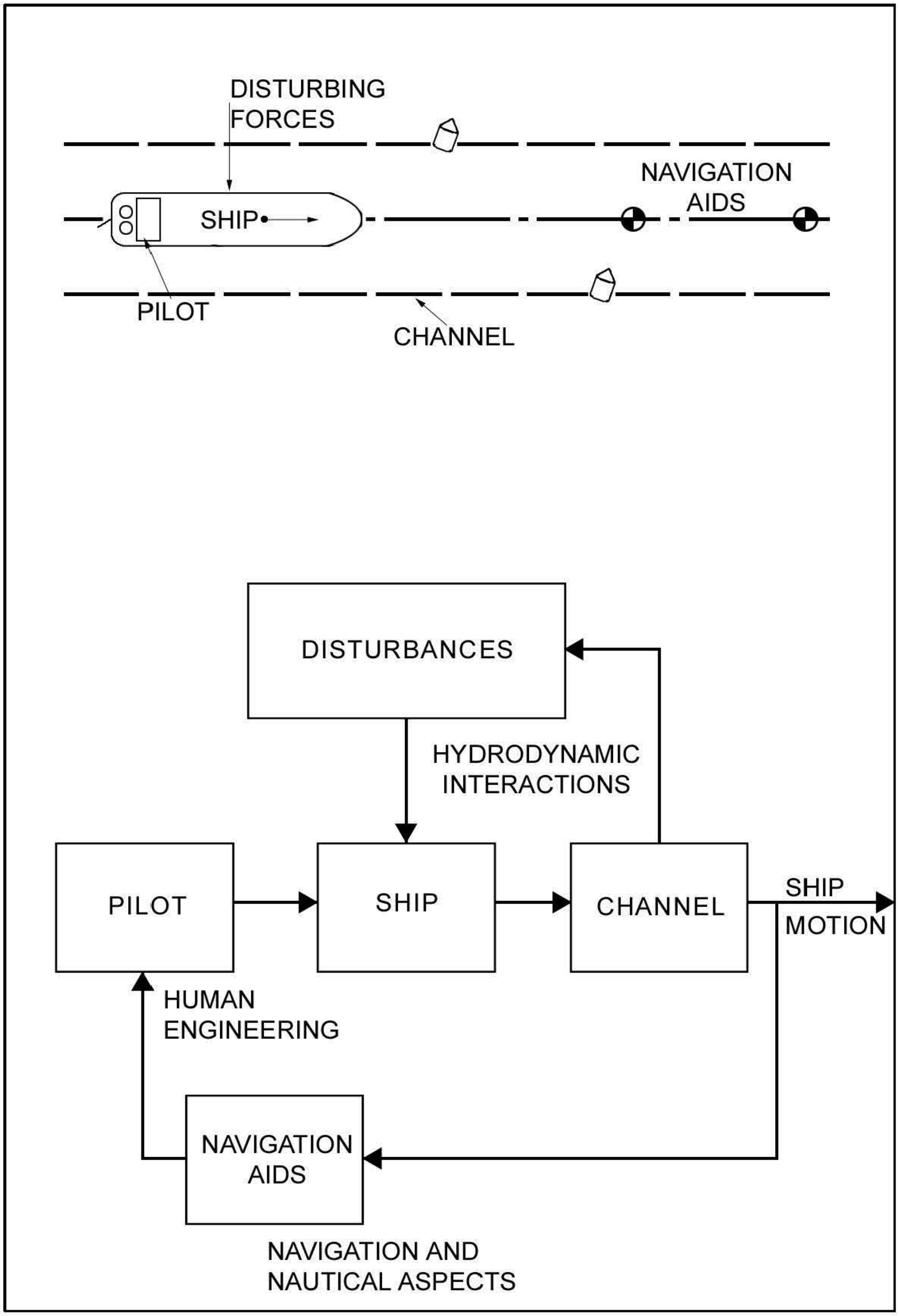


Figure 4-1. Ship control system

d. Specific rudder commands are issued to the steersman upon approaching a channel turn, such as “right--20 degrees,” etc. The engine rpm setting is often briefly changed to “full ahead” to provide the kick to start the ship turning. The channel turns or way points are locations where special caution is required as a result of rapid changes in ship position with respect to channel banks and current effects. A small-turn angle is usually easy; the larger angular turns (say 30 or more degrees) are often much more difficult. Pilots familiar with the channels know when to issue the proper commands and how to monitor the ship response and will not hesitate to give “full right rudder” if it seems necessary. In some ports, specially difficult circumstances along the transit may occur, such as at very narrow overhead bridges or meeting or overtaking situations. The port entrance channel is often particularly troublesome because of complex crosscurrents, waves, frequent shoaling problems, and wind effects. Difficult control situations will demand special diligence and specific rudder and engine commands by the pilot.

e. The ship is slowed down well before approaching the berth or terminal, usually with the assistance of tugs when ship control is lost at speeds below 3 to 4 knots (1.5 to 2.0 m/sec (5.0 to 6.7 ft/sec)). The upper end of most port channel systems usually includes many docks, terminals, small craft harbors, and other forms of congestion, which call for very slow speeds to prevent waves and moored ship hawser breakage. The final phase of the ship transit is with the tugs pushing the ship to the dock face and mooring lines made fast to the ship and the dock.

f. The outbound ship transit from the berth back to the open sea where control is transferred from the local pilot to the master is much the same as the inbound transit, except in reverse sequence.

g. The normal ship transit sequence of events outlined above should not obscure the fact that ships can always be brought into a port by operational modifications, provided the channel depth and width are adequate. If need be, the timing of the transit can be changed to avoid wind, currents, or other difficult environmental factors. Alternatively, use of adequate tugs to handle the ship as a tow is possible. Such operations, however, would not usually provide an economically viable solution. Navigation channels are thus designed to allow normal ship handling under ship self-powered operation at sufficient speeds over a wide operational window to provide an adequate port throughput for economic viability.

4-4. Ship Resistance.

a. Overall ship resistance is an important parameter that has been thoroughly studied by naval architects since this determines the power required to propel a ship. A ship-like body moving through a fluid is a fundamental concept in understanding resistance. An example of such a moving body submerged in deep water is depicted in Figure 4-2. Ideal potential flow fluid theory shows that positive pressure is produced on each end of the body with negative pressures along the ship middle body. Because of viscous effects from real fluids on the body surface, a boundary layer is generated along the body causing body frictional resistance. Flow separation will occur at the ship stern, causing increased resistance from eddy drag. The sum total viscous and eddy resistance of the ship is called the wetted surface drag and can be readily calculated or obtained from tabulated towing tank data.

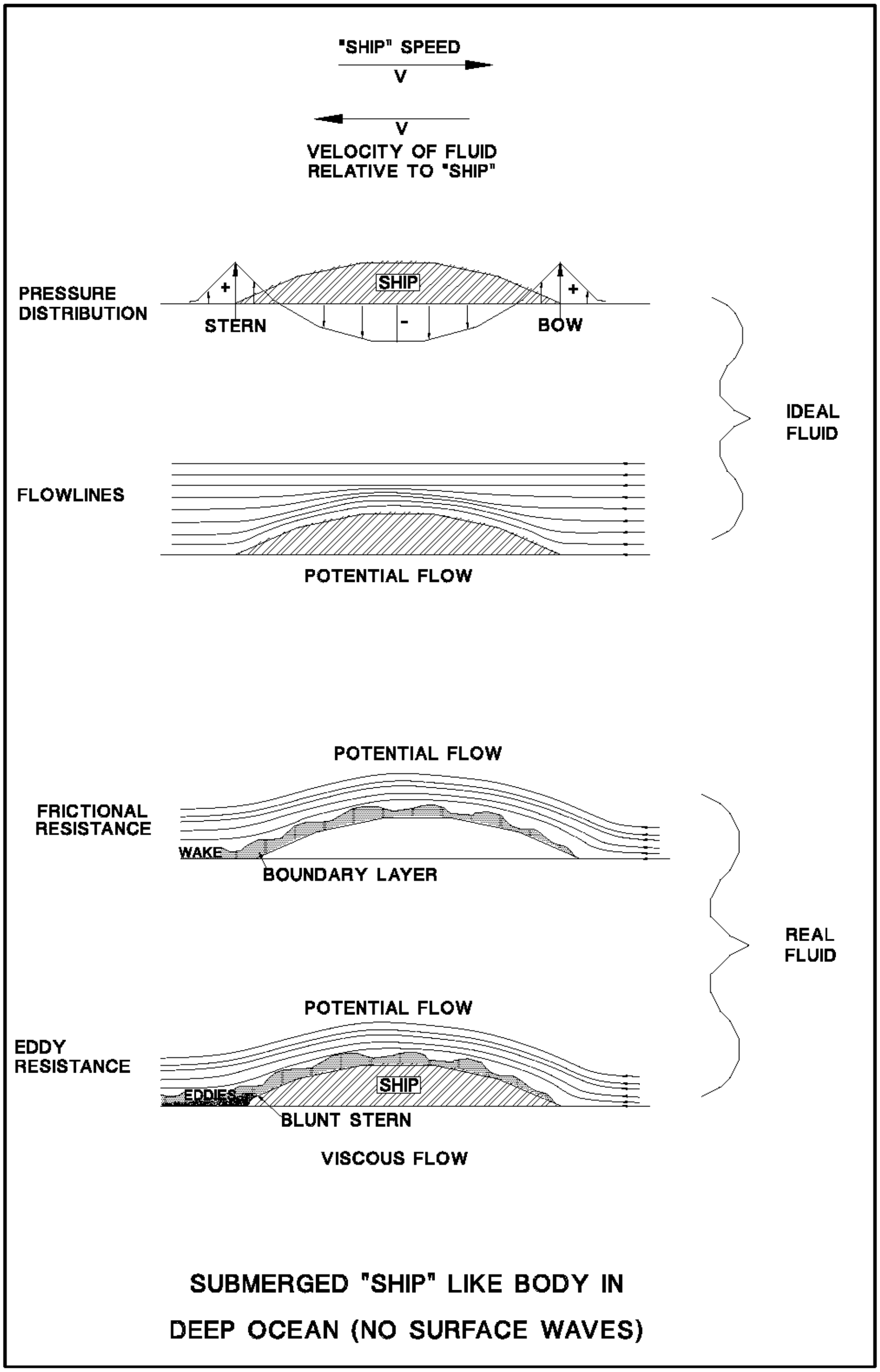


Figure 4-2. Submerged shiplike body

b. The ideal pressure distribution on the moving ship in deep water causes a system of waves on the free surface moving with the ship. The fact that a ship sailing over the deep ocean at constant speed generates a wave system is well known by any sailor or casual observer. As shown in Figure 4-3, these waves are composed of both divergent and transverse waves and are generated at the bow and the stern of the ship as well as at various positions along the ship length. The waves at the free surface waterline are generated by the pressure distribution around the ship and cause significant resistance to the ship. More important to the navigation planner and designer is that the ship also sinks and trims with respect to the static ship. Thus, the ship will sink in the water and trim because of the wave train caused by the ship. While this occurs in deep water, the waves and ship sinkage become much more prominent in shallow water. The wave making by the ship, therefore, has an important impact on the design of the channel.

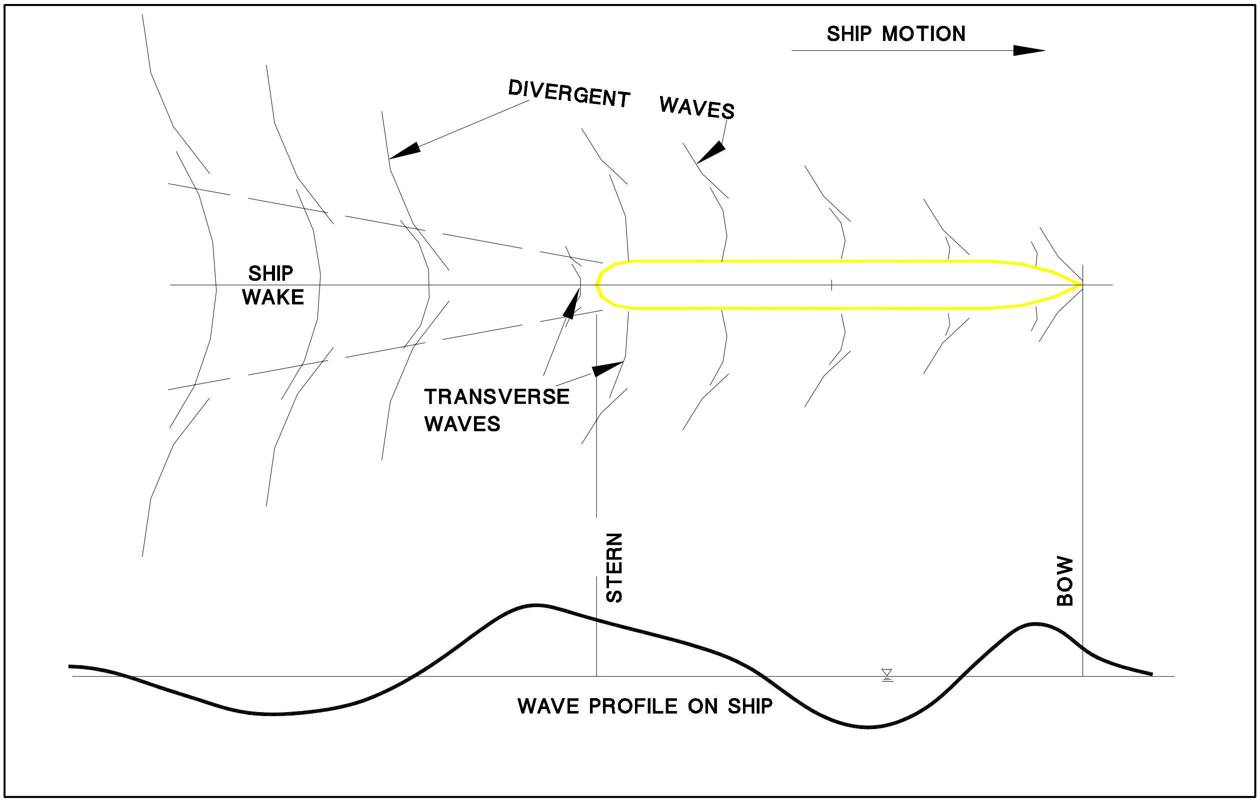


Figure 4-3. Schematic of ship wave system

c. At very low speeds, most of the ship's resistance is the result of wetted surface drag; as the speed is increased, wave-making drag grows higher. The ship length Froude number (F_l) has been an important parameter in determining wave effects. This may be given as the ratio of ship's speed to the square root of the acceleration because of gravity and the ship's length:

$$F_l = \frac{V}{\sqrt{gL}} \tag{4-1}$$

where

F_l = ship's length Froude number

V = ship's speed in meters (feet) per sec

g = acceleration as a result of gravity in meters (feet) per sec^2

L = ship's length in meters (feet)

The normal value of this dimensionless parameter is usually very small for commercial ships — perhaps varying from near 0.04 for tankers at slow ship speeds near 5 knots (2.6 m/sec (8.4 ft/sec)) to near 0.40 for fine-line containerships at 25 knots (12.8 m/sec (42.0 ft/sec)). Navy warships, which may operate at much higher speeds, of course, would sail at higher design Froude numbers. Wave drag becomes increasingly important at Froude numbers of about 0.2 or higher and can become two or three times the ship's surface resistance at Froude numbers of 0.4.

d. The total drag on a ship determines the selection of the ship thrust and power required to sail the ship at the design speed. The engine power is crucially important in the maneuverability of the ship, especially at the typical moderate harbor speeds, when engine acceleration effects are used to provide kick turns. The ratio of installed engine shaft horsepower to the ship deadweight tonnage may be called specific power and used to relate the relative ship powered maneuverability. Values of the ship specific power vary from about 0.05 to 50 for displacement ships of various types, both naval warships and maritime commerce. The values for warships are listed in Table 4-1.

Table 4-1
Ship Specific Power

Ship	Specific Power	Maximum Speed, knots
Battleship	3.7	35
Cruiser	6.5	35
Destroyer	19.0	35

The evolution of tankers from the small 13,000-dwt size with typical specific power ratio of about 0.5 has grown progressively smaller to under 0.1 at the highest 500,000-dwt size. While these power levels are adequate to move the ships at the design speed, their ability to accelerate and decelerate is significantly impaired.

4-5. Shallow Water. The resistance of a ship increases appreciably in shallow water because of speed increases around the ship's hull and changes of the wave pattern. The effects of shallow water can be characterized by the simple ratio of water depth (h) to ship draft, (T). The increased frictional resistance and wave patterns in shallow water both modify the sinkage and running trim and the squat of a ship and required underkeel clearance. For most merchant ships, which travel at 25 knots (12.8 m/sec (42.0 ft/sec)) or less, this effect becomes important when water depth-to-ship draft ratios (h/T) are less than 4.0. Since most ship navigation channels operate at very small depth to draft ratios (typically h/T less than 1.5), shallow-water effects have major impacts on ship navigation. The important parameter that governs ship waves in shallow water is the depth Froude number:

$$F_h = \frac{V}{\sqrt{gh}} \tag{4-2}$$

where

F_h = depth Froude number

V = ship speed in meters/sec (feet/sec)

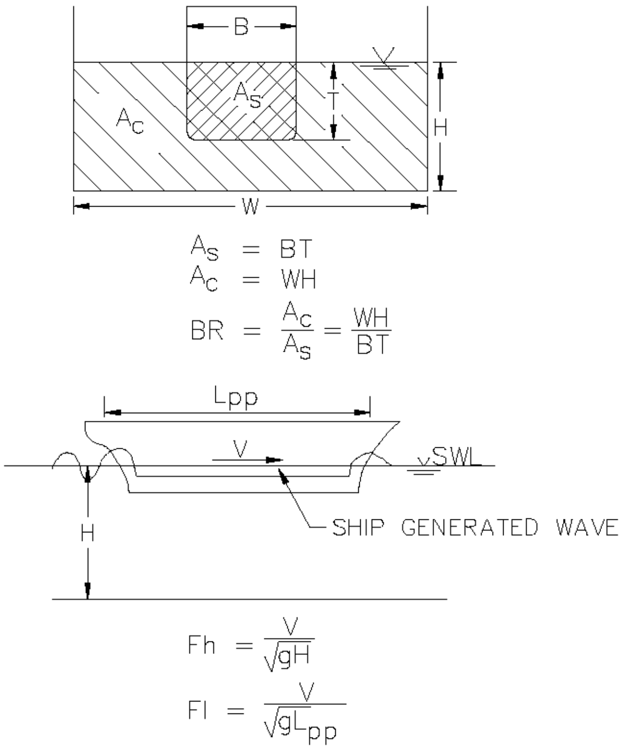
h = water depth in meters (feet)

As the ship speed increases, the shallow-water effects will increase up to the value of depth Froude number equal to unity, where critical open channel flow would occur. In practice, wave effects, squat and running trim, and ship resistance become very high at F_h values well below $F_h = 1.0$, so that normally a self-propelled merchant ship would not exceed F_h of about 0.6.

4-6. Restricted Channels.

a. A further increase of wave effects, squat, and ship resistance occurs when ships sail in navigation channels. The ratio of midship cross-sectional area (normally, A_s is ship beam times draft or B T), and the channel cross section (A_c) is used to characterize the relative channel restriction (see Figure 4-4 for a definition sketch). The inverse of the above value of ship area (A_s) to channel area (A_c) is often described as the channel blockage ratio (B_R). Typical channel blockage ratios may vary from 2 to 3 for very restricted narrow canals and channels up to situations with open channels at ratios of 20 or more. The critical depth Froude number will change accordingly from $F_h = 0.2$ at $B_R = 2$ to $F_h = 0.7$ at $B_R = 20$ as shown in Figure 4-4. The Schijf limiting velocity, to be further discussed in Chapter 6, imposes an upper limit on the ship speed for self-propelled ships sailing in restricted channels, especially canals. For the normal channel blockage ratio from about 3 to 10, this can be an important limitation. For example, at $B_R = 3$ in 12.2-m (40-ft) water depth, the maximum ship speed is about 6.4 knots (3.3 m/sec (10.8 ft/sec)). Even at a $B_R = 10$ in 15.2 m (50 ft) of water, the maximum ship speed is 14.3 knots (7.3 m/sec (24.0 ft/sec)).

b. These considerations assume the ship engine has the power and thrust to overcome the ship resistance. The restricted channel, the increased return currents, and wave effects cause a substantial ship resistance above deep-water, oceangoing conditions. Figure 4-5 presents the flow pattern and drawdown accompanying a ship sailing in a canal. Extensive towing tank testing in Sweden (Norrbin 1986) has resulted in the development of relationships that describe the ship power and speed loss as a function of depth of water and channel blockage. This diagram is presented in Figure 4-6. Ship propeller rpm and delivered power to drive the ship are reduced in shallow water and canal blockage. The diagram shows that for a ship in shallow water typical of many channels at depth-to-ship draft ratio of about 1.1, only 70 percent of the ship design sea speed could be sustained. A typical tanker designed to achieve 15 to 16 knots (7.7 to 8.2 m/sec (25.2 to 26.9 ft/sec)) in the open ocean would thus sail at about 11 knots (5.6 m/sec (18.5 ft/sec)) in shallow water.



$$A_S = BT$$

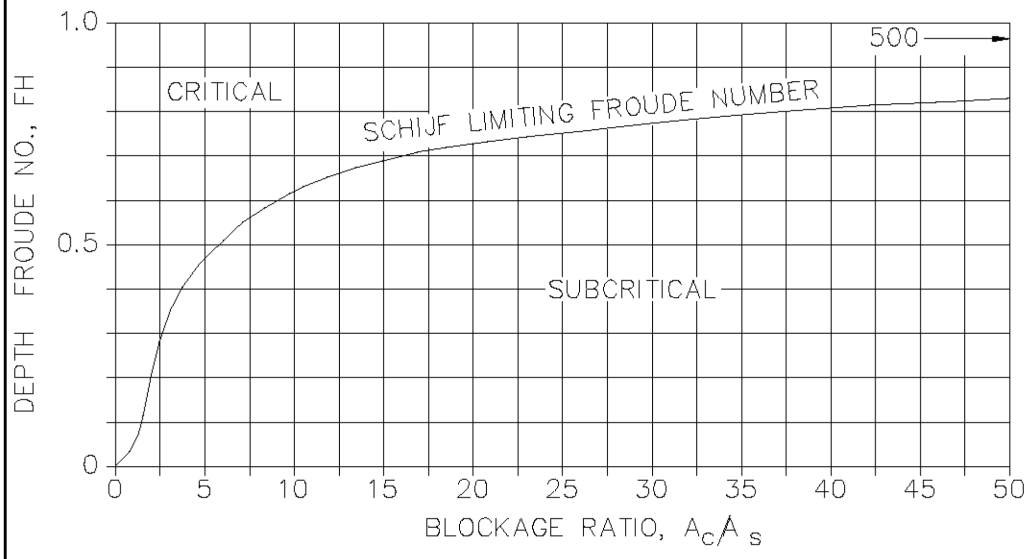
$$A_C = WH$$

$$BR = \frac{A_C}{A_S} = \frac{WH}{BT}$$

$$Fh = \frac{V}{\sqrt{gH}}$$

$$Fl = \frac{V}{\sqrt{gL_{pp}}}$$

DEFINITION SKETCH OF SHIP SAILING IN A RESTRICTED CHANNEL (RECTANGULAR CANAL)



SHIP LIMITING SPEED IN A CANAL

Figure 4-4. Ship limiting speed in a canal

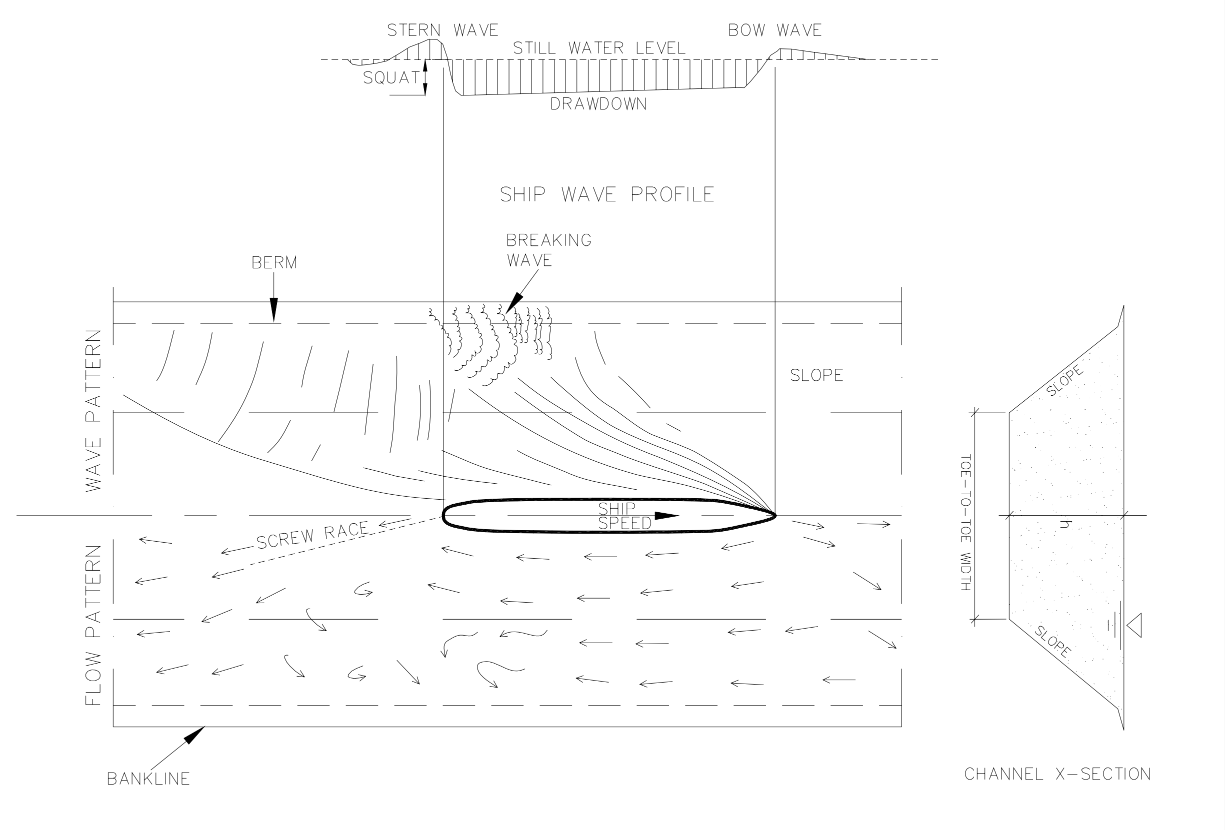


Figure 4-5. Ship wave and flow pattern in a canal

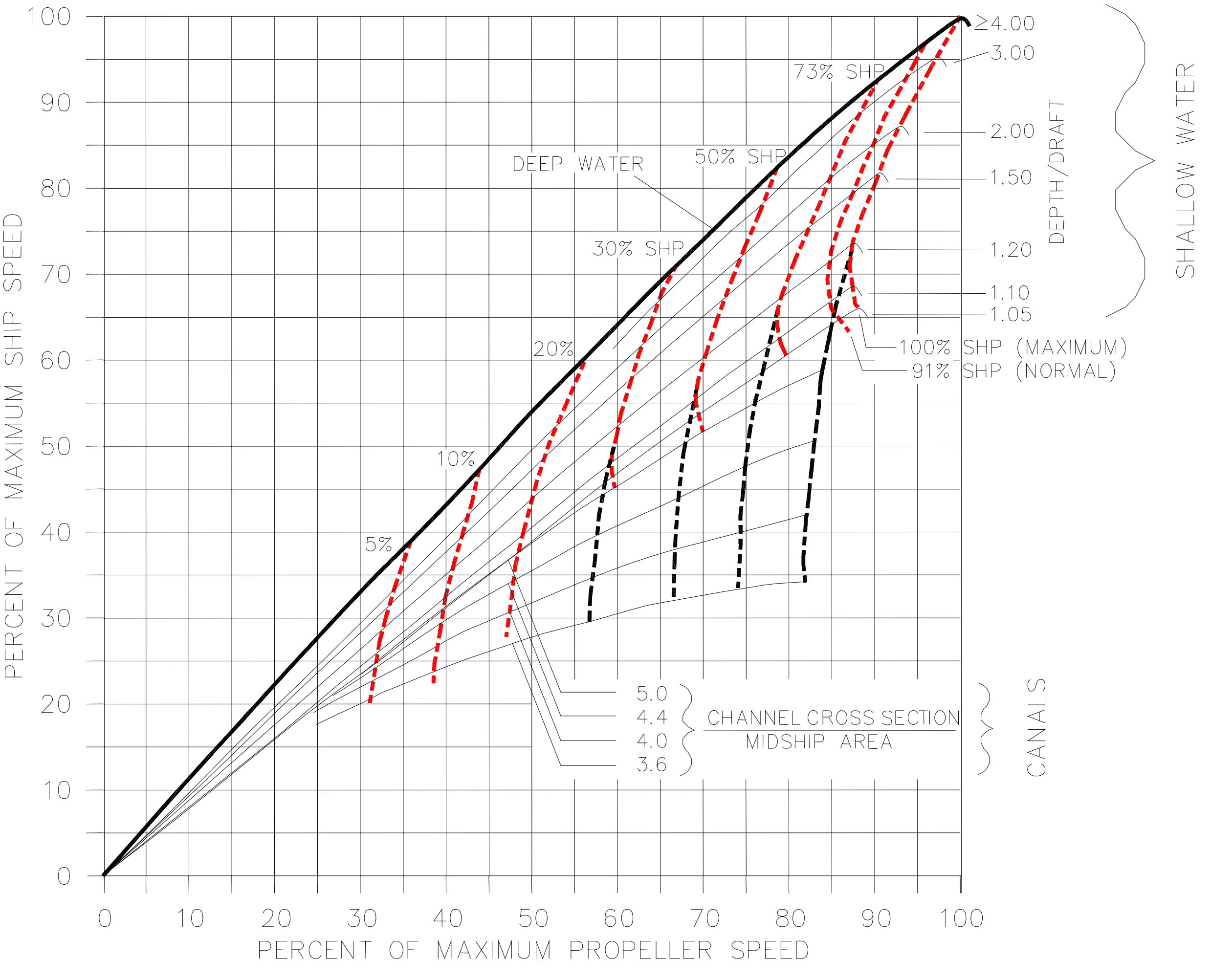


Figure 4-6. Ship speed relation in restricted waters for typical tankers

CHAPTER 5

Design Factors and Studies

5-1. Tides and Currents.

a. *Currents.* In most navigation project design studies, tidal or river currents are usually the most important environmental conditions and dominate environmental ship forces. Measurements and predictions of currents are needed to determine the effects on ship motions and controllability for analysis of project navigation. The current patterns are also used to estimate the rates of sediment erosion and deposition, to determine the extent and characteristics of salinity intrusion, and to define the possible environmental impacts, such as changes in flushing characteristics. Currents may be caused by tidal forces, tributary stream inflow, or upland river discharge. Wind stress effects on open-water bodies will also generate currents, such as in coastal regions and large lakes or bays. Project current patterns (speed and direction) should be available for a variety of discharges and/or tide ranges for typical navigation situations, including the existing and proposed project design conditions. Tidal currents in some coastal harbor channels are predicted and available from the National Oceanographic and Atmospheric Agency (NOAA). River discharge data are measured and published by the U.S. Geological Survey (USGS). These data sources can be used as starting points for initial studies but should be supplemented by field data and physical or mathematical model studies during continued design studies.

b. *Current Forces.* Current effects on ship navigation are dependent on the direction and pattern of currents with respect to the direction of the navigation channel. Currents aligned with a straight channel centerline coincident with the ship sailing direction will cause a simple addition or subtraction to the ship speed, depending on whether the current is adverse or fair. Sailing with a fair tide can make control of a ship difficult due to the reduced propeller speed and rudder forces, while the ship moves with increased ground speed. A ship sailing in a channel will require a constant yaw angle if a crosscurrent is present in the channel causing a transverse ship force. Strong current forces can adversely affect navigation while the ship is maneuvering through the harbor channels and turning basins, especially when ships are being decelerated before turning around or berthing. The project planner/designer must consider current forces and their navigational impact on the channel and turning basin dimensions. Crosscurrents and spatially nonuniform flow are particularly hazardous to ships where the bow and stern are affected by different magnitudes and/or direction of currents, thus inducing a turning moment about the ship. Locally increased channel width may be required where currents are strong to compensate for the increased difficulty. Current effects on ship navigation are also important in channel turns, even when currents are aligned with the channel, due to the change in ship attitude with respect to the current direction.

c. *Current Modeling.* In most cases, navigation project design studies will require the development of a mathematical current model for use in predicting tidal or river currents with various project flow conditions. Early in the project formulation phase during the initial study, such an investigation should be planned by the navigation project study manager. For ship simulator studies, current patterns along and across the navigation channel are required. A two-dimensional (2-D) finite element model that gives depth-averaged current calculations has been most advantageous. The same hydrodynamic model can often be used to drive salinity, water quality, and sedimentation studies if the project study requires these considerations. Examples of applications of this model and additional guidance are available in EM 1110-2-1607 and Thomas and McAnally (1985).

d. *Water Levels.* Both maximum and minimum water surface level frequencies and durations as well as amplitudes of water level fluctuations are needed for design. Water levels can be affected by ocean tides, storm surges, harbor seiches, lake fluctuations, and river discharges. High-water levels are used to determine wave penetration and height of jetties, training structures, and overhead obstructions. Low-water levels are used to determine available and needed depths for various size ships and other vessels.

e. *Tide Predictions.* NOAA calculates and publishes tide height predictions and tide ranges for all major coastal ports and harbors in the United States. Published tide predictions are suitable for initial studies; other sources of published data should be inventoried and used in design where suitable and available. Tide level and current modeling for existing and proposed navigation project conditions is usually required at later design stages.

f. *Tidal Datums.* Channel depths for navigation projects are usually authorized and referred to some long-term average low-water datum plane based on measured field water level data. These measurements are usually conducted by NOAA and are used in their chart and tidal prediction tables and in establishing appropriate tidal datums. All project design features should be developed in a consistent manner, using the appropriate low-water datum plane. It is especially important to reconcile different datums presented in a variety of maps, charts, hydrographic data, etc., which can lead to confusion and possible mistakes. The relationship of the low-water datum to the National Geodetic Vertical Datum (NGVD) will also be needed for vertical control of design and construction. The low-water datum for the Atlantic and Gulf Coasts is being converted to mean lower low water (mllw) to be consistent with the Pacific Coast. The appropriate low-water datums for various localities are listed:

(1) Tidal ocean coastlines: mllw.

(2) Great Lakes: International Great Lakes Datum (IGLD).

(3) Nontidal rivers: Mean 15-day lowest navigation season water level referred to as the Low-Water Datum Plane.

5-2. Wind and Waves.

a. *Effects on Ships.* Wind effects on a project include the direct forces on ships sailing through the navigation channels and the indirect development of wind waves in the harbor or coastal ocean region. Waves generated in the harbor or bay area are usually small in height and normally have minor effects on typical design ships. However, wind waves generated by local storms near the port entrance channel (seas) may have an impact on ships. Estimates of wind are needed for project design, mainly because of the effect on ship motions and controllability. Historical wind data are usually available from the National Weather Service. Local topography may modify the wind data, usually available only at the local airport, and change the wind patterns at the navigation channel. Wind studies should include prevailing wind directions and speed, both averages and variability. Seasonal variations of the mean and extreme wind conditions with appropriate statistics (return period, frequency of occurrence, duration, etc.) are to be included in the wind study.

b. *Wind Forces.* Direct forces on ships from the wind are of primary importance for certain types of ships, especially when ship speeds are restricted or are reduced during normal operations. The forces are in direct proportion to the ship area exposed above water (projecting areas, also called the wind or sail area), which varies due to superstructure design and ship loading condition. The following situations are especially important and require careful consideration:

(1) Tankers in ballast (light ship) condition.

(2) Bulk carriers in ballast (light ship) condition.

(3) Automobile or car carriers.

(4) Containerships with containers on deck.

(5) Ferry boats.

(6) LNG and liquified petroleum gas (LPG) ships.

5-3. Sedimentation. The following aspects of sedimentation must be considered for deep-draft navigation projects: characteristics of the native soils or materials to be removed within the project channel; characteristics of sediments introduced into the upper reaches of the navigation project by riverine or other upland discharges; characteristics of sediments introduced into the lower reaches of the project by littoral processes, including wave action, resulting in beach erosion, and salinity intrusion; hydrodynamic and water chemistry conditions in the project region; and limitations or restrictions on dredging ,dredged material disposal techniques and beach erosion control using sand bypassing methods. More detailed discussion on beach erosion and sand bypassing is available in EM's 1110-2-1502, 1110-2-1616, and 1110-2-2904.

a. *Native soils.* Native soils must be considered first from the standpoint of channel construction. Problem soils encountered in channel construction may consist of consolidated clays, cemented sands, or outcroppings of bedrock. These materials may require special dredging equipment, techniques, and disposal and will thus have an impact on construction costs. Channel location and alignment may be determined by the existence of hard-to-remove materials along alternate channel routes. Native soils must also be considered from the standpoint of maintenance dredging following project construction. The existence of fine sands, silts, or easily erodible clays along the route of the project may indicate large dredging requirements to maintain the project channel in future years. For example, wind or ship waves in shallow areas adjacent to the navigation channel may resuspend significant quantities of unconsolidated fine sediments that might eventually be transported toward and deposited in the navigation channel. Surficial sediment sampling should be conducted throughout the project area, and core borings and/or subsurface acoustic measurements should be made along the most attractive channel routes to fully assess the composition and characteristics of native soils or the presence of rock. Methods will be discussed later to predict the fate of sediment particles located near the navigation channel.

b. *Riverine sediments*. Sediments transported to the project by riverine flows in estuaries or embayments usually consist of coarse to medium sands carried primarily as bed load, medium to fine sands carried as bed and/or suspended load, and silts and clays carried as suspended load. When the project channel includes the zone where rivers enter embayments, the coarse and medium sands and even some of the fine sands and silts may deposit as flow velocities are reduced below that necessary to maintain motion of the sediment particles. These deposits of sand and silt are often in the form of delta-shaped shoals that recur annually and require maintenance dredging for control. The finer sands and silts will usually be deposited in the lower reaches of the navigation project, but the deposition will usually be distributed over a fairly long reach of the channel. High stage-discharge events may alter the pattern of deposition from time to time and distribute the coarser particles over a longer reach of the channel than usual. Deposition of clay particles is dependent on the hydrodynamics and water characteristics of the lower reaches of the navigation project. If the project is in an estuarine setting where salty water from the ocean can mix with the sediment-carrying riverine waters, such as Savannah Harbor for example, a phenomenon known as flocculation occurs, whereby the clay particles aggregate into larger and heavier flocs that are likely to deposit. In some instances, very heavy concentrations of the flocs remain in suspension in a layer near the bottom, referred to as fluff or fluid mud. Prior to permanent deposition of clay sediments, which is a time-dependent process, the tidal hydrodynamics of an estuarine system tend to concentrate the location of the flocs. If the estuarine system is of the stratified type, i.e., there is a well-defined saltwater layer underlying the freshwater layer, the bulk of the clay-particle shoals will be concentrated in a zone mapping the upstream intrusion of the saltwater layer. If the saltwater-freshwater interface is less well defined, the clay-particle shoals will be distributed more widely through the middle and lower reaches of the project. In nonsaltwater settings, such as the Great Lakes, the clay particles may remain in suspension and be introduced into the lake region as suspended load. Maintenance dredging is almost always required to maintain channel depths and widths through the areas of clay particle deposition. Methods for predicting the locations and magnitudes of the sand- and clay-particle deposits in the navigation project will be discussed later.

c. *River reaches*. In cases where the deep-draft project extends well upriver (above the zone of flow reversal), such as the Columbia River or the lower Mississippi River, deposition of medium to coarse sands occurs in the river crossings, with most of the fine sand and silt moved downstream to estuarine or coastal zones. Not all river crossings along a navigation project require maintenance dredging. In many cases, the minimum crossing depth that occurs naturally over a water year is greater than the project depth. For example, of the several river crossings that exist on the lower Mississippi River from Baton Rouge, LA, downstream to the Head of Passes, a distance of about 225 river miles, only about 7 of the 225 miles require annual maintenance dredging. Of course, if the project were deepened, the number of crossings requiring maintenance dredging would most likely increase.

d. *Littoral sediments*. Sediments are introduced into the navigation project from the littoral systems that exist in all lakes and oceans. Nearshore currents driven by waves, wind, tides, or water-mass movement cause sediment particles, usually medium to fine sands but occasionally clays and silts, to be moved along the shore. As the sand-size sediments reach the deeper waters of the navigation project, deposition occurs in and near the entrance channel. Clays entering from the lower end may be transported upstream by estuarine circulation. Structures such as jetties are used to trap the sands and keep shoals from forming in the navigation project. A sand-bypassing arrangement may be necessary to maintain the trapping capability of the jetty structures and to minimize damage to adjacent beaches that interruption of the littoral process usually causes. The planner/designer is required to study and develop predictions of erosion and accretion for a distance of 10 miles on either side of an entrance channel improvement project.

e. *Predictive techniques*. Four basic approaches are available to study sedimentation processes in deep-draft navigation channel projects: field studies, physical hydraulic model studies, numerical model studies, and combinations of these study techniques. Field studies include collection of prototype data in such a manner that future behavior can be extrapolated or developed into general design principles, and also trial-and-error remedial measures in which proposed remedial schemes are constructed without the benefit of corroborating studies. The collection of prototype data is always recommended for deep-draft navigation projects; trial-and-error remedial schemes must be highly justified prior to installation because of the high risk of failure involved. Physical models have been used for many years to study sedimentation problems associated with deep-draft navigation projects, but it is not possible to accurately predict deposition volumes. Numerical modeling of sedimentation phenomena is becoming a relatively well-developed technique that employs special computational methods such as finite difference or finite element approximations to solve mathematical expressions that do not have closed-form solutions. In some situations, numerical models can provide a reasonable prediction of deposition volumes. Physical and numerical models are discussed in more detail in EM 1110-2-1607. It should be stressed that both physical and numerical models rely heavily on prototype observations; therefore, if model studies are anticipated, the lead time and resources must be provided to collect the quality and quantity of data necessary to support these studies. In some cases, combinations of the various techniques may be used that involve the application of physical and numerical models as well as prototype data and analytical procedures to take advantage of the strong points of each technique.

f. *Channel shoaling*. Sediment budget and shoaling studies are needed for before- and after-construction conditions. These studies provide the basis for estimating maintenance dredging requirements, disposal area locations, training structures, and entrance sand-bypass assessment. Shoaling rates are needed for river expansions caused by port facilities and turning basins. Information on sediment budget is contained in the *Shore Protection Manual* (1984).

g. *Beach erosion*. Many navigation channels connect the ocean to an estuary or bay through sandy beaches. When jetties are built to prevent littoral drift from entering the channel, the volume of sand reaching the downdrift beach is reduced. This reduced littoral drift usually results in erosion of the downdrift beach. If the erosion is unacceptable from an economic or environmental standpoint, mitigation measures will be required. Traditional methods of erosion control are shoreline protection with revetments, breakwaters, groins, and nourishment by bypassing sand from one side of the inlet to the other. Some bypassing methods involve the use of weirs with sand traps, detached breakwaters, and various methods of dredging and sand pumping, including jet pumps.

h. *Bank protection.* To reduce bank erosion, bank protection is sometimes provided. Guidance on the design of riprap protection on navigable waterways is provided by Maynord (1984). A computer program, NAVEFF, is available to assist in determining the drawdown and return flow velocities generated by a ship moving through a restricted waterway (Maynord 1996, 1999). Information on the design of flexible revetments is also available, (Permanent International Association of Navigation Compresses (PIANC) 1987). This reference also provides guidance on the computation of ship wake waves. Use of reinforced vegetative bank protection using geotextiles may also be useful (PIANC 1996).

5-4. Water Quality Impacts.

a. *Physical Changes.* The development of a navigation channel that is larger than previously existed in an estuary or bay could cause physical, biological, and water quality changes affecting the ecosystem. The following physical changes require evaluation:

(1) Salinity.

(2) Tide heights (water levels).

(3) Current velocities and duration.

(4) Water circulation pattern.

(5) Shoaling and erosion in the vicinity of the channel.

(6) Possible effects on adjacent shoreline resulting from changes in wave patterns.

(7) Tidal flushing rate.

(8) Pollution dispersion rate.

These changes could be negligible when the channel improvement is small compared with the natural ecosystem cross-sectional area. When the physical changes are estimated, a biological assessment of project effects on estuary aquatic life is needed to determine if design changes and mitigation measures are justified. Numerical models are presently the most reliable method of predicting post project conditions and determining the most effective remedial measures that might be required.

b. *Ecological Considerations.* An interdependence exists between the physical, chemical, and biological components of a system. Modification or manipulation of any component will have some effect on the others. Tides, currents, and salinity characteristics determine tidal circulation patterns and thus have a profound influence on the movement and distribution of aquatic plants and animals. The means and extremes of salinity and temperature influence the types and distribution of aquatic life. The effects of navigation projects, including the dredging operations and disposal facilities, upon the environment or ecological relationships are the results of both the direct physical alterations associated with construction activities and the physical or chemical changes that develop after construction. These activities influence water movement, water quality, sediment movement and quality, substrate physical and chemical properties, etc. and will always cause some environmental change in the project area. The effect need not be adverse, and engineering modifications in a tidal ecosystem may be used to enhance ecological conditions by remedying adverse conditions in an estuary caused by previous impacts from urbanization and industrialization. Engineering modifications can also be used to stabilize large variations in natural conditions thereby increasing biological diversity or improving conditions for an individual or group of species. Some of these modifications may provide desirable habitat where that habitat is not presently available.

5-5. Local Coordination.

a. Pilot Interviews. Navigation project planners/designers should develop strong coordination with the local pilot groups throughout the project development. Pilot interviews can be used to determine the user's opinion on existing channel navigation safety and wind and wave conditions to be used for design analysis, and the feasibility and safety of proposed channel design alternatives.

b. U.S. Coast Guard. The local U.S. Coast Guard (USCG) office should also be contacted early in the project development to solicit views and coordination on channel dimensions and alignment relative to safe navigation. The USCG can also provide guidance on aid to navigation placement and waterway analysis study results.

5-6. Accident Records. Accident Records. Marine accident records are available from the U.S. Coast Guard annual compilation of casualty statistics in an automated system called Coast Guard Automated Main Casualty Data Base (CASMAIN). Accident data on existing navigation channel projects proposed for enlargement or improvement should be studied to determine the number, cause, and location for analysis. In some accidents, the Coast Guard will conduct an inquiry, which may also be valuable in determining navigation problems. The National Transportation Safety Board also reviews specific accidents and develops reports and recommendations on site-specific safety issues. Information from the local pilots and, at some ports, data from vessel traffic services (VTS), if available, can provide valuable information in designing proposed channel improvements. The local Coast Guard District Office and Captain of the Port should be consulted for any available data and investigation summaries.

CHAPTER 6

Channel Depth

6-1. Depth Design. The depth of the project design channel should be adequate to safely accommodate ships with the deepest drafts expected to use the waterway and call at the project port on a frequent and continuing basis. Normally, the project depth is based on the development of one or more design ships with an appropriately loaded or ballasted draft. Selection of the design ship and project design depth is determined jointly by an economic analysis of the expected project benefits compared with project costs. Once the design ship and channel depth are determined, the safety and adequacy of the channel depth for operational design ship transits will be determined using the analysis presented later in this chapter. The channel depth economic analysis is described in ER 1105-2-100. Paragraph 6-2 summarizes the procedure with an emphasis on applications to deep-draft navigation channels.

The design depth of the channel need not be constant throughout the project but may vary as necessary so that the design ship will be able to make a safe, efficient, and cost-effective transit of the channel under normal operational conditions. Upon project authorization, the design depths are considered, nominally, to be the authorized depths. This should not preclude minor adjustments in depth during continued design, construction, and operation as circumstances warrant and delegated authorities permit.

6-2. Economic Analysis.

a. *Optimization.* The optimum design of a deep-draft navigation project requires studies of estimated costs and benefits of various plans and alternative designs considering safety, efficiency, and environmental impacts. These studies are used to determine the most economical and functional channel alignment and design depth considering costs for various alternative designs. Generally, several alternative channel depth design levels are developed, since depth is often one of the major cost-determining parameters. The adaptability of each design to future improvements for increased navigational capability should also be considered. Economic optimization analysis should consider various elements involved in development and maintenance of the project, including dredging, disposal, and structures such as jetties, breakwaters, and aids to navigation. The optimum economic channel is selected from a comparison of annual benefits and annual costs for each channel plan.

b. *Project Cost.* The economic optimization of a channel requires selection of several design alignments and dimensions (width and depth) that are acceptable for safe and efficient navigation. Costs are developed for the alternative plan alignments and dimensions. These should include:

(1) Initial construction including fixed facilities cost.

(2) Replacement cost.

(3) Operation and maintenance cost.

c. *Project Benefits.* Benefits are determined by transportation savings considering ship trip time and cargo capacity and delays for tides, weather conditions, and transit interference from reduced depths in channels that have rapid shoaling tendencies. Deeper channels will permit the use of larger ships, which are more economical to operate. Some ships could use the channel with a deeper draft and greater cargo loading and may eliminate or reduce the need for offloading (lighterage) some of the cargo before proceeding to the port. Benefits are evaluated by determining the transportation costs per ton of commodity for each increment of channel depth. This evaluation has to consider the trends in shipbuilding to determine the most likely future ship sizes and an estimate of the future ship fleet that will be using the channel. Transportation costs are based on ship annual operating cost for each type of ship, including fixed cost and annual operating expenses. The HQUSACE Water Resources Support Center periodically releases ship operating cost data for evaluating deep-draft channel and harbor improvement projects.

d. *Evaluation Procedure.* The basic economic benefits from navigation projects are the reduction of costs required to transport commodities and the increase in the value of output for goods and services. Benefits are usually derived based on costs reduced or not incurred with the proposed project improvements. Project benefits may also be "lost opportunity" costs because of unimproved or undeveloped navigation channels. Specific transportation savings may result from the following:

(1) More efficient use of larger ships.

(2) More efficient use of present ships.

(3) Reductions in transit or delay times.

(4) Reduction of cargo handling costs.

(5) Reduction of tug assistance costs.

(6) Reduction of insurance, interest, and storage costs.

(7) Use of water rather than land transport mode.

(8) Reduction of accident rate and cost of damage.

The evaluation procedure to estimate navigation benefits includes nine individual steps shown on the flowchart (Figure 6-1). The key step in the procedure is the accurate projection of commodity movements over the proposed alternative project designs, steps 3 and 7. Details of the procedure are given in ER 1105-2-100.

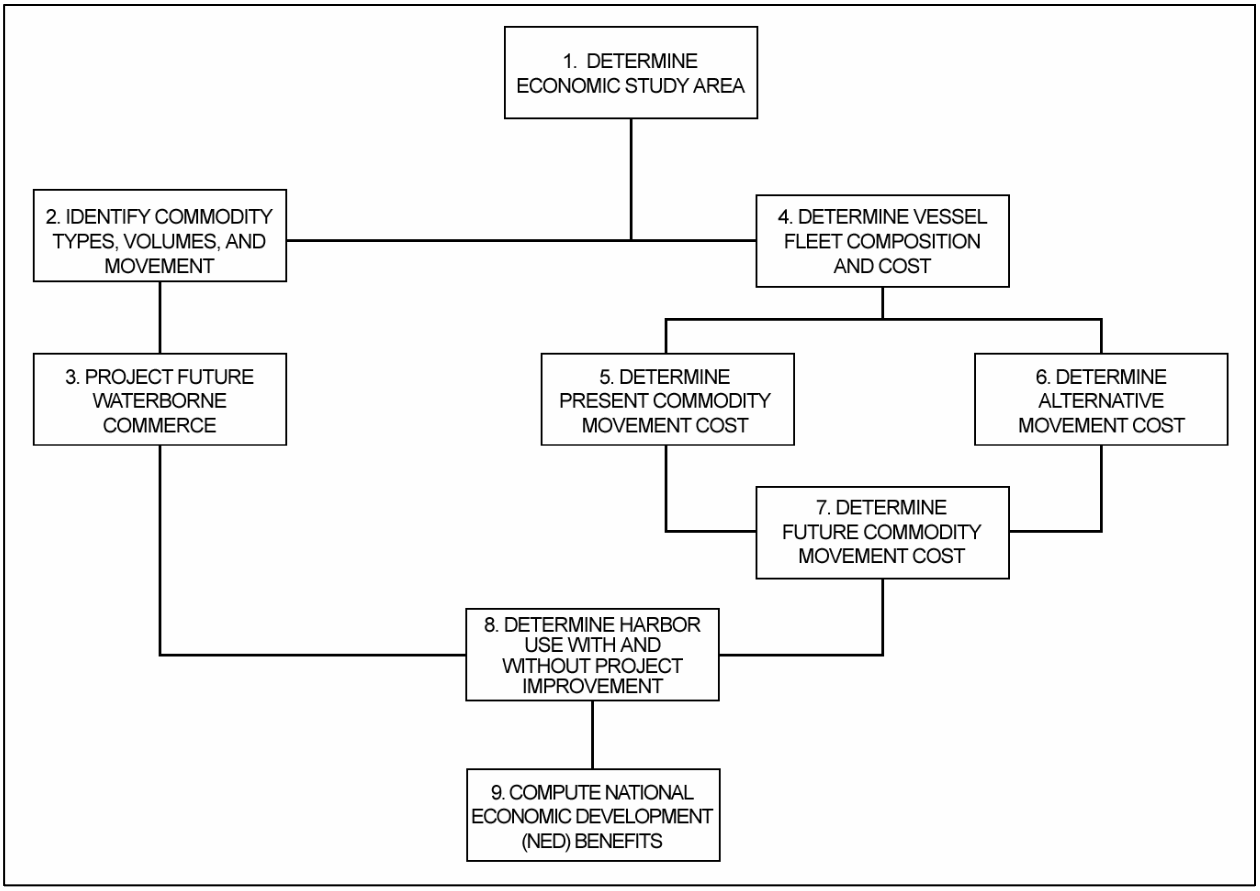


Figure 6-1. Navigation benefit evaluation procedure

6-3. Ship Squat

a. *Introduction.* A ship in motion will be lowered (ship sinkage) vertically below the still water surface because of the increased velocity past the ship causing the pressure on the ship hull to be decreased. This phenomenon occurs in deep, open-water situations, such as out at sea as well as in shallow water. However, the effect is greatly increased in shallow, restricted water, such as a canal- or trench-type open navigation channel. The running trim of a ship is also modified by the pressure on the ship hull: blunt-bowed ships tend to be lowered by the bow (i.e., at the bow), while fine-lined ships are trimmed by the stern. Ship squat is a well-known phenomenon by seamen, and efforts to estimate the effect have been used by pilots for many years. However, many of these techniques are often based on crude approximations or are site-specific, and usually couched in general rules for use by pilots. The following presents a general calculation procedure for use in channel design in shallow water, in canals, and in trench channels with channel banks.

b. *Shallow-Water Squat.* Total ship vertical response in shallow water from speed ahead in a laterally unrestricted waterway was derived by Tuck and Taylor (1970) using ship slender body theory and put into practical use by Huuska (1976). The ship sinkage and running trim equations are given by the following:

$$\frac{z}{L} = C_Z \frac{F_h^2}{\sqrt{1-F_h^2}} \frac{\nabla}{L^3} \tag{6-1}$$

$$\Theta = C_\Theta \frac{F_h^2}{\sqrt{1-F_h^2}} \frac{\nabla}{L^3} \tag{6-2}$$

where

z = sinkage or vertical drop of ship center of gravity in meters (feet)

L = ship length in meters (feet)

C_z = sinkage coefficient characteristic of hull form .1.5

Λ = volume displacement of the ship in cubic meters (cubic feet) (Figure 3-3)

Θ = trim angle of ship in radians, positive is bow up

C_Θ = trim coefficient characteristic of hull form .1.0

F_h = channel depth Froude number (Equation 4-2)

Typical values of the two coefficients, which have been determined by experiments and calculations, are 1.5 and 1.0. For channel design purposes, the maximum vertical ship motion below the vessel's static position may be found from the combination of Equations 6-1 and 6-2 to give the ship squat as follows (Norrbin 1986, Rekonen 1980):

$$\frac{z_{\max}}{T} = 2.4 \frac{C_B}{L/B} \frac{F_h^2}{\sqrt{1-F_h^2}} \tag{6-3}$$

where

$z_{\max}$ = ship squat (sinkage and trim) at bow or stern in meters (feet)

T = ship full load molded draft in meters (feet)

$C_B = \dfrac{\nabla}{LBT}$

B = ship molded beam at the maximum section area in meters (feet)

c. *Simplified Equation.* The combined ship vertical movement resulting from sinkage and trim (the squat) may be calculated by the following simple relation presented by Norrbin (1986), to be used when Froude numbers are less than 0.4:

$$z_{\max} = \frac{C_B B T V^2}{15 L h}$$

where $z_{\max}$ is in meters and V is in knots. Adjusting this relation for $z_{\max}$ in meters (feet) yields

$$z_{\max} = \frac{C_B B T V^2}{4.573 L h} \tag{6-4}$$

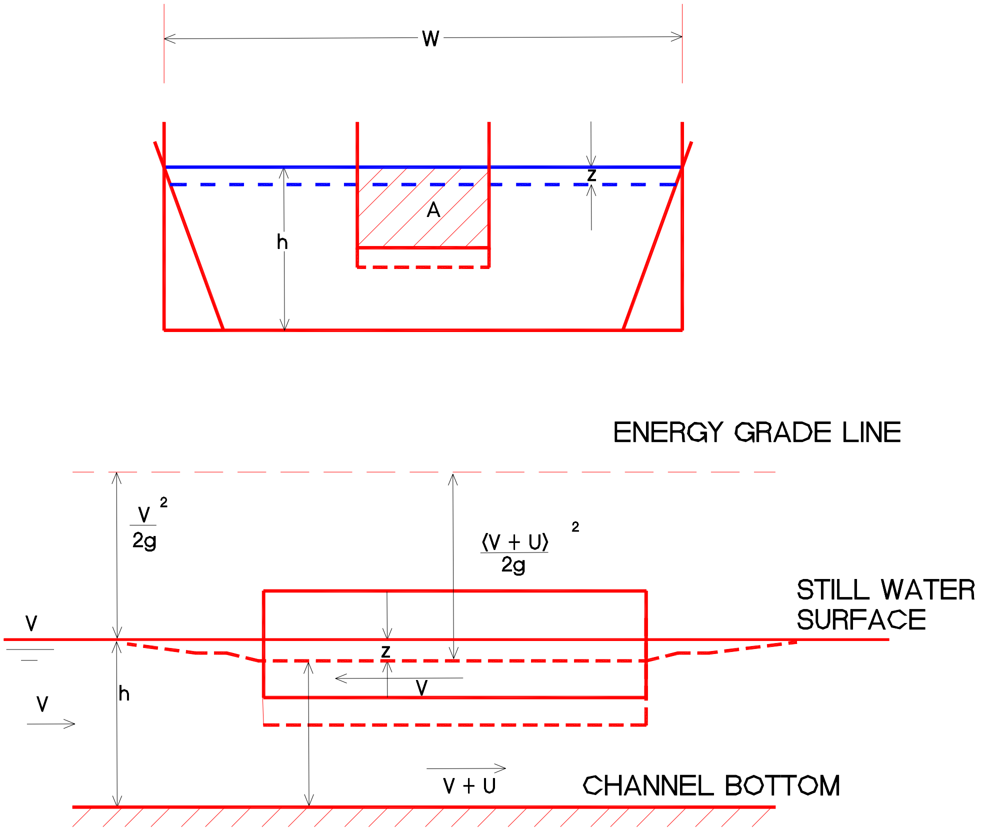
This equation shows that the amount of squat depends on several factors, including the square of the ship speed, depth of the channel, and geometric characteristics of the ship.

d. *Example.* As an example application, for tankers the following values are typical: $C_B = 0.85$, and $L/B = 6.5$. A channel depth-to-ship draft ratio (h/T) of 1.1 is also typical for harbor channels. With these values, the following equation is thus obtained:

$$z_{\max} = 0.026 V^2 \tag{6-5}$$

For a ship speed of 5 knots (2.6 m/sec (8.4 ft/sec)), this gives $z_{\max} = 0.2$ m (0.63 ft); and for a ship speed of 10 knots (5.1 m/sec (16.8 ft/sec)), $z_{\max} = 0.8$ m (2.6 ft). These results suggest that an increase in channel depth of about 0.3 m (1 ft) may be needed for ship maneuvering in wide channels with deep overbank areas where ship speeds are 6 knots or less. For harbor fairway or entrance channels without channel banks, where ship speeds are typically high, i.e., near 10 knots, channel underkeel clearance of 0.8 m (2.6 ft) or more would normally be required.

e. *Restricted Channel Squat.* A ship sailing in a canal or trench navigation channel will cause the water surface elevation to be lowered because of the increased velocity past the ship due to the Bernoulli effect. A one-dimensional (1-D) approximation (sometimes called the canal theory), which has been reviewed in many publications (Blaauw and van der Knaap 1983), can be used to develop graphical or computer-based computational methods to calculate the resulting water level depression or drawdown. The lowering of the water level is equal to the mean ship sinkage and therefore the squat. Ship squat in a restricted channel depends especially on the ship speed, varying as the square of the speed. Other factors are also important, including the channel cross-sectional characteristics and the ship geometry. The simple canal theory used to calculate squat depends on certain flow assumptions as presented in Figure 6-2. The assumption of a rectangular channel cross section is especially limiting since real channels are generally trapezoidal and often become irregularly shaped over time. Many channels are of the trench type with overbank depths on each side of the channel, which further complicate the computations and would tend to reduce the squat. Nevertheless, this simple model provides useful design guidance showing the main parameters and their functional relationships. An outlined derivation of the numerical method is shown in Figure 6-3. The reader should refer to Figure 6-2 for explanation of parameters in the derivation.



DEFINITION SKETCH

ASSUMPTIONS

- STEADY (NO ACCELERATION)
- INFINITE LONG CHANNEL
- NO RESISTANCE
- RECTANGULAR SHIP X-SECTION
- RECTANGULAR CHANNEL X-SECTION
- RETURN FLOW UNIFORM OVER CHANNEL
- WATER LEVEL DRAWDOWN UNIFORM OVER CHANNEL WIDTH

DEFINITIONS

Z = SQUAT
V = SHIP SPEED
U = RETURN WATER SPEED UNDERNEATH VESSEL (RETURN VELOCITY)

Figure 6-2. Squat analysis definition

f. Limiting Conditions. An important parameter for characterizing the ship's interaction with the water flow generated by the ship in the navigation channel is the ship speed. In particular, as previously discussed in Chapter 4, the ship speed in a given channel is limited by a parameter called the Schijf limiting speed. Self-propelled ships cannot exceed this limit; indeed, for economic reasons, maximum ship speeds are well below this speed (about 80 percent). The value of the Schijf limiting Froude number can be calculated using the following explicit formula (Huval 1980b, Balanin et al. 1977, Zernov 1970):

Bernoulli=s: $h+\frac{V^2}{2g}=h-z+\frac{\left(V+U\right)^2}{2g}$ (1)

Continuity: $WhV=\left(Wh-A_S-Wz\right)\left(V+U\right)$ (2)

Simplify Equation (1): $\frac{V^2}{2g}=\frac{\left(V+U\right)^2}{2g}-z$ (3)

Multiply by 2 and divide by h:

$$\frac{V^2}{gh}=\frac{\left(V+U\right)^2}{gh}-2\frac{z}{h} \tag{4}$$

Rearrange Equation (2):

$$V+U=\frac{V}{\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)} \tag{5}$$

Substitute Eqn (5) into (4), and calling $\frac{V^2}{gh}=F_h^2$:

$$F_h^2=\frac{F_h^2}{\left(1-\frac{A_S}{Wh}-\frac{Z}{h}\right)^2}-2\frac{z}{h} \tag{6}$$

Divide by F_h^2 and rearrange:

$$\frac{2z}{F_h^2 h}=\frac{1}{\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}-1 \tag{7}$$

Simplify:

$$F_h=\sqrt{\frac{2\frac{z}{h}\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}{1-\left(1-\frac{A_S}{Wh}-\frac{z}{h}\right)^2}} \tag{8}$$

Figure 6-3. Squat analysis definition

$$F_{hL}=\sqrt{8\cos^3\left(\frac{\pi}{3}+\frac{\arccos}{3}\left(1-\frac{1}{B_R}\right)\right)}$$

Furthermore, (6-6)

$$F_{hL}=\frac{V_L}{\sqrt{gh}}$$

where

F_{hL} = depth Froude number at limiting ship speed

V_L = Schijf limiting ship speed

B_R = blockage ratio (cross-sectional area of the channel divided by the cross-sectional area of the ship)

The ship limiting speed can readily be obtained from the Froude number for a given channel water depth.

g. *Limiting Squat.* It is also possible to relate the maximum ship squat at the Schijf limiting Froude number by the equation

$$z_L = \frac{F_{hL}^2}{2}\left(F_{hL}^{1/3} - 1\right)h \qquad (6\text{-}7)$$

In a similar fashion, the return velocity Froude number is

$$\frac{U_L}{\sqrt{gh}} = F_{hL}^{1/3} - F_{hL} \qquad (6\text{-}8)$$

where

U_L =limiting return velocity

z_L =squat at limiting ship speed.

h. *Computer Model.* The solution to the general equations for squat and return velocity may be obtained by an approximation method involving iteration which can be programmed on a calculator or computer (Huval 1993). An approximate analysis for nonrectangular channel cross sections can be made by replacing the channel depth h by the cross-sectioned mean depth, which is equal to the channel area divided by the top width, $d = A_c / W$. A more complete analysis for trapezoidal channels has also been presented.

i. *Computational Procedure.* Most navigation channels are dredged over a wide waterway with variable overbank depths on each side of the channel, called trench channels. Figure 6-4 gives example navigation channel cross sections. A first approximation to the ship squat for trench channels may be made bycalculating the weighted average (based on overbank depth) of squat in shallow water and in canal-type channel without the overbanks. This type of trench channel has been tested for ship squat by Guliev (1971) and has been implemented in a calculation procedure developed by Huuska (1976) and adopted for this manual. This more complete squat calculation model applicable for shallow water, canals, and trench-type channels has been developed as a software program on a computer and is available from Huval (1993). The results of computations using this model are presented in Figure 6-5.

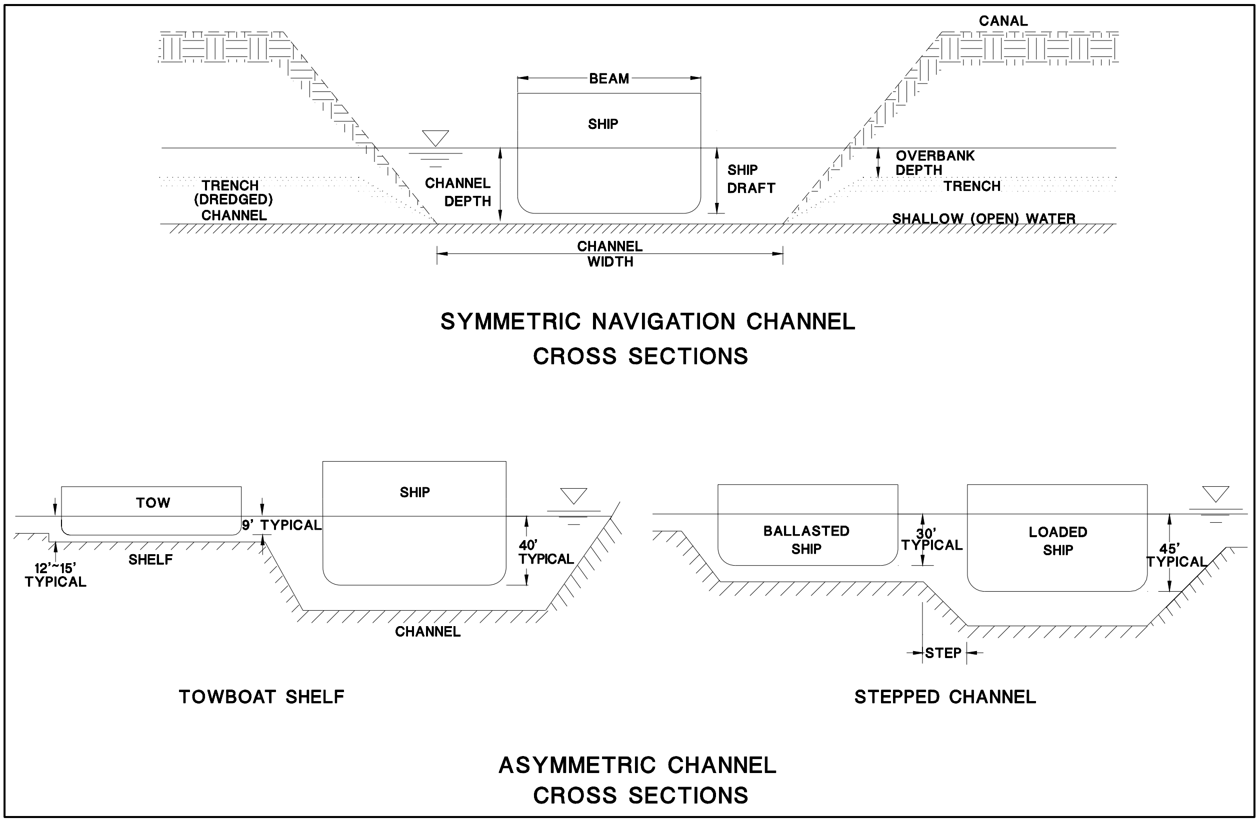


Figure 6-4. Channel cross sections

6-4. Ship Motion in Waves.

a. Ship Response. Ship response from waves is a factor that must be considered in the design of navigation channel depths and widths. The movement of the ship bottom below the static water surface caused by waves will affect the design of channel depth. Usually, wave effects are more pronounced and important in the design of the entrance channel or harbor fairway, which is open to ocean waves leading from the ocean into a bay or river with a port. Wave effects on commercial ships transiting entrance channels tend to increase as the wave heights increase and decrease with longer ship lengths. Maximum ship response occurs with wavelengths equal to or nearly equal to the ship length. Normal commercial deep-draft design ships will respond very weakly to wave periods less than 6 sec, mainly a result of the fact that natural ship periods are much greater.

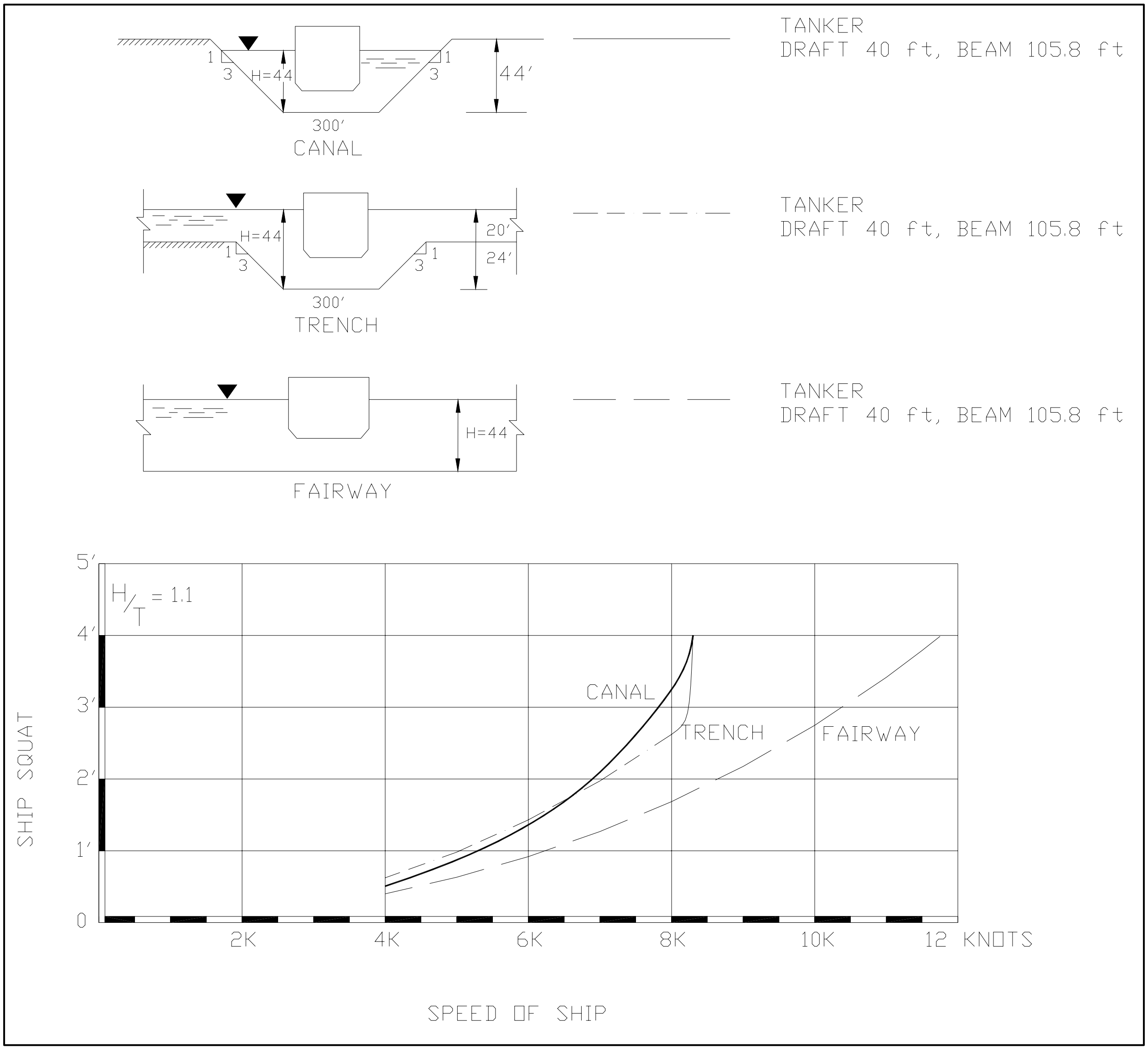


Figure 6-5. Example squat calculations

b. Roll, Pitch, and Heave. Ships will respond to waves by the vertical motions of roll, pitch, and heave from local seas and swell in harbor entrance channels. Figure 6-6 presents a definition sketch of the six possible modes of ship response to wave action. The vertical ship motion should be used in setting the vertical depth in the entrance channel above the depth in the interior harbor channels. The magnitude of the vertical motion of a ship transiting a harbor fairway is a function of many factors, some of which include:

(1) Sea or swell conditions.

(2) Wave height, period, and duration.

(3) Direction and celerity of wave propagation.

(4) Ship transit direction.

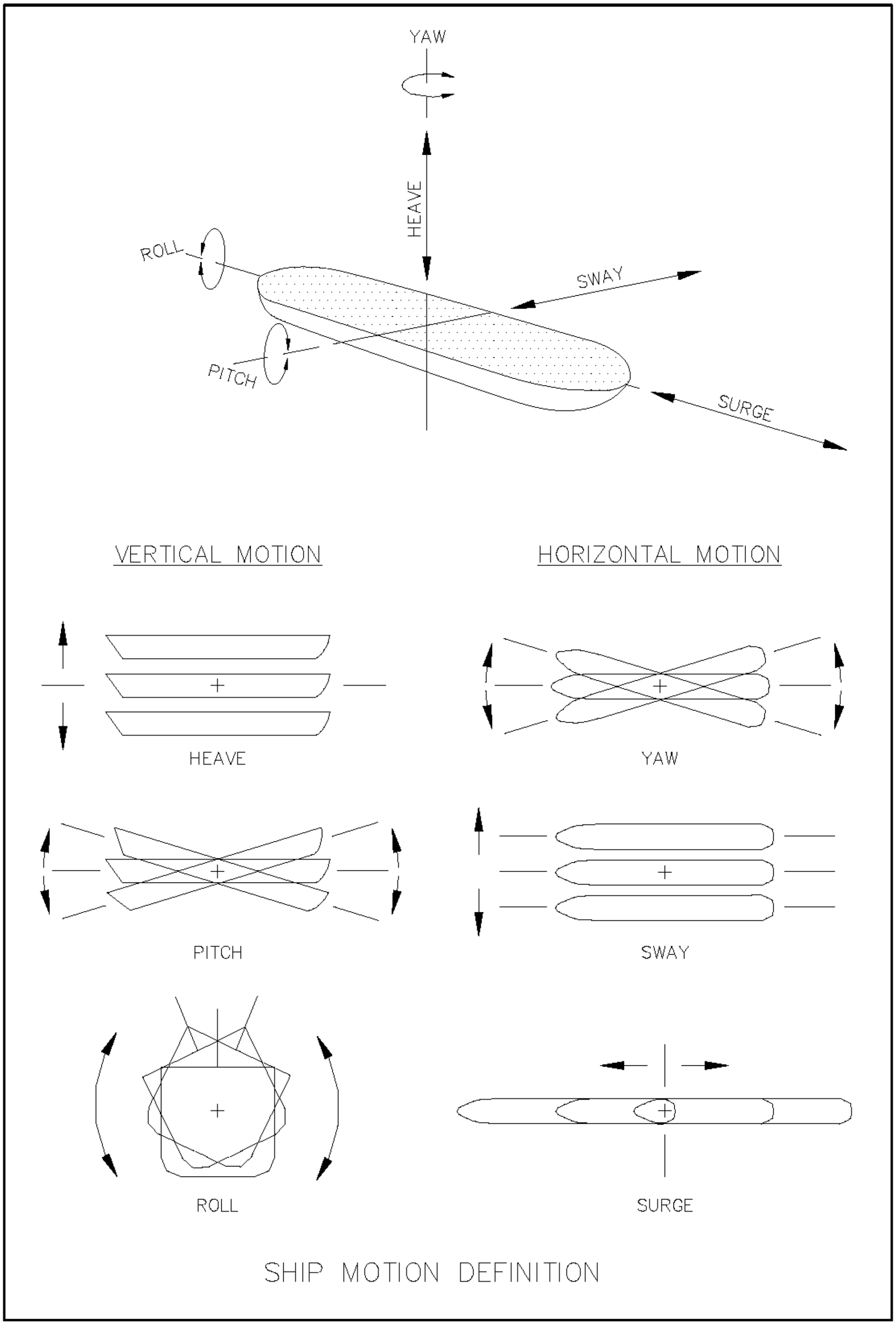


Figure 6-6. Ship wave motion definition

(5) Ship speed.

(6) Natural period of ship roll, pitch, and heave.

(7) Channel depth, ship draft, and underkeel clearance.

(8) Ebb or flood tide current condition.

(9) Channel overbank depth.

(10) Wave length and ship length and beam.

(11) Pilot strategy and response to waves.

(12) Wind speed and direction.

c. Waves.

(1) Waves are important to ship response in harbor fairways or entrance channels. Ocean waves are usually divided into two classes, depending on the period and origin of the waves. Seas are waves produced by local storms, while swell waves are propagated into the area of interest from distant storm systems. Ocean swell waves usually have longer periods than local seas, while wave heights of local seas may frequently exceed the heights of swell waves, particularly swell waves that have propagated over long distances. Observed wave heights are the combined heights of sea and swell, if both are present.

(2) Data on wave height, period, and direction are essential. These data and other offshore wave statistics are available for the U.S. coasts of the Atlantic and Pacific Oceans, the Gulf of Mexico, and the Great Lakes from the USACE Wave Information Study (WIS). These wave statistics are based on hindcasting waves from historical meteorological data as reported by Jensen (1983). The WIS data are contained in a series of published reports by McAneny (1995) and in a computer database maintained at the ERDC/WES. Wave data are available from the National Data Buoy Center (NDBC) for 3- and 12-m (10- and 40-ft) buoys as reported by Gilhouser (1983) and from the ERDC/WES Coastal and Hydraulics Laboratory (CHL) for nearshore pressure gage and small buoy data. When planning to collect local wave data as part of a project study, guidance is provided in EM 1110-2-1004, “Coastal Project Monitoring.” Advice and assistance in selecting equipment and siting equipment can be obtained from CHL.

(3) Deep-water wave data can be used to determine general trends in wave characteristics for the project area, but complexities in local bathymetry and shore orientation will produce a local wave climate that is different from the offshore data. The effects of the direction of water currents, ebb and flood tidal currents, on the waves must also be taken into account in determining the characteristics of the waves being encountered by the ship in an entrance channel. It is important that wave characteristics represent the waves that the ship will encounter since the motions of the ship (Figure 6-6) are the result of the ship’s response to the waves. The response of the ship is a function of the relative speed of the wave, the relative direction of the ship to the wave direction, the length of the wave to the ship’s length, the mass of the ship, and the ship type or hull form.

(4) Ignoring tidal current effects and irregular bathymetry, the local wave length for any depth of water can be approximated by Echart's (1952) equation for wave length:

$$\lambda = \frac{gT^2{}_w}{2\pi}\sqrt{\tanh\frac{4\pi^2 h}{T^2{}_w g}} \tag{6-9}$$

where

λ = wave length

T_w = wave period

h = water depth

g = acceleration of gravity

Table 6-1 may be used to quickly approximate the wave length (λ_2) and maximum nonbreaking wave height (H_2) that is translated from deep water (λ_2 and H_o) into shallow water at an entrance, assuming idealized conditions of normal wave approach and straight and parallel depth contours with a nearshore slope of 1/100. Wave refraction is not included. Breaking wave heights (H_b) are controlled by wave steepness and water depth (h_b).

(5) More precise estimates of the nearshore wave climate can be obtained by using wave transformation procedures or math models with local bathymetry and offshore wave data. Some of these models are discussed in EM 1110-2-1414, "Water Levels and Wave Heights for Coastal Design," (paragraph 5-8a(8), Figure 5-54, and Table 5-5).

d. *Wave-Induced Ship Motion.* The vertical excursion of the ship bottom as a result of wave action is composed primarily of motions in the three response modes of heave, pitch, and roll (Figure 6-6). Because of response phase differences, the three vertical motion response modes may not necessarily be added together linearly. Pitch and heave are important when ships are transiting entrance channels with incident waves propagating along or near the channel axis. The ship will then respond to a head or following sea, with the wave crests being perpendicular to the predominant wave direction coming toward the ship bow or stern, respectively. Ship roll becomes important when waves are propagating in a direction perpendicular to the channel axis; this is called a beam wave.

e. *Ship Response to Waves.* Predicting ship response in harbor fairway for channel depth design is a major problem without easy solution. The seakeeping models used by naval architects are very difficult to apply and require a high level of specialized knowledge for useful interpretation and application. Physical models can be used to predict ship response from monochromatic waves, if model ships are properly scaled, constructed, balanced, instrumented, and tested. Spectral wave generators have been used (for example, at ERDC/WES to model statistically meaningful wave situations) to gain accurate ship response information for entrance channel design. Relatively few data have been collected for the variables of interest in determining ship response in waves, particularly for ship motions in relatively shallow-water conditions. This lack of data results in difficulty in verifying proposed models to predict the motion of a ship induced by waves and the extra depth required in entrance channels to compensate for this motion.

Table 6-1
Shallow Water Waves at Entrances (To convert feet to meters, multiply by 0.3048)

Period, sec	λ_o, feet	H_o, feet	λ_2, feet	H_2, feet	H_b, feet	h_b, feet
Depth at Entrance – 30 ft						
8	328	21	225	19.7	21	27
10	512	21	292	20.9	23.6	29.4
15	1152	17	453	19.7	24.7	29.7
20	2048	16.9	612	18	24.4	29
Depth at Entrance – 35 ft						
8	328	21	238	19.5	21	27
10	512	26	311	25.3	27.6	34.8
15	1152	20	487	22.5	27.9	33.7
20	2048	16.9	659	21.4	28.5	33.9
Depth at Entrance – 40 ft						
8	328	21	250	19.3	21	27
10	512	30	329	28.7	30.7	39.2
15	1152	24	518	26.2	32	38.8
20	2048	20.1	702	24.7	32.4	38.7
Depth at Entrance – 45 ft						
8	328	21	261	19.2	21	27
10	512	33	345	31.2	33	42.3
15	1152	29	547	31	36.8	45
20	2048	24.3	743	29.1	37.4	44.7
Depth at Entrance – 50 ft						
8	328	21	270	19.2	21	27
10	512	33	360	30.8	33	42.3
15	1152	33	574	34.6	40.6	49.8
20	2048	27.5	782	32.3	40.9	49.1
Depth at Entrance – 55 ft						
8	328	21	278	19.2	21	27
10	512	33	373	30.6	33	42.3
15	1152	37	599	38.1	44.2	54.7
20	2048	31.7	818	36.5	45.5	54.9

f. Preliminary Design Guidance for Entrance Channel Depths. For the purpose of preliminary design of entrance channel depths exposed to waves, several recommendations have been made. These are provided as follows:

(1) The Permanent International Association of Navigation Congresses (PIANC) sponsored an International Commission for the Reception of Large Ships (ICORELS) in 1974. Working Group IV reported these recommendations for determining the depth of channels (Netherlands Ship Model Basin 1980):

(a) Open Sea Area. When exposed to strong and long stern or quarter swells where speed may be high, the gross underkeel clearance should be about 20 percent of the maximum draft of the large ships being received.

(b) Waiting Area. When exposed to strong or long swells, the gross underkeel clearance should be about 15 percent of the draft.

(c) Channel. When sections are exposed to long swells, the gross underkeel clearance should be about 15 percent of the draft.

The gross underdeel clearance is by definition the minimum margin remaining between the keel of the ship and the nominal channel bed level when the ship moving at planned speed under the influence of the design wind and wave conditions.

(2) The International Association of Ports and Harbors (IAPH) also assembled a Committee on Large Ships (COLS), now the Committee on Port Safety, Environment, and Construction, which made these recommendations (Marine Board 1981). In the initial planning stages, the following generalizations may be valuable:

(a) Sections exposed to strong and long swell, gross underkeel clearance to be about 15 percent of the maximum drought.

(b) Sections less exposed to swell, gross underkeel clearance to be about 10 percent of the maximum drought.

(3) A more recent report by a joint PIANC-IAPH Working Group II-30 (PIANC) 1995) prepared in cooperation with the International Maritime Pilots Association (IMPA) and the International Association of Lighthouse Authorities (IALA) gives a more generous allowance for preliminary guidance for setting entrance channel depths. It suggests that values of 1.3 times the maximum ship draft or more may be used for preliminary design purposes.

g. Empirically Based Method for Estimating Vertical Ship Excursions in Waves. Exxon International Company published a report entitles “Underkeel Clearance in Ports” in 1982. Included in that report is a procedure to estimate the allowance required for a tanker due to wave-induced motions. Based on the model tests conducted at the Netherlands Ship Model Basin (NSMB) (Koele and Hooft 1969) and reported by PIANC (1975), the responses of a loaded, untrimmed 200K dwt tanker in shallow-water waves were estimated. The majority of the tests were conducted with ship speeds of 7 knots. Based on SOREAH model tests (1973a-c) and some theoretical predictions for a 21K dwt tanker performed by NSMB (1980), Kimon (1982) extrapolated the 200K dwt tanker responses and other vessel sizes. Vessel root mean squared (RMS) responses to 0.305-m (1-ft) waves are presented for a 200K dwt tanker in Figures 6-7 through 6-11 for relative wave headings of 0, 45, 90, 135, and 180 deg. Figures 6-12 and 6-13 provide information to adjust ship responses for different displacements, while Figures 6-14 and 6-15 provide allowances for wave encounters and periods. In general, the vertical motion is largest for the bow and beam waves. For a given direction, the response increases with wave period going from wind driven to swell type seas. Only relatively long waves, with periods greater than about 10 sec, have a significant effect on underkeel clearance. The response decreases with decreasing H/T ratio, i.e., shallower water, as the proximity of the bottom has a large damping effect as reported by Van Oortmerssen (1976). The effect of vessel speed is largely the result of its effect upon period of wave encounter. In head seas, the encounter period decreases with increased speed, whereas in following seas, the encounter period increases. Because of the shorter apparent wave period in head seas, the vertical motion response decreases. Conversely, in following seas, there is a longer apparent wave period and, thus, increased response. In beam seas, there is no appreciable variation with ship speed. Tanker size is most significant for quartering, head, and following seas, since the response in these seas is sensitive to ship length. In quartering seas, pitch has a much greater effect on vertical motions of smaller-size vessels.

An example of the computation of the underkeel clearance allowance for waves is provided. Assume a 270K dwt tanker that is loaded to a 21-m (68-ft) draft having a 52-m (170-ft) beam, a roll period of 10 sec and a pitch period of 10 sec operating at 5 knots in charted water depths of 17 meters (55 feet) and a tide level of 7 meters (22.9 ft). The channel length is 2 nm, and the sea state has an average wave height of 3 m (10 ft), a period of 15 sec, and a relative wave heading of 180 deg to the ship's motion. From Figure 6-11, the RMS response for a 200K dwt tanker in 0.3048-m (1-ft) seas is 0.296. The RMS response for a 200K dwt tanker at the given wave height is 0.296 times the significant wave height of 0.40 m (2.96 ft). The displacement response ratio from Figure 6-12 is 0.86, and the RMS response for the given ship is 2.96 times 0.86 or 0.77 m (2.55 ft). The period of encounter from Figure 6-15 is 17 sec. The number of wave encounters is estimated by the distance/speed over ground (2nm/5knts) times 3600/17 sec or 85. The wave encounter multiplier from Figure 6-14 is 4.25, and the wave allowance is 4.25 times (0.77 m (2.55 ft) or 3.3 m (10.85 ft).

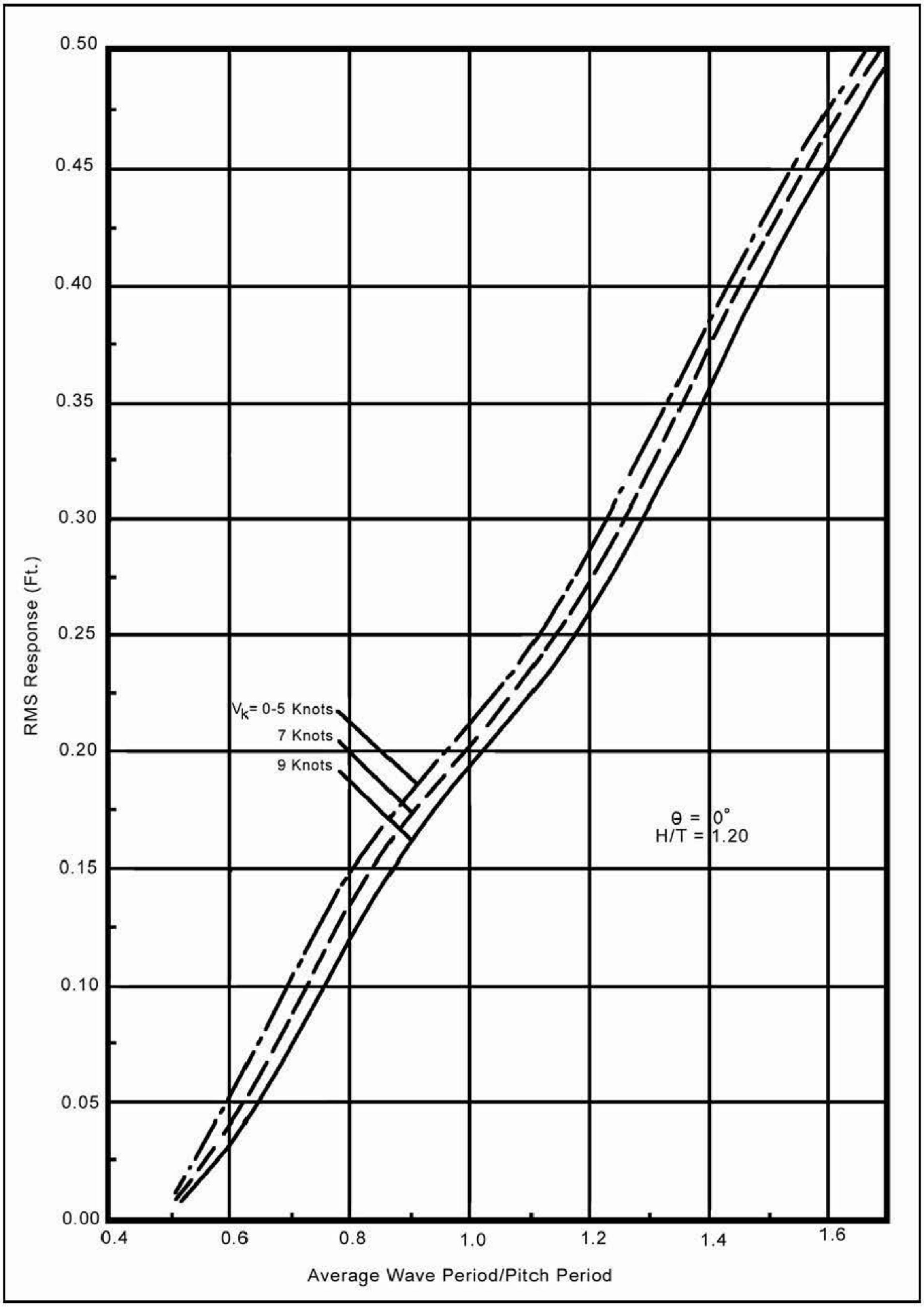


Figure 6-7. Head sea response, V_k = 0-9 knots

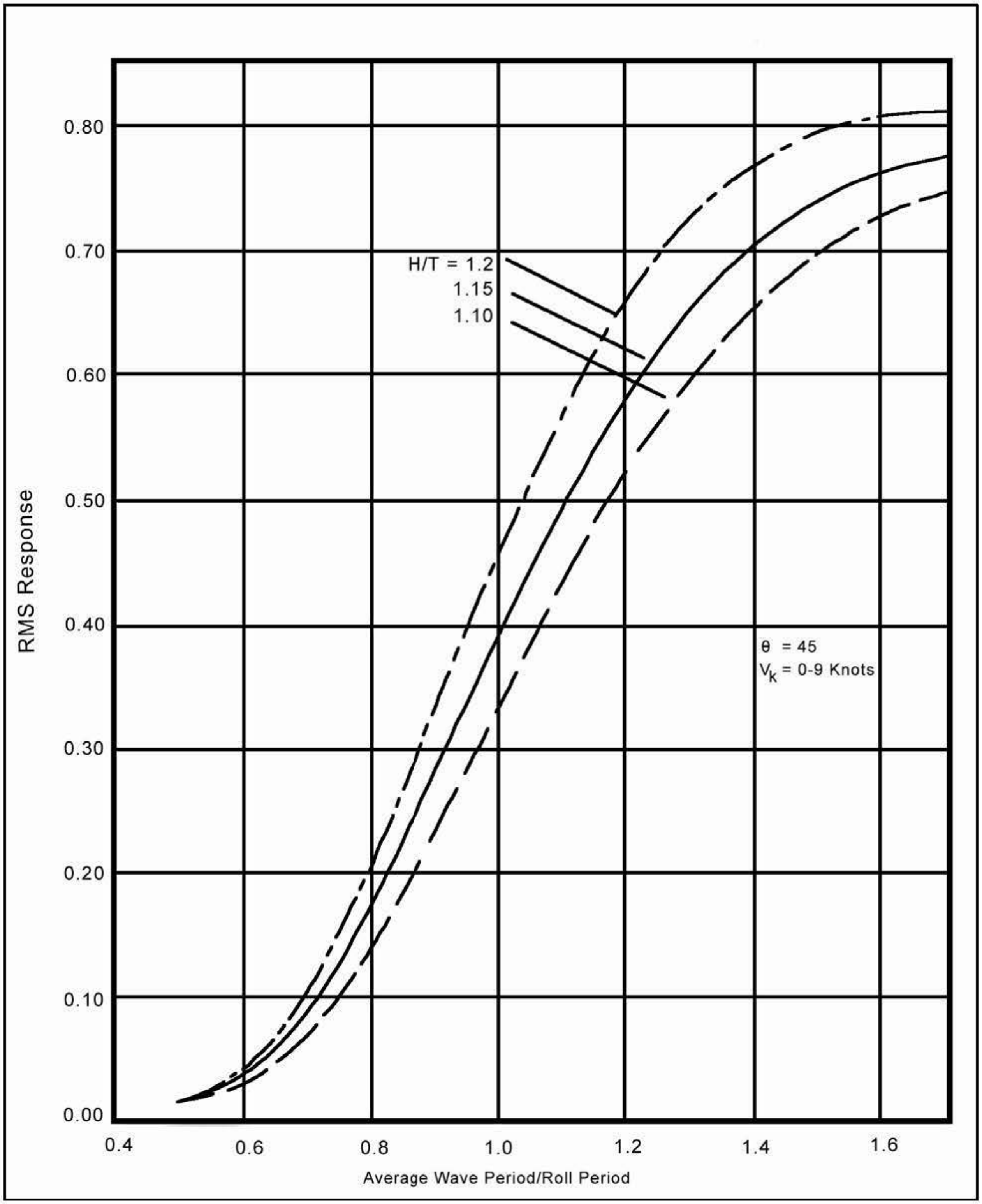


Figure 6-8. Bow sea response, V_k = 0-9 knots

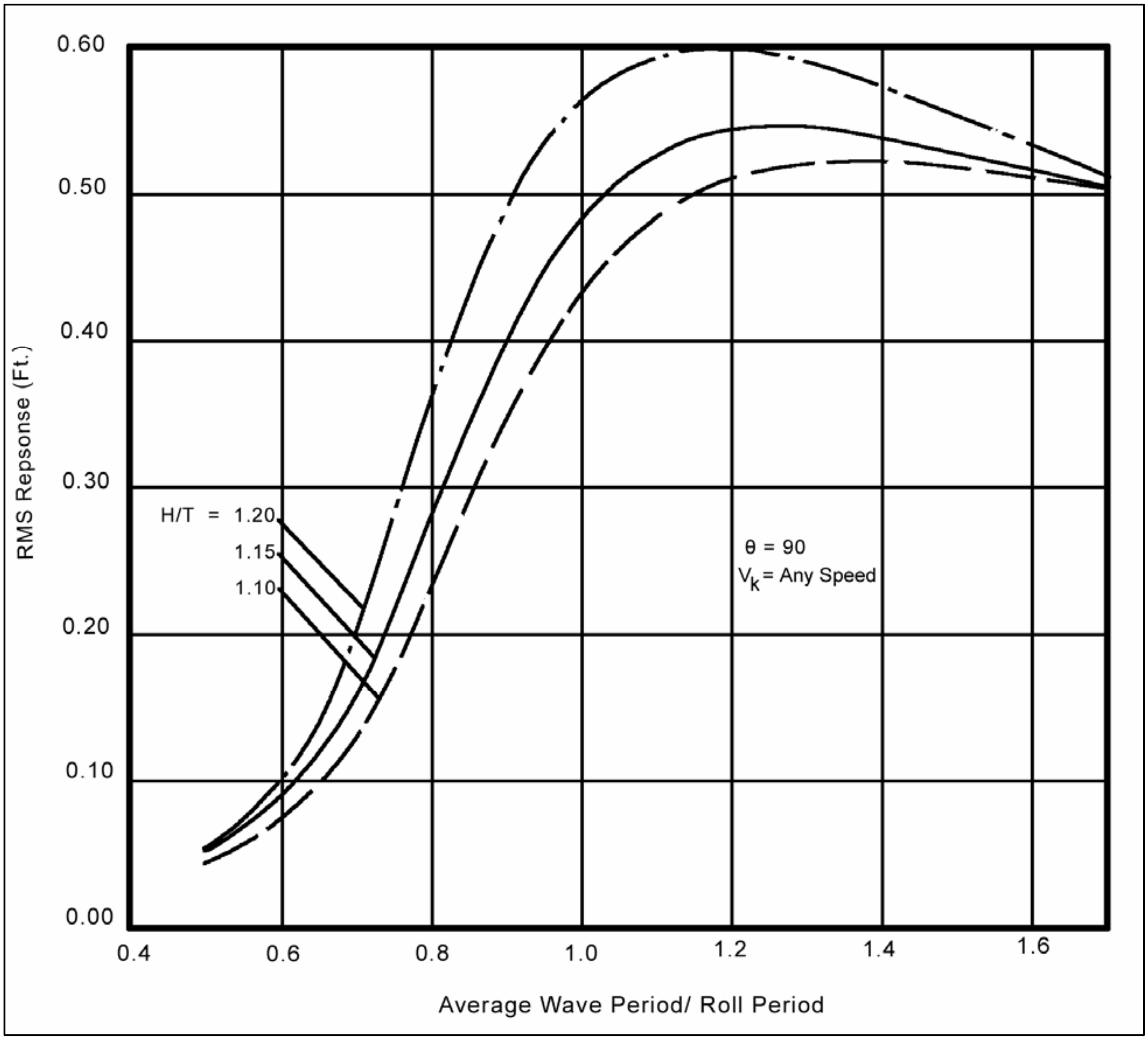


Figure 6-9. Beam sea response, V_k = any speed

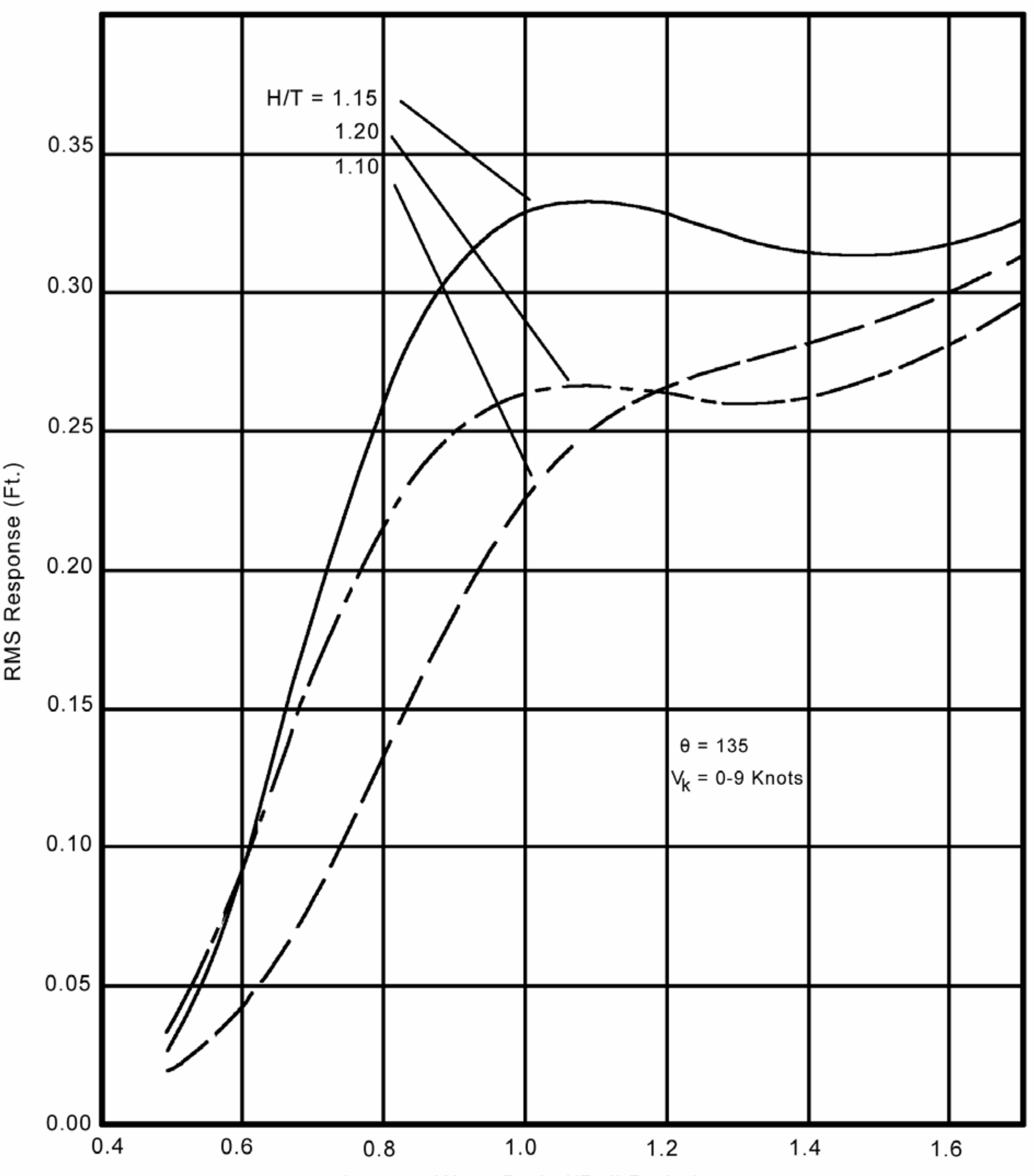


Figure 6-10. Quartering sea response, V_k = 0-9 knots

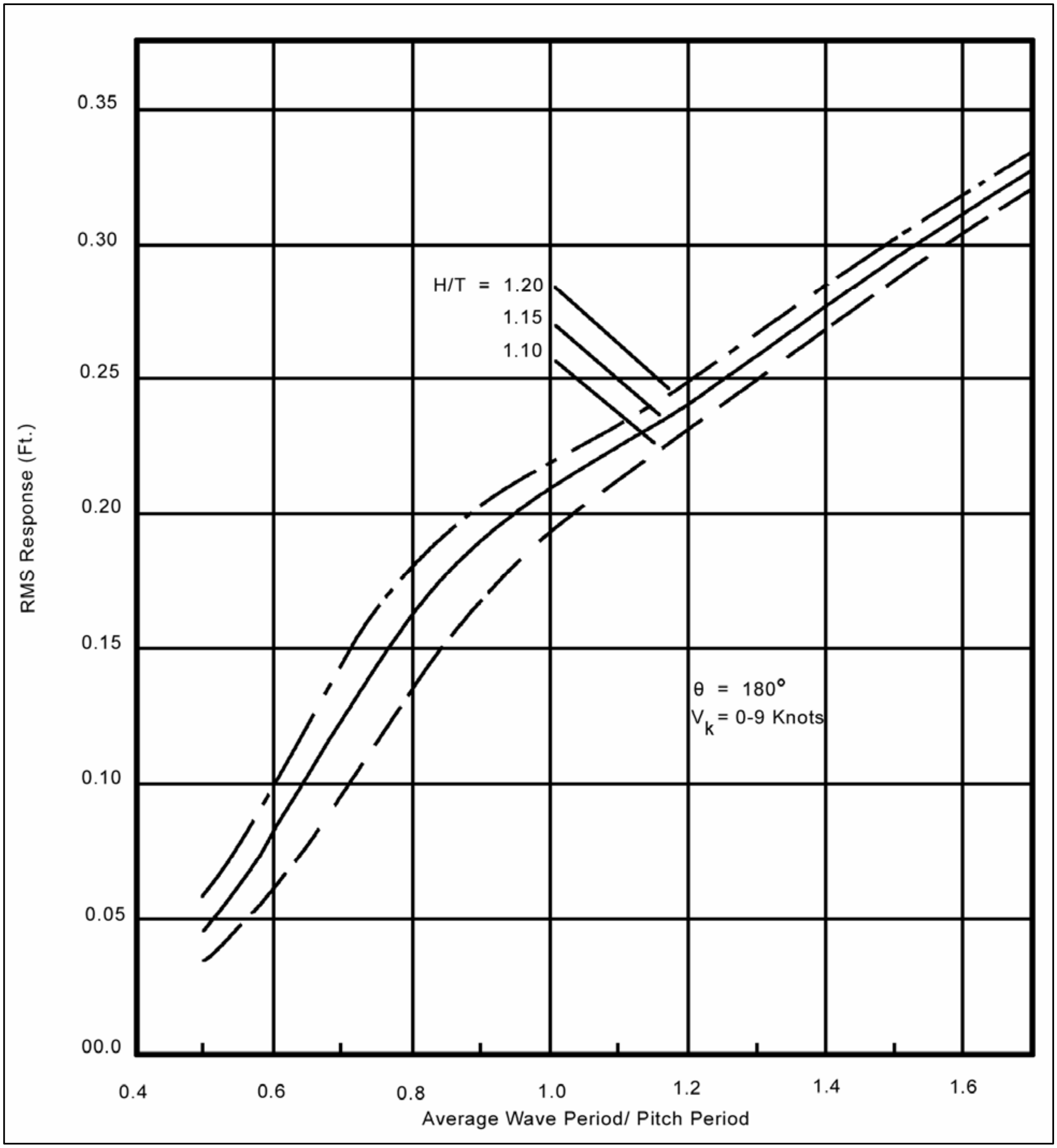


Figure 6-11. Following sea response, V_k = 0-9 knots

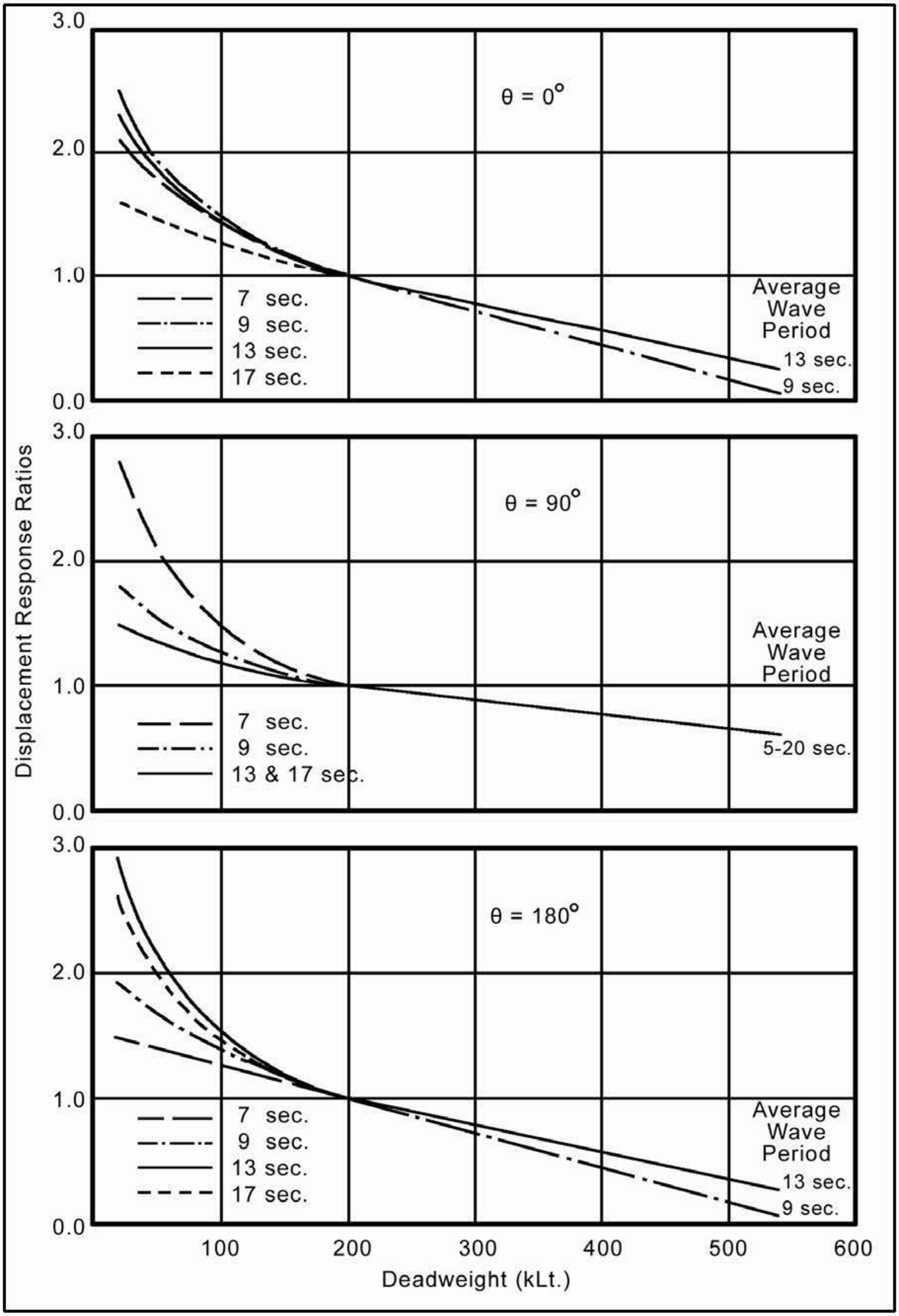


Figure 6-12. Displacement response ratios, θ = 0°, 90°, 180°

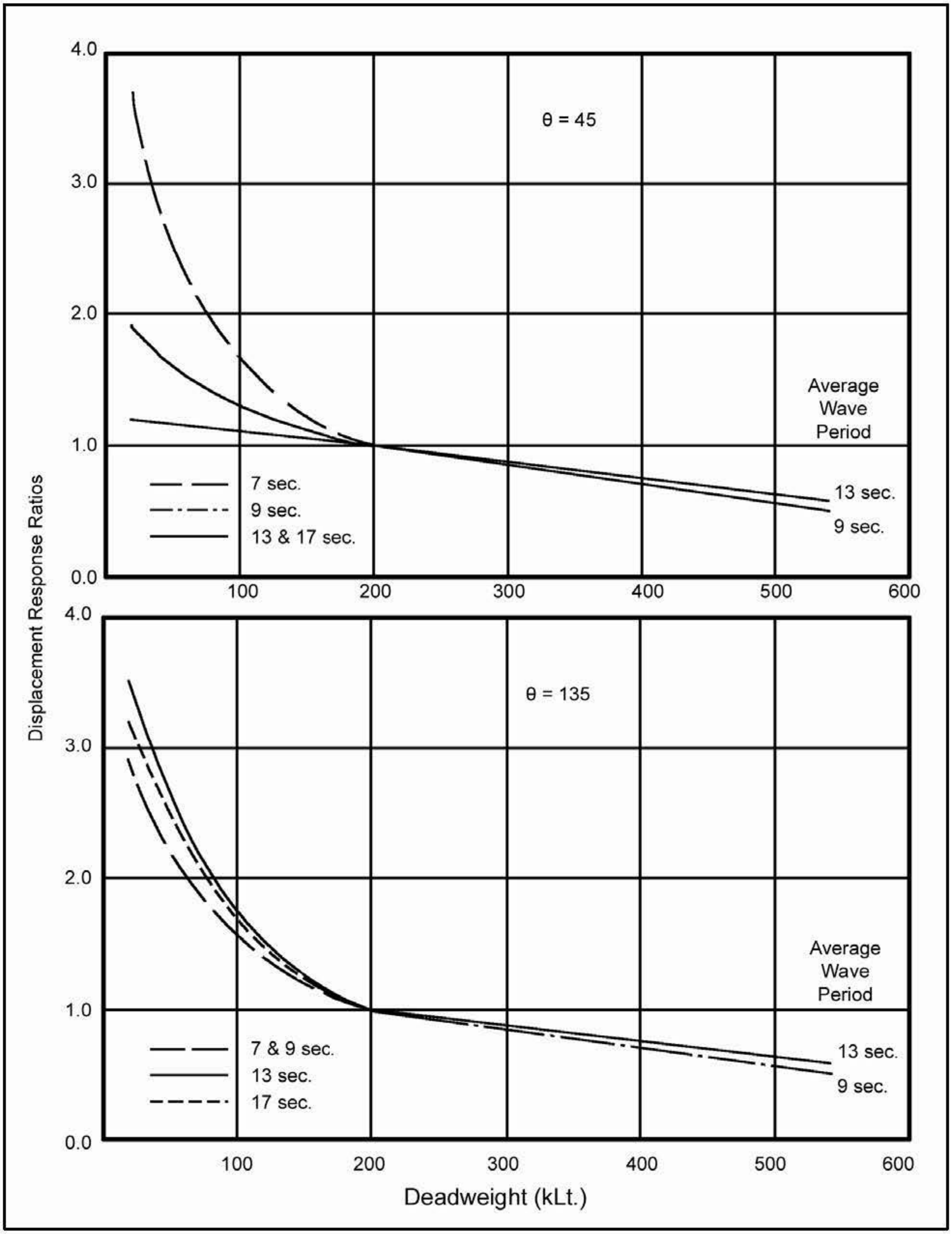


Figure 6-13. Displacement response ratios, θ = 45°, 135°

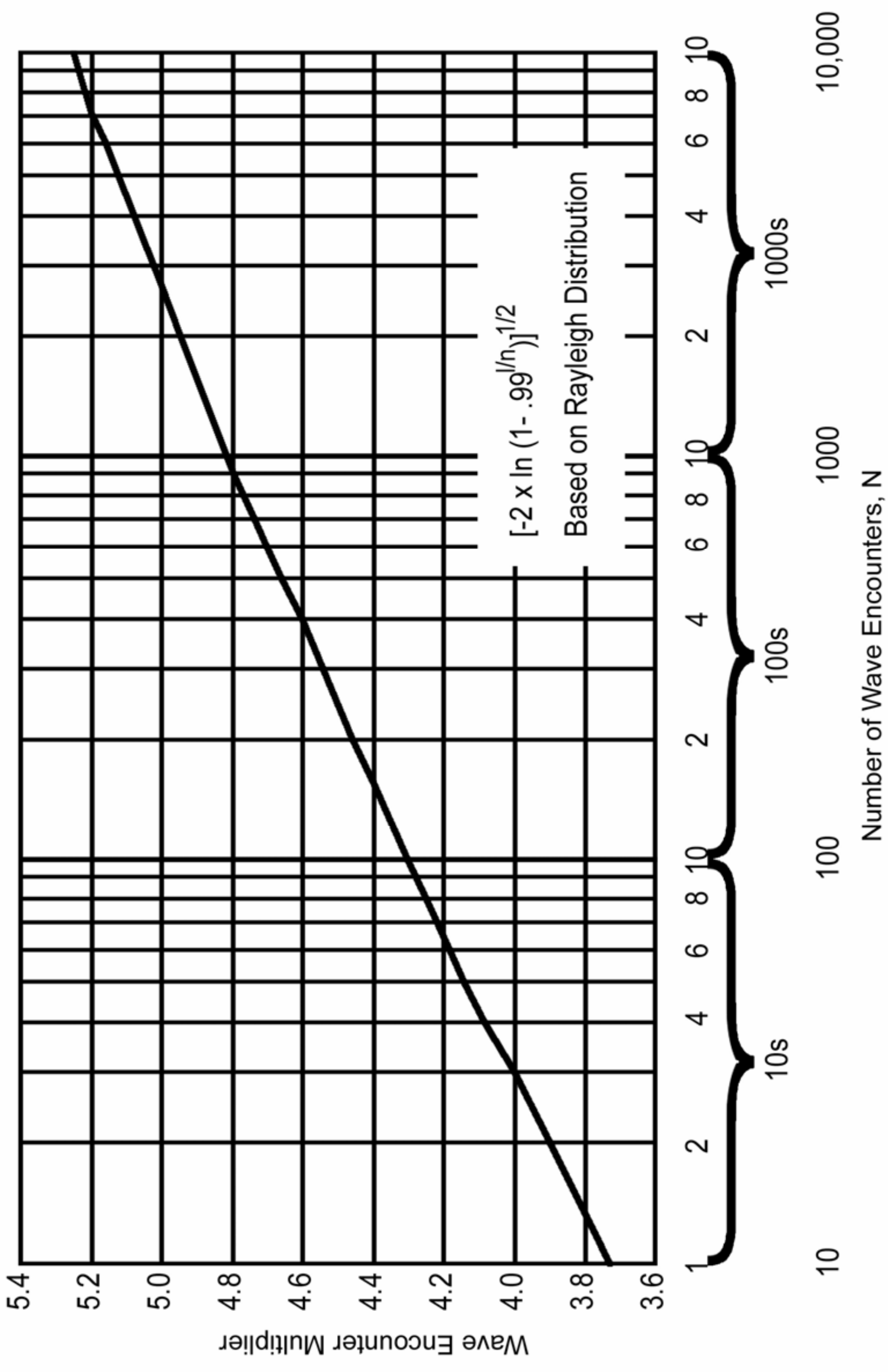
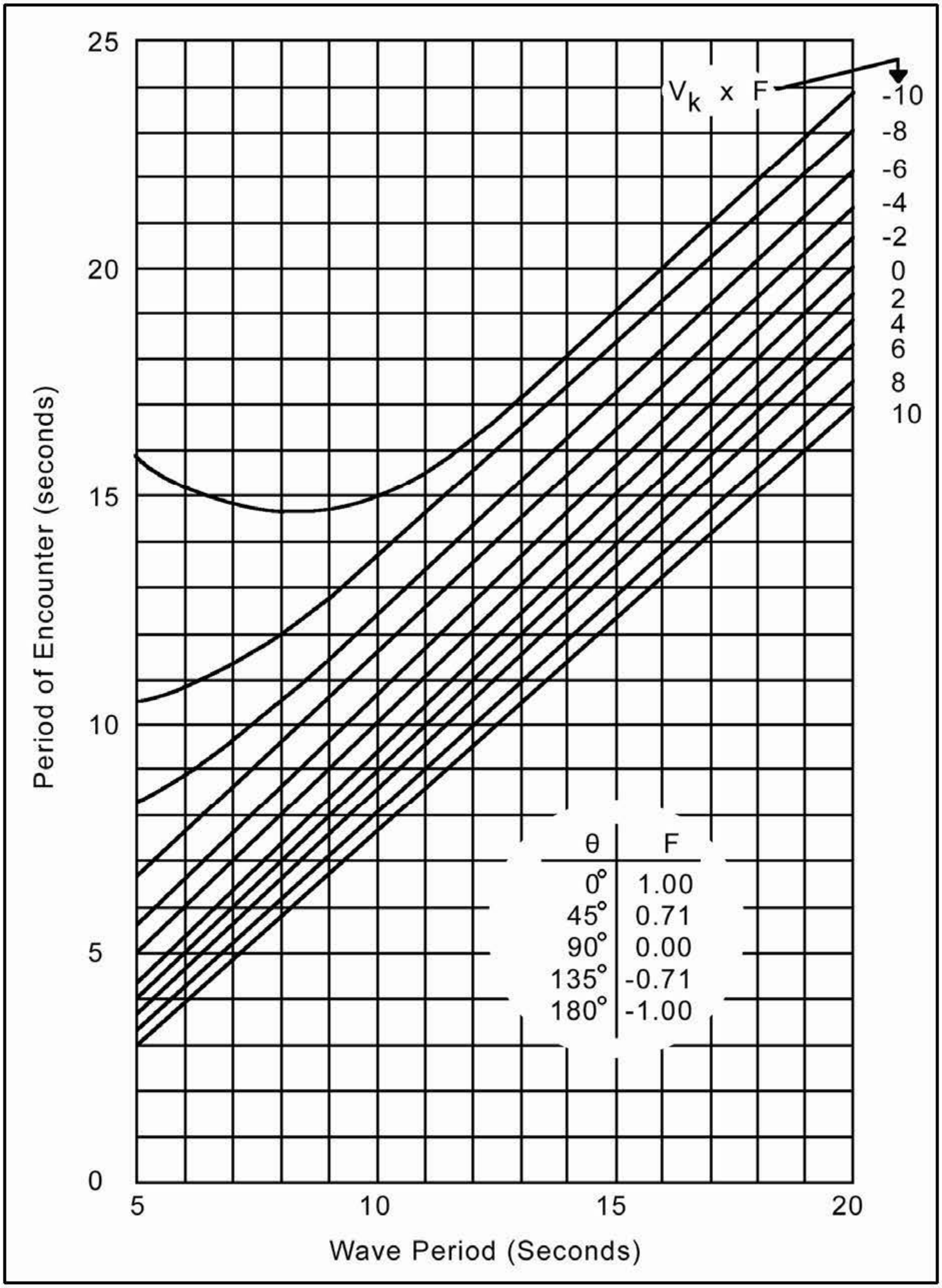


Figure 6-14. Wave encounter multiplier



θ	F
0°	1.00
45°	0.71
90°	0.00
135°	-0.71
180°	-1.00

Figure 6-15. Wave encounter period

h. Columbia River Entrance Study. Ship response data were collected over a 2-year period at the mouth of the Columbia River, Washington/ Oregon (WA/OR), by the U.S. Army Engineer District, Portland (Wang et al. 1980). Because of the open nature of the entrance geometry, ship squat was considered negligible.

(1) Noble (1983) provides the summary of ship motions shown in Table 6-2. Myers (1969) indicates that the ship's natural period of roll is generally two or three times that of pitch. Table 6-2 indicates this is generally true of the degrees of roll and pitch as well.

Table 6-2
Summary of Heave, Roll, and Pitch Motions (after Noble 1983)

Σ% Freq Occ	Heav in ft Avg	Heav in ft Max	Roll Deg Avg	Roll Deg Max	Pitch Deg Avg	Pitch Deg Max
75	0.8	2.0	0.8	2.3	0.4	0.9
50	1.3	3.6	1.3	3.8	0.5	1.3
25	2.2	6.0	2.2	5.7	0.7	2.1
10	2.8	8.4	3.1	13.0	1.7	4.9
5	3.1	9.7	5.1	13.4	1.7	4.9
Max	4.1	12.4	5.5	17.5	2.2	6.0

Critical motions of a ship occur at the bow and stern and are most dependent on the wave height and encounter period. While wave height has the most influence on ship motion, the Columbia River study showed that the outbound voyages generally exhibited greater motions than inbound voyages. This demonstrates that shorter encounter periods cause greater bow/stern motions than longer periods. A relationship was derived using the independent variables wave height, natural pitch period, and encounter period of the ships to give the dependent variable of average bow or stern ship motion in waves for each voyage.

$$P_{avg} = 0.57 + 0.99\left(\frac{H_s T_\phi}{T_e}\right) \tag{6-10}$$

where

P_{avg} = average bow or stern ship motion in waves (meters (feet))

H_s = significant wave height (meters (feet))

T_ϕ = natural ship pitch period (seconds)

T_e = encounter period (seconds)

The relationship and the values used to develop it are found in Noble (1983). The 95 percent confidence limits are shown, and the relationship is reported to have a 0.86 correlation coefficient.

(2) The distribution of ship motions on an individual voyage follows the Rayleigh distribution. This distribution can be stated as:

$$P_{(p)} = 1.13 P_{avg} [-1n(1-p)]^{1/2} \tag{6-11}$$

where

$P_{(p)}$ = bow or stern ship motion with a probability of 1-p of not being exceeded (meters (feet))

P_{avg} = average bow or stern ship motion during a transit (meters (feet))

p = probability of exceedence (percent)

If we assume that the critical ship motion for a particular transit should be $P_{(95)}$, then Equation 6-11 becomes:

$$P_{(95)} = 1.96 P_{avg} \tag{6-12}$$

By considering the frequency of occurrence of each wave condition, a distribution of the critical ship motion (critical ship motion being the $P_{(95)}$ or other selected $P_{(p)}$ of a transit under a particular set of conditions) is obtained for a particular ship (Figure 4, Noble 1983).

(3) Designers are most interested in extreme events. The ship response in wave data was reviewed, and the maximum ship motion for each of the outbound transits was plotted against the incident wave wave height. A linear regression was fitted through the maximum ship motion data and the 95 percent (two standard deviations) confidence limit added. The data and curves normalized by the wave height are shown in Figure 6-16. It is noted that use of Equations 6-10 and 6-11 result in nearly the same answers a the regression curve for the maximum ship motion. However, if it is desired to ensure that none of the ships will strike the bottom, then the recommended design curve should be used. Consultation with the bar pilots at the entrance will indicate the local practice.

i. Analysis Methods. For more accurate determination in final design, it is possible to investigate ship wave response in entrance channels using the following alternatives:

(1) Analytically, using strip theory or other theoretical calculation methods as developed by naval architects.

(2) Experimentally, using radio-controlled, free running, scaled ship models with wave response measurements.

(3) Direct, onboard ship measurements while transiting through the entrance channels.

Methods to conduct these types of investigations have been developed and are being used in entrance channel design on an experimental or research basis at present. However, further development of such techniques for entrance channel design is still being pursued, especially the analytical techniques.

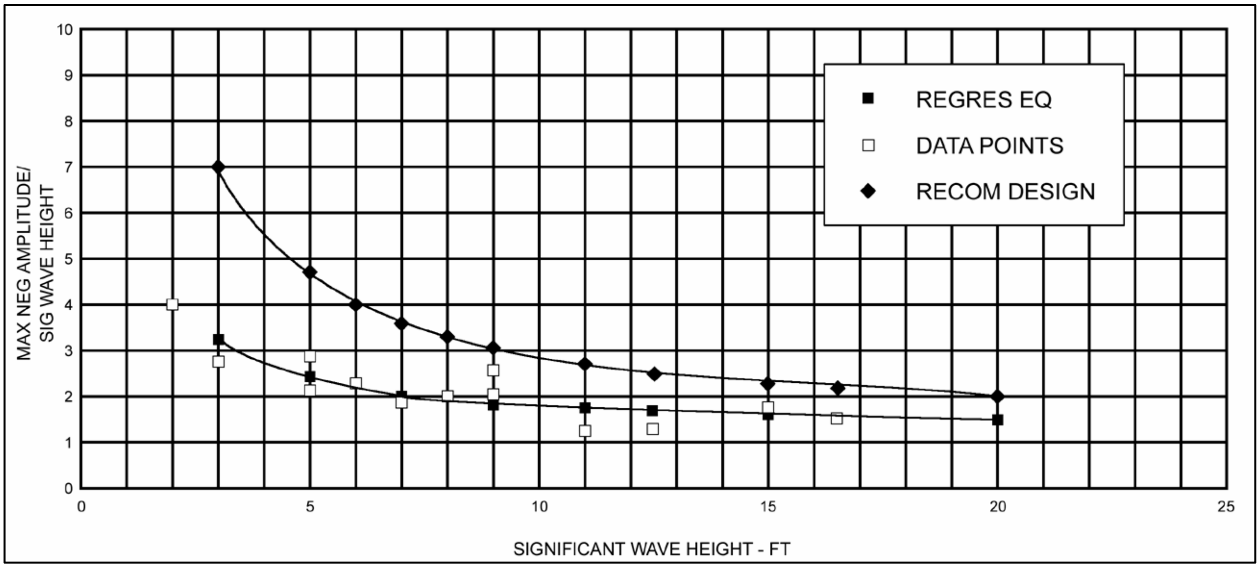


Figure 6-16. Maximum ship motion response, mouth of Columbia River - Outbound

j. *Alternative Approaches.* Some theories (Lewis 1989) are available and appear to be good for deep-water conditions. Naval architects use these computational methods for structural ship design for practical applications. However, use in shallow water for a typical entrance channel has not been demonstrated. A major factor affecting design includes operational considerations, e.g., when are ships brought into harbor and under what adverse conditions. Pilot strategy and response to wave conditions are also important, e.g., reducing speed generally will reduce ship response. Course changes can also modify the ship response; however, this is not usually possible in a dredged entrance channel. Ships will also sway or yaw in wave conditions, which can affect control of the ship, thus, all ship motions need to be calculated considering proper pilot control.

k. *Future Research.* Recently, ERDC/WES has been working with a research naval architecture company to develop and provide a ship motion response model to use on the ERDC/WES ship simulator. To date, results are encouraging; however, this effort is still considered a research tool and needs further verification.

Statistical approaches based on measured ship response functions to wave conditions have been developed and are being used by the U.S. Navy and the Ministry of Transport, The Netherlands. Research to develop a similar approach for U.S. ports is being proposed.

6-5. Depth Allowances

a. *Design Basis.* The designer must take care that the design channel depths developed from the economic analysis are at least equal to the loaded draft (summer, salt water) of the design ship, plus an allowance for the following factors:

(1) Ship squat.

(2) Ship lowering in fresh water.

(3) Vertical ship motion due to wave action.

(4) Safety clearance.

A diagram depicting these allowances and its relation to the channel bottom is shown in Figure 6-17.

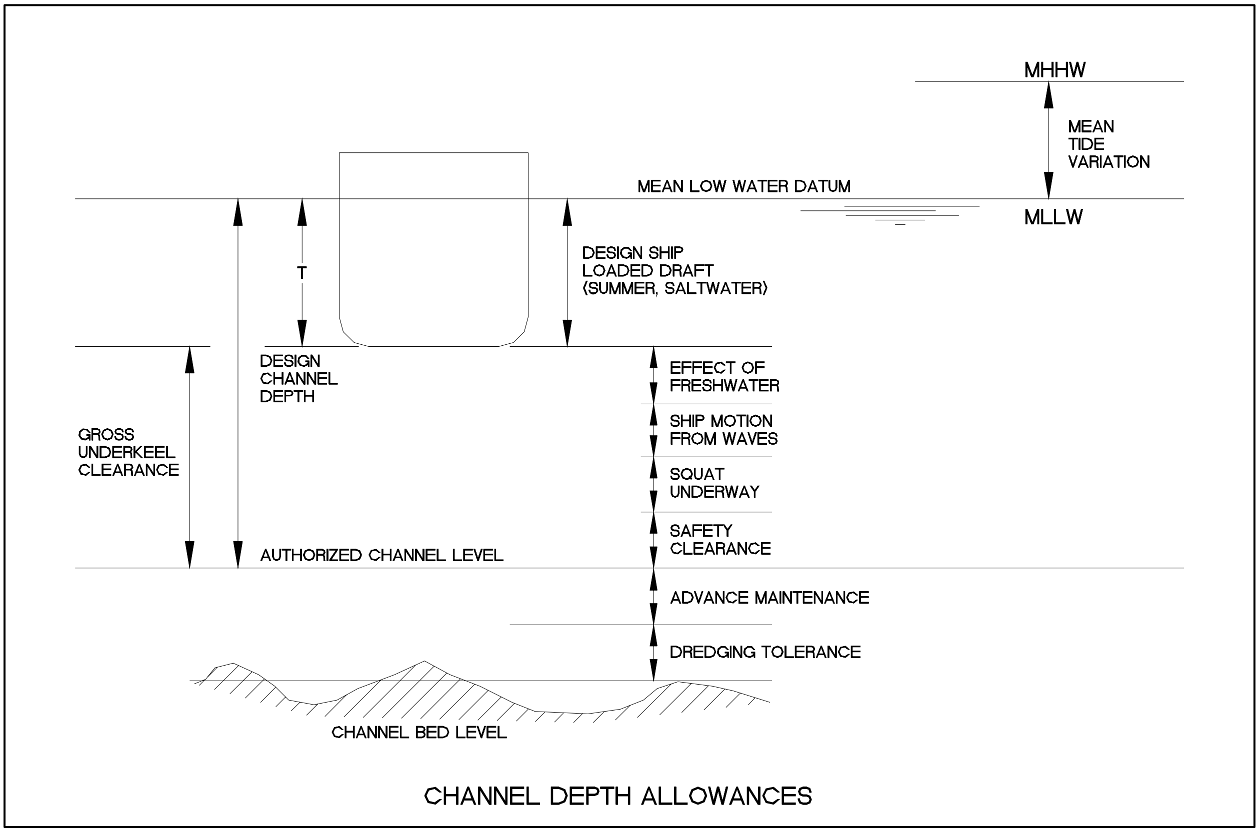


Figure 6-17. Channel depth allowances

b. *Effect of Fresh Water.* When ships call at ports with fresh or brackish water, the ship draft will increase because of a decrease in density of the water. The difference in unit weight between salt and fresh water is from 1025.84 kg/m^3 (64.043 lb/cu ft) to 998.98 kg/m^3 (62.366 lb/cu ft) or 26.86 kg/m^3 (1.68 lb/cu ft). Therefore, the ship draft will increase by 2.619 percent going from sea water to fresh water; brackish water at half the salinity would be 1.3095 percent. A ship with a 10.7-m (35-ft) draft would be increased in fresh water to 10.95 m (35.9165 ft) or about a 0.25-m (1-ft) increase. A maximum allowance of 0.25 m (1 ft) is appropriate in cases where the port is located in freshwater; 0.15 m (0.5 ft) is recommended when the port area is brackish.

c. *Trim.* In normal operations, most ships have capabilities to change the load and ballast conditions to provide desirable trim position. A ship in ballast (without any cargo) is loaded by pumping seawater into ballast tanks to provide sufficient draft to submerge the ship propeller and rudder. A small trim by the stern is usually beneficial for improved maneuverability and usually required by local pilots. Ships in motion will tend to change static trim conditions; tankers tend to trim down by the bow and containerships (and other fine-formed ships) trim down by the stern. The provision of a channel depth allowance for ship trim conditions is usually not necessary, since this is an operational decision to be determined by the local pilots as reflected by local port needs and requirements.

d. *Shallow-Water Effects.* Channel design bottom clearance should consider safety and efficiency of ship traffic in project operation. Small underkeel clearance will affect ship squat, maneuverability, and resistance compared to normal deep-water ocean operations. Pilots report that ships become more difficult to handle at small underkeel clearances, requiring large rudder angles to steer and turn ships in curves. Ships sailing in shallow water call for increased engine speed and power, which has an impact on fuel consumption. The potential for bank failure, bottom material movement, and scour increases considerably as power is augmented to the propeller to maintain desired ship speed.

e. *Safety Clearance.* In the interest of safety, a clearance of at least 2 ft (0.6 m) is normally provided between the bottom of a ship and the design channel bottom to avoid damage to ship hull, propellers, and rudders from bottom irregularities and debris. When the bottom of the channel is hard, consisting of rock, consolidated sand, or clay, the clearance should be increased to at least 0.9 m (3 ft).

f. *Advance Maintenance.* Advance maintenance consists of dredging deeper than the channel design depth to provide for the accumulation and storage of sediment. Justification for advance maintenance is based on depth reliability and economy of less frequent dredging. Economic consideration should also be given to providing a sediment trap near a project entrance channel as an alternative to advance maintenance. Deeper channels will tend to be more efficient sediment traps and can shoal at faster rates (Trawle 1981). However, a deeper channel might tend to localize shoaling and could reduce the length of channel to be dredged and cost of maintenance dredging. Estimates are needed on several depth increments of advance maintenance and expected effect on shoaling rates to determine the optimum depth. Conditions will vary with each project, and the design depth and overdredging that might be applicable for advance maintenance should be based on an evaluation of local conditions at each project. Generally, depth increments of 0.6 or 0.9 m (2 or 3 ft) are normal advance maintenance allowances.

g. *Dredging Tolerance.* In addition to advance maintenance dredging, an additional 0.3 to 0.9 m (1 to 3 ft) below the selected dredging depth is generally provided as a dredging pay item because of the inability to dredge at a uniform depth with fluctuating water surface. This additional dredging allowance is referred to as dredging tolerance. Depth allowances for advance maintenance and dredging tolerance are provided in addition to the design (authorized) depth.

h. *Total Depth.* The design (authorized) depth will include the various allowances as shown in Figure 6-17. Advance maintenance and dredging tolerance are provided in addition to the design depth.

CHAPTER 7

Channel Dredging and Disposal

7-1. <u>Channel Dredging.</u>

a. Channel dredging involves initial construction to provide the navigation channel design depth with allowances for advance maintenance dredging and dredging tolerance, and for the periodic removal of sediment deposited on the channel bed, which is referred to as channel maintenance after construction. The type of material that must be excavated and the location of dredged material disposal areas are important factors that enter into the channel cost estimate. Estimates of both construction and maintenance dredging for various channel alignments and dimensions have to be included in the project optimization analysis. Deep-draft channels are usually dredged by hopper dredges in entrance channels or where the dredge may be exposed to wave action, during dredging or during the material disposal operation. This is usually the case when offshore disposal is proposed. Pipeline dredges usually are more economical than hopper dredges with greater production but are restricted to protected or semiprotected areas. The Dredged Material Research Program (DMRP) resulted in excellent evaluation of current dredging methods, disposal techniques, and environmental impacts. DMRP results, published in a series of ERDC/WES technical reports, provide useful information for dredging and disposal plans. Most of the information is available in EM 1110-2-1202 and EM 1110-2-5025.

b. An ongoing research and development program, the Dredging Research Program (DRP), is implementing new technology for dredging operations, equipment, control, and measurements. Study results are being published in a series of ERDC/WES technical reports, bulletins, DRP technical notes, newsletters, etc. The planner/designer should consult these publications for recent research results and availability of products.

7-2. <u>Disposal Sites.</u> Disposal sites can be ocean-continental shelf or deep-water, estuary, intertidal, streams, bay, lake, or upland. Ocean disposal remote from the channel has the advantage of assuring that the material will not reenter the channel; however, costs are usually the highest. Disposal in estuaries should be in areas where tidal currents will not move the material back into the channel being developed or adversely affect the environment. Intertidal disposal (between low-tide and high-tide levels) might be feasible where the creation of marshes for fish and wildlife habitat or beach restoration is desired. Upland disposal will usually require dikes and weirs to control the solids content of carrier water returning to the waterway, and temporary restraining structures might be required for marsh creation. The effect of disposal in streams on channel maintenance and development and the environment must be considered. Predictive models are available to estimate the location and extent of dredged material movement after disposal (Johnson 1990).

7-3. <u>Use of Dredged Material.</u> A study of beneficial uses of the dredged material might indicate an increase to project benefits. Some beneficial uses of dredged material would be:

a. Landfill for industrial development.

b. Construction materials.

c. Topsoil.

d. Marsh creation.

e. Beach restoration.

7-4. Environmental Effects. Studies must consider all positive and negative environmental effects of the alternative dredging and material disposal plans considered. Some of the environmental effects may be changes in water levels, erosion, water circulation, flushing rates, saltwater intrusion, shoaling pattern, or distribution of wave energy along the shoreline. Any plan recommended must have an environmental assessment. The assessment will indicate whether a Statement of Findings or an Environmental Impact Statement will be required, including a comprehensive mitigation plan with cost for any adverse effects. In the development or improvement of deep-draft navigation projects, the effects of dredging disposal on fish and wildlife resources and possible productive use of dredged material must be considered. Special consideration will be required for both dredging method and disposal when dealing with contaminated materials. Public Law 409, Section 5, requires the study and prediction of erosion and accretion for a distance of not less than 16 kilometers (10 miles) on either side of an improvement of the entrance at the mouth of a river or inlet. Project limits should be extended beyond the project features to allow future mitigation work, if needed. Mathematical and physical model studies are currently the best method to predict project-caused changes in salinity, shoaling patterns, current velocities, tidal flushing, and dispersion rates. Prototype verification data for model studies are essential and should cover a wide range of conditions. Quantitative biological assessment of project impact to the aquatic life is needed to plan mitigation measures.

CHAPTER 8

Channel Width

8-1. Design Criteria.

a. Design Factors. The design width of the channel will be determined to accommodate the design ship(s) representative of the project forecasted user fleet. This width need not be constant throughout the project but may vary as necessary so that the design ship can make a safe, efficient, and cost-effective transit of the channel under the set of operational conditions chosen. The channel width required will depend on the following main factors:

(1) Design ship beam, length, and draft.

(2) Local piloted ship control.

(3) Channel cross section and alignment.

(4) River and tidal currents.

(5) Navigation traffic pattern (one- or two-way).

(6) Vessel traffic intensity and congestion.

(7) Wind and wave effects.

(8) Visibility.

(9) Quality and spacing of navigation aids.

(10) Composition of channel bed and banks.

(11) Variability of channel and currents.

(12) Speed of design ship.

b. Other Considerations. The design channel width is defined as the width measured at the bottom of the side slopes on each side of the channel at the design depth. Upon project authorization, the design widths are considered, nominally, to be the authorized widths. This should not preclude minor adjustments in width during continued design, construction, and operation as circumstances warrant and delegated authorities permit. The specified width provides for local increases at entrances, bends, turns, sidings, and maneuvering and turning basins as required to allow normal ship operations in a safe and efficient manner. Physical models and ship simulator techniques can be used to assess the safety and efficiency of alternative channel design widths. Paragraph 8-2 discusses preliminary channel design, especially at the initial stage of navigation projects.

8-2. Channel Alignment.

a. *Design.*

(1) To minimize initial and maintenance dredging, the alignment of a navigation channel is usually designed to follow the course of the deeper channel in a river or estuary. The channel layout should also consider the effects of speed and direction of currents as well as predominant wind conditions on ship navigation. In general, currents aligned with the channel are desirable to reduce the adverse navigation effects from crosscurrents. In tidal flow situations, there are often separate flood and ebb natural channels, which may not be the same. In meandering river waterways, navigation channel crossings from one outside bend channel to the next will also require dredging through natural shoal areas. Circular bends in alignment should not be necessary, except in large angular deflection channel turns. An alignment consisting of straight reaches with small turns between channel segments permits pairs of range markers to be located on the channel centerline. This provides for better channel location and ship pilot control than other possible channel aids to navigation. The straight segments between turns should be at least five times the length of the design ship. Most channel turns should be designed with cutoffs on the inside of the turn as described later in this chapter. Training structures, such as dikes, jetties, breakwaters, revetments, and wave absorbers, might be required to maintain acceptable channel alignment and dimensions and reduce wave conditions. The location and placement of these structures will have an impact on the channel navigability in addition to sediment movement and require careful design. Channel alignment that cuts across sandbars and mud banks should be avoided, if possible; training structures to control the movement and deposition of sediment will usually be required. As a general rule, entrance channels should be aligned parallel to the propagating direction of predominant waves. With this alignment, wave-generated crosscurrents and ship wave response are avoided and result in advantageous effects on both sedimentation control and ship handling.

(2) Channel alignment option studies should consist of selecting several alternate routes and developing construction and maintenance costs for each. Project benefits for each alignment will involve improvements associated with relative ship transit times. A comparison of annual project costs and benefits will determine the optimum channel alignment.

8-3. Channel Cross Section.

a. *Channel Variability.* The cross section of navigation channels varies substantially, depending on local project conditions, as well as along the length of the channel in the same waterway. Figure 8-1 presents example cross sections for three of the main types. It is possible to classify the channel geometry into four types of cross sections to develop channel-width criteria in a rational way, taking into account parameters that govern ship navigation. The usual “at sea” unconfined ship operating water environment is modified considerably in the normal restricted channel or waterway cross sections, which are defined and explained below:

(1) *Shallow water*. Wide, unrestricted waterways without channel banks, near the ocean end of entrance channels, usually provided with range markers and channel edge buoys. Substantial bottom effects but negligible bank forces and thus no noticeable vessel reaction to the proximity of the channel edge. Strong ship yawing forces from crosscurrent effects and wave action.

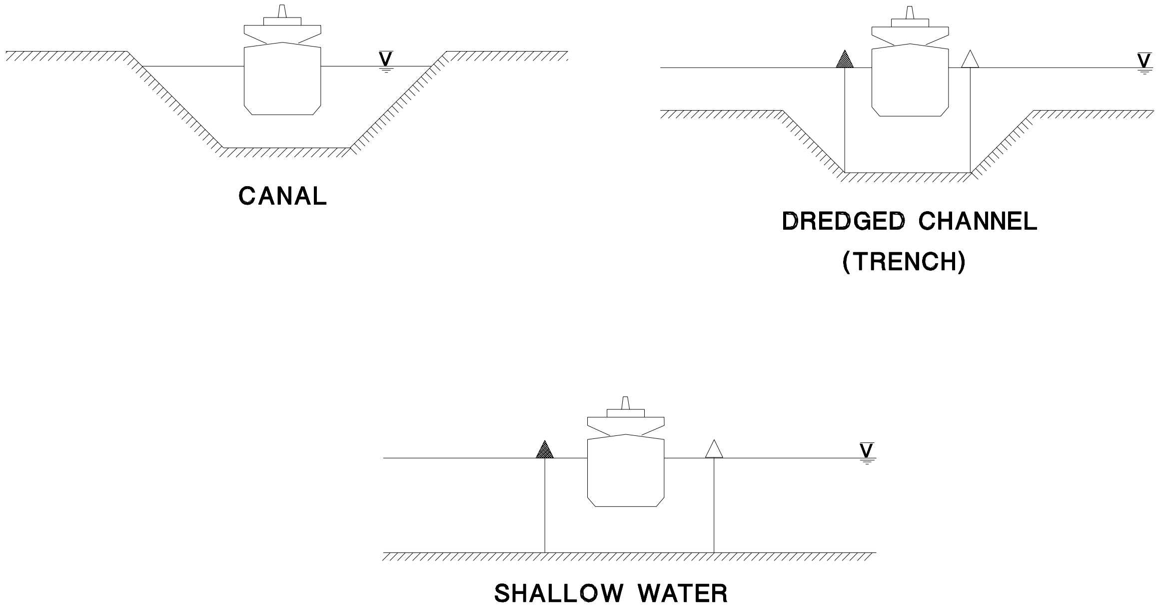


Figure 8-1. Channel cross sections

(2) *Canal*. Narrow, fully restricted channels with clear and visible banks often with only minimal aids to navigation. Negligible yawing forces occur, since currents are aligned with the channel, except at turns. Strong bank effects with off-center-line ship position and good bank cues.

(3) *Trench*. Dredged- or open-type restricted channels, intermediate between canals and shallow water, with submerged banks on each side, usually provided with range markers and channel edge buoys or beacons. Some ship yawing forces from crosscurrent and wave effects on ship navigation are often present with variable bank effects. Bank cues can be important in piloting. Magnitude of yawing forces dependent on overbank depth on each side of the sailing ship and crosscurrents, waves, and winds.

(4) *Asymmetric*. Different depths or bank conditions on each side of a channel centerline (stepped channels) or other combinations of asymmetry about the center or sailing line. In addition to range markers and beacons, channel edge steps are sometimes marked by special buoys. Possible strong bank force effects can be experienced with some ship yawing. There is a tendency for a ship to drift away from channel centerline.

8-4. Interior Channels.

a. Design Methodology. Harbor access channels leading from the bar or entrance channel to the port area are referred to as interior channels. For straight channels without any turns, the required channel widths to accommodate a given design ship should be determined based on the following factors in the order of importance:

(1) Traffic pattern (one-way or two-way).

(2) Design ship beam and length.

(3) Channel cross section shape.

(4) Current speed and direction.

(5) Quality and accuracy of aids to navigation.

(6) Variability of channel and currents.

Design widths have, in the past, been based on dividing the total required width into a maneuvering lane and a bank clearance lane. The criterion was developed by assigning three levels of ship controllability and judgment as the main factors to consider in channel width design. Methods to deal with these factors have not been developed. Evaluation of many navigation project studies on the ERDC/WES Ship Simulator has shown that professional pilots do not think in a manner or control ships in a way that makes such channel width division logical. In fact, pilots routinely use the bank effects as a cue in determining ship position by deliberately moving the ship off the channel centerline toward the bank. Since there is no particular advantage in assigning a value to a maneuvering and a bank clearance lane, an alternative method has been developed. The following procedure refers to total channel width and incorporates the six factors listed above as the most important in deciding the design channel width. Figure 8-2 presents two examples of channel width definition.

b. *Width Criteria.* Numerous studies have been made reviewing generally accepted design practice in dimensioning channel widths for ship navigation. For one-way ship traffic, values vary from 2.0 to 6.0 or even 7.0 times the design ship beam. A range of 2.8 to 5.0 had been developed based on McAleer, Wicker, and Johnston (1965) and used for design criteria. Simulator studies have consistently showed that it is possible to control ships sailing in quite narrow channels and that the available Corps and international design criteria are overly conservative. In particular, simulator tests on the Sacramento River and the Brazos Island Harbor both indicate that uniform, straight canals with very small currents resulted in recommended channel widths near 2.0 times the design ship beam. Table 8-1 summarizes these test results.

Table 8-1
Channel Design Width Tests

Simulation Study	Design Ship Beam, m (ft)	Recommended Channel Width, m (ft)	Width/Beam, m (ft)
Brazos Island Harbor	32 (106)	76 (250)	0.7 (2.4)
Sacramento River	28 (93)	61 (200)	0.3 (2.2)

Based on these test results, a value of 2.5 times the design ship beam for canals with negligible currents should be conservative. Using this value and other available data, Table 8-2 is proposed for interim use in one-way channels:

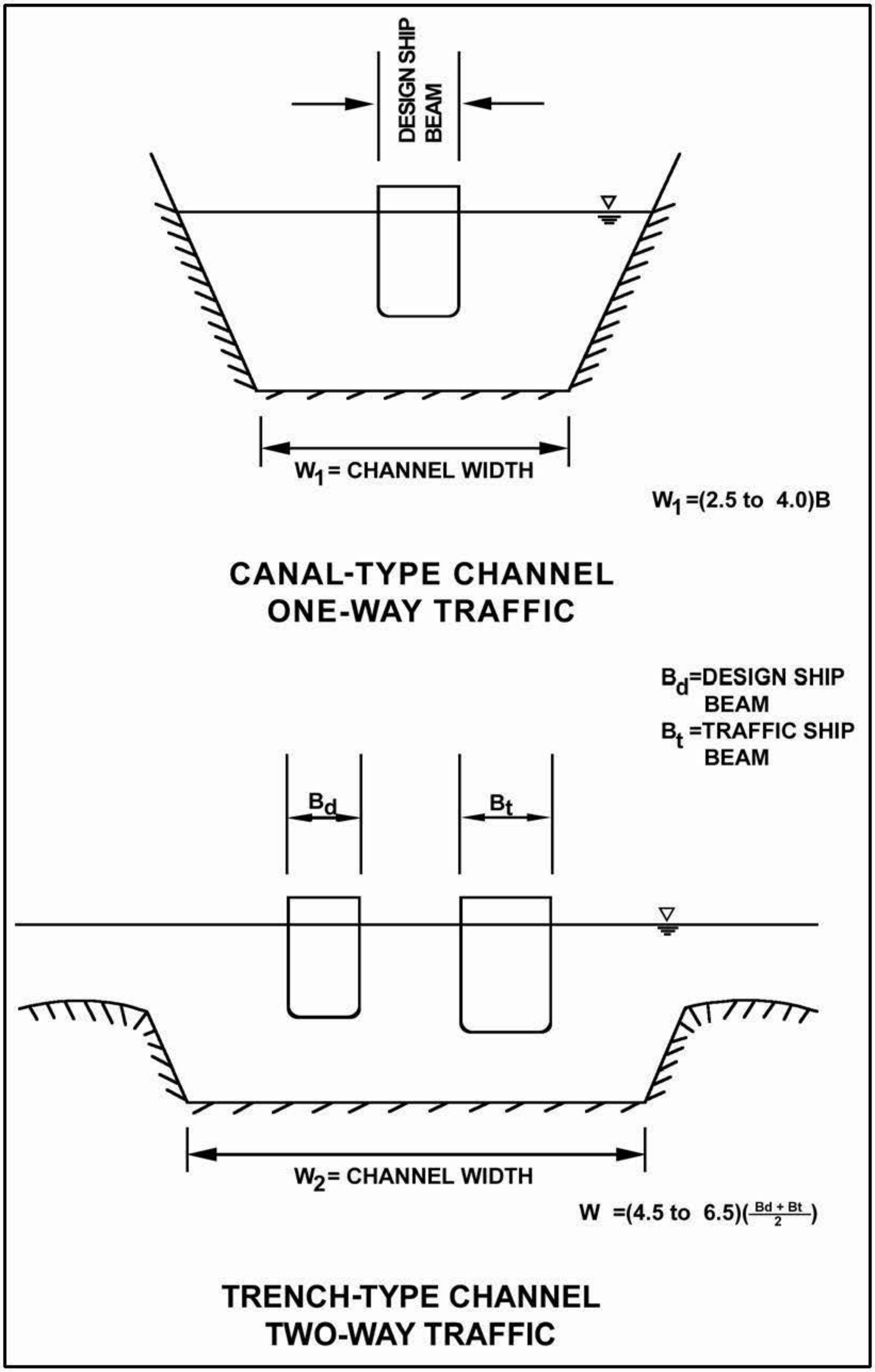


Figure 8-2. Channel design width

Table 8-2
One-Way Ship Traffic Channel Width Design Criteria

Channel Cross Section	Design Ship Beam Multipliers for Maximum Current, Knots 0.0 to 0.5	0.5 to 1.5	1.5 to 3.0
Constant Cross Section, Best Aids to Navigation			
Shallow	3.0	4.0	5.0
Canal	2.5	3.0	3.5
Trench	2.75	3.25	4.0
Variable Cross Section, Average Aids to Navigation			
Shallow	3.5	4.5	5.5
Canal	3.0	3.5	4.0
Trench	3.5	4.0	5.0

Developing a similar table for two-way ship traffic is difficult because of lack of simulator data. An analysis of published criteria shows a similar highly conservative basis for design. Recent testing on the Houston Ship Channel resulted in data that were also used to develop Table 8-3.

Table 8-3
Two-Way Ship Traffic Channel Width Design Criteria

Uniform Channel Cross Section	Design Ship Beam Multipliers for Maximum Current, Knots (ft/sec) 0.0 to 0.5 (0.0 to 0.8)	0.5 to 1.5 (0.8 to 2.5)	1.5 to 3.0 (2.5 to 5.0)
Best Aids to Navigation			
Shallow	5.0	6.0	8.0
Canal	4.0	4.5	5.5
Trench	4.5	5.5	6.5

The design channel width for navigation projects with maximum currents greater than 3.0 knots should be developed with the assistance of a ship simulator design study. Furthermore, bank suction can significantly affect ship maneuvering in narrow channels; however, there is no simple analytical relationship between these effects and channel width design criteria. Bank effects should be considered during channel design and can be handled most efficiently through the use of numerical modeling techniques such as those used in a ship simulator.

8-5. Entrance Channels.

a. Entrance Channel Navigation.

(1) Navigation in entrance channels is often affected adversely by strong and variable (in space and time) tidal currents, rough seas and swell, breaking waves, and wind. In some places, frequent fog, snow, and rain will also cause visibility problems. At some level of ship control difficulty, the navigation traffic may be stopped through the port entrance channel or bar by the U.S. Coast Guard, local pilots, or other entity, i.e., the bar is "closed." It is important that the project planner/designer develop operational information on bar closure conditions to be able to design an optimum entrance channel width without compromising safety. Depending on local conditions, safe navigation will usually require a wider and deeper entrance channel than the port interior channels. The magnitude of this is difficult to estimate but should be based primarily on horizontal ship motion from wave effects. It may be necessary in some cases to design the entrance channel for two-way traffic because of the intensity of port navigation, which would increase channel width even more.

(2) Bar channels and entrances protected by jetties and training structures will require special studies of tidal currents, wave conditions, littoral drift, and shoaling tendencies to determine the optimum channel width and structure arrangement. Other design parameters such as channel alignment, required cross section, and degree of harbor wave action can also be developed during such a study. Each project will require substantial information on local conditions for the design analysis and evaluation studies needed for judicious overall project design.

b. *Entrance Channel Width.* The width allowance in excess of the interior channel width to account for wave effects on horizontal ship motion is difficult to estimate. A recent project for Barbers Point Harbor using a physical model study at the Coastal and Hydraulics Laboratory (CHL) at ERDC/WES (Briggs et al. 1994) included extensive measurements of ship model motion and piloting to help design the entrance channel. Another project on the San Juan Harbor involved a mathematical model of ship response and piloting on the WES ship simulator (Webb 1993) to develop a safe and adequate entrance channel. These two references should be reviewed and the individuals at ERDC/WES consulted to gain the most recent information. Field data measurements of ship horizontal motion were also conducted at the Mouth of the Columbia River project and should also be reviewed (Wang et al. 1980).

8-6. Channel Turns and Bends.

a. *Ship Turning Maneuver.* The swept path of a ship making a turn is wider than its swept path in a straight channel simply because of the geometry of the turning ship. Experience has shown that controllability of a ship while turning is degraded compared to maneuvering in a straight channel, thus causing a wider swept path. The width of the swept path is dependent on the following:

(1) Ship yaw angle while turning.

(2) Length and beam of the ship.

(3) Ship rudder angle.

(4) Possible use or nonuse of kick turning by the pilot.

(5) Location and spacing of aids to navigation in the turn.

(6) Local current and other environmental conditions.

If the turning is in a given channel configuration, the channel turn radius, the deflection angle of turn, and the channel width and variability will also have an impact. Generally, channels with turns and bends are more difficult to navigate compared with straight reaches because of reduction in sight distance, reduced effectiveness of aids to navigation, changing channel cross-sectional area, and greater effect from varying current and bank suction forces.

b. *Channel Width in Turns.* Since the swept path of a ship making a turn is wider than the path in a straight channel reach, a greater channel width is required in turns and bends. The swept path of a turning ship is dependent mainly on the channel turn radius and the ship length. Figure 8-3 presents a definition sketch of the relevant variables and a plot giving required channel width increase in turns. The deflection angle of the channel turn may also be a factor resulting from the piloting and ship control difficulty while maneuvering a ship around a channel turn. Since pilots often use the bank effects to assist in a turn, the bank conditions are also very important to the design of the turn. However, the recommended turn design does not include bank effects. The graph shown in Figure 8-3 can be used to relate the required channel width increase in a turn for design purposes. Channel turns should not be designed for turn radius-to-ship length ratios less than 3, because ships cannot hydrodynamically maneuver around a sharper turn. Table 8-4 summarizes the recommendations on channel turn configurations including channel width increases in the turn. The table includes recommended turn radius-to-ship length ratios as a function of the turn deflection angles. Figure 8-4 gives a definition and geometric relations for each recommended turn type.

c. *Turn Design.* The channel turn width increase indicated in Table 8-4 can be designed in several ways. Recommendations for specific turn types varying from a straightforward (unwidened) angle to connecting circular arcs are also presented in the table as a function of the turn deflection angle (Figure 8-4). In general, the greater the deflection angle, the longer the channel turn or curve for a given turn radius. A common method to provide the additional channel width is the apex or cutoff method, which provides the turn width increase on the inside of the turn using a single straight line. Alternatively, multiple straight lines can be used to replace the single line on the inside of the turn. In some cases, the outer point can also be cut off, since ships would not use the outer turn apex. The apex turn may produce adverse current patterns, especially in canals or high current situations, which would be detrimental to ship navigation. An alternative turn may be designed using circular arcs with parallel or nonparallel banks. The width increase is provided through the turn with transitions to the straight channel segments on each end of the turn. Transitions assist pilots in maintaining control as the ship is steered out of the turn.

Table 8-4
Recommended Channel Turn Configurations

Deflection Angle, Deg	Ratio of Turn Radius/ Ship Length	Turn Width Increase Factor (* Ship Beam)	Turn Type
0 - 10	0	0	Angle
10 - 25	3 - 5	2.0 - 1.0	Cutoff
25 - 35	5 - 7	1.0 - 0.7	Apex
35 - 50	7 - 10	0.7 - 0.5	Curved
>50	>10	0.5	Circle

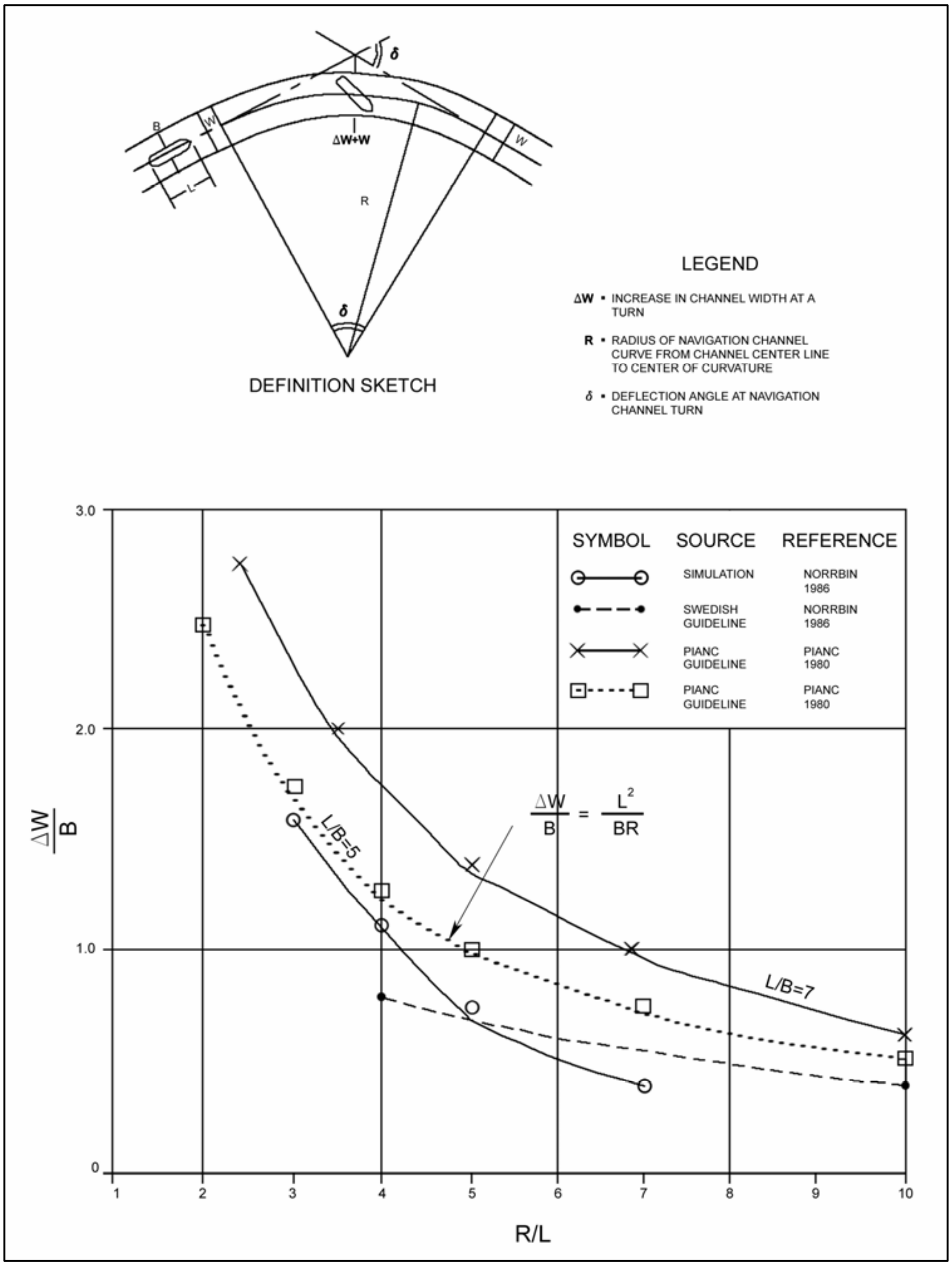


Figure 8-3. Channel width increase in turns

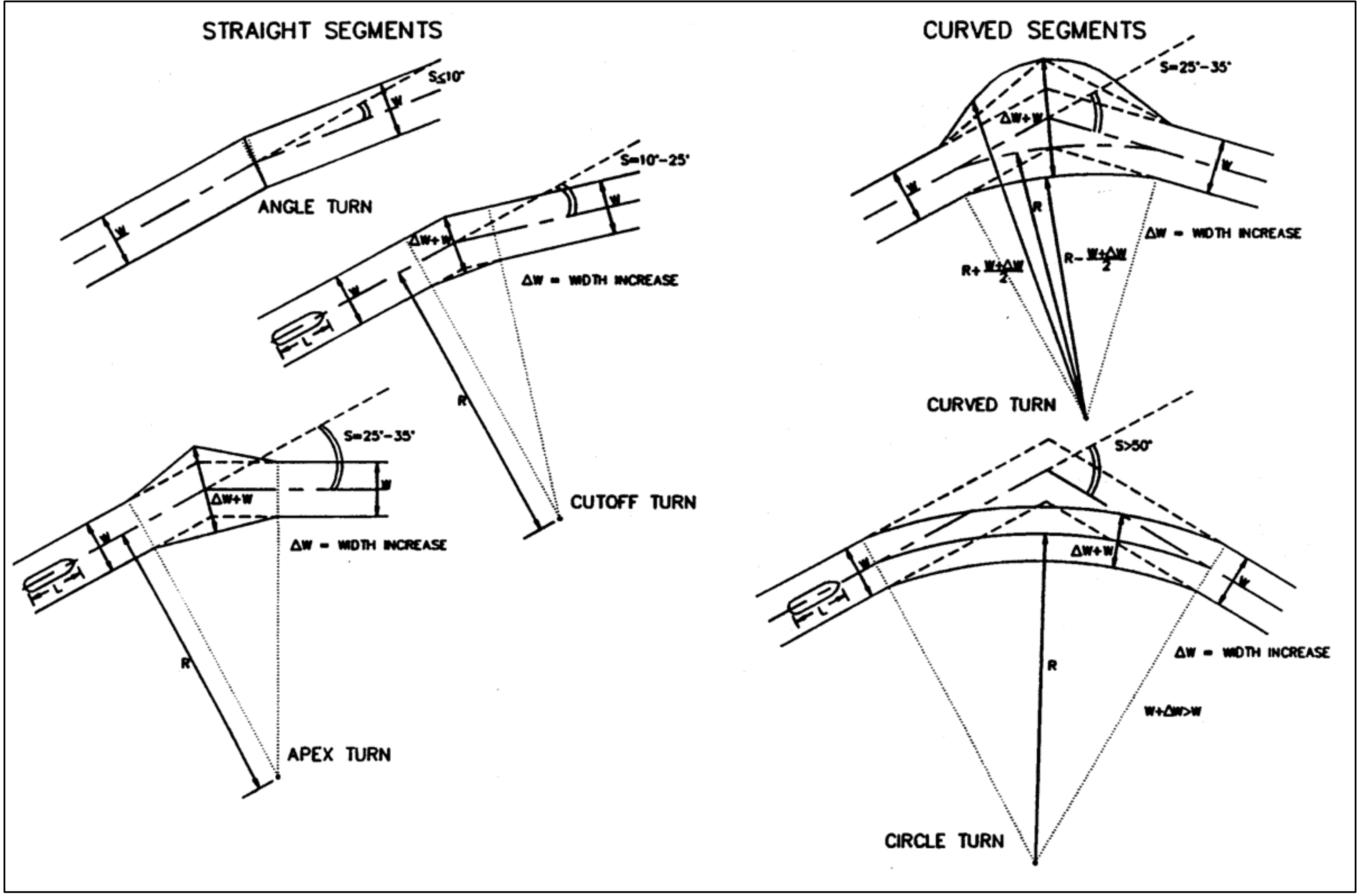


Figure 8-4. Channel turn configurations

d. *Width Increase.* Increasing the width of channels in turns could affect the current pattern alignment, which may tend to cause ship steering problems. Channel shoaling tendencies could also be affected and rates and location of shoaling areas changed. The local effects of currents, wind, waves, and visibility on ship piloting must be evaluated for each project. Physical ship models and appropriate testing facilities are available at ERDC/WES to conduct design studies when required. Numerical models of currents and sediment movement in conjunction with the ERDC/WES ship simulator can provide comprehensive study capabilities when warranted by the project.

e. *Successive Turns.* Successive turns or double bends can be reverse turns (S-bends) or consecutive (U-type) turns. An important variable is the length of straight segment between turns that should be provided to allow the ship pilot to regain control prior to starting the maneuvers for the second turn. Swedish research by Norrbin (1986) indicates that at least five times the design ship length of straight segment should be allowed between successive turns. In some cases, the physical constraints will dictate tighter turns, perhaps with little, if any, straight segments between turns. Design of such special circumstances should be done by using ship simulation testing to develop appropriate channel alignments and dimensions.

CHAPTER 9

Integral Project Features

9-1. Navigation Features. The following is a list of navigation features normally considered as a part of the overall improvement project:

a. Turning basins.

b. Anchorage areas.

c. Jetties and breakwaters.

d. Dikes and other channel training or control structures.

e. Salinity barriers.

f. Diversion works.

g. Aids to navigation.

h. Ice barriers.

i. Maneuvering areas.

j. Ship locks.

k. Channel wideners at turns or bends (local width increases).

These individual features when pertinent are usually integral to and necessary for the day-to-day operation of the port and allow the design ship to sail through the proposed channel improvement project in a safe and efficient manner.

9-2. Turning Basins.

a. *Ship Turning.* In normal operations, turning basins are used by the pilots in conjunction with two or more tugs to bring the ship about. Full advantage is also taken of the prevailing currents and wind conditions to help maneuver the ship. The pilot strategy may be different on flood or ebb tide current and may change with wind direction. If the ship is equipped with thrusters (bow or stern, sometimes both), then these will be used to the fullest. The ship engine and rudder are usually manipulated, which will provide additional control. Care is usually taken to keep the ship stern away from shoals, rocks, banks, and docks to minimize possible damage to propellers and rudders. Pilot strategy may change, however, depending on the location of the ship bridge on the ship. When the bridge is located at or near the stern of the ship, turning will be accomplished using the stern with another visible reference to control and monitor ship position.

b. *Location.* Navigation channel project improvements will provide for a turning basin to enable the ships to be turned about to reverse ship direction and allow an outbound sailing transit. The basin is usually located at the head of navigation near the upstream end of the channel project, upstream of a group of terminals and docks on a long channel, or at the entrance to a side channel with berthing facilities. The turning basin will be designed to provide sufficient area to allow the design ship to turn around using ship bow and stern thrusters (if available) and with local port tug assistance. Preference in turning basin location should be given to a site with the lowest current effects, since this has a major impact on the turning ship and therefore the size of the turning basin. Figure 9-1 gives recommended shape and size of turning basins in low and high current situations.

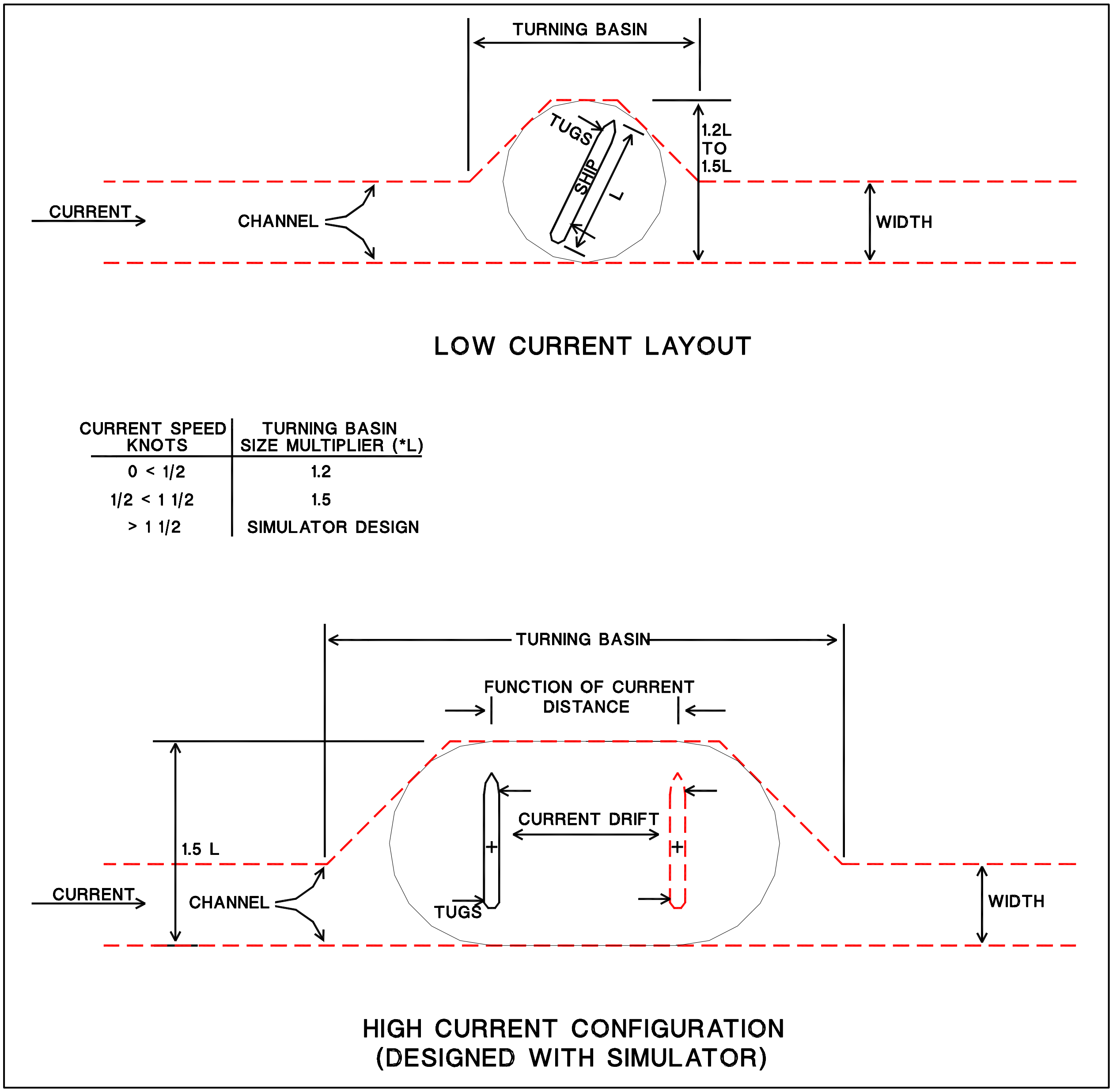
c. *Size.*

(1) The size of the turning basin should provide a minimum turning diameter of at least 1.2 times the length of the design ship where prevailing currents are 0.5 knot or less. Recent ERDC/WES simulator studies have shown that turning basins should provide minimum turning diameters of 1.5 times the length of the design setup where tidal currents are less than 1.5 knots. The turning basin should be elongated along the prevailing current direction when currents are greater than 1.5 knots and designed according to tests conducted on a ship simulator (Figure 9-1). Turning operations with tankers in ballast condition or other ships with high sail areas and design wind speeds of greater than 25 knots will require a special design study using a ship simulator.

(2) Where traffic conditions permit, the turning basin should use the navigation channel as part of the basin area. The shape of the basin is usually trapezoidal or elongated trapezoidal with the long side coincident with the prevailing current direction and the channel edge. The short side will be at least equal to the design multiple (1.2 or 1.5, depending on the current) times the ship length. The ends will make angles of 45 deg or less with the adjacent edge of the channel, depending on local shoaling tendencies. Modifications of this shape are acceptable to permit better sediment flushing characteristics or accommodate local operational considerations.

d. *Depth.* Normally, the depth of a turning basin should be equal to the channel depth leading or adjacent to the basin proper. This is done to prevent any possibility of confusion by the channel project users that could cause grounding accidents. The normal dredging tolerance and advance maintenance allowance are included in the depth of the turning basin. In some operational circumstances where design ships will always turn in ballast, the turning basin could be designed to a smaller ballasted ship draft, which could provide substantial cost savings.

e. *Shoaling.* A turning basin will tend to increase shoaling rates above normal channel rates because of the increase of the channel cross-sectional area, which modifies current patterns. Increased shoaling in the basin could cause modifications in shoaling patterns farther downstream or upstream.



CURRENT SPEED KNOTS	TURNING BASIN SIZE MULTIPLIER (*L)
0 < 1/2	1.2
1/2 < 1 1/2	1.5
> 1 1/2	SIMULATOR DESIGN

Figure 9-1. Turning basin alternative designs

9-3. Anchorages. Anchorages are provided near the entrance to some ports for vessels awaiting berthing space, undergoing repairs, receiving supplies and crews, awaiting inspection, and lightering off cargo. In cases with long navigation channels to get to the port area and heavy traffic, additional anchorages may also be provided along the channel. As shown in Figure 9-2, design of the required anchorage area depends on the method of ship mooring, the size and number of the ships in the anchorage, and the environmental forces (wind, currents, and waves) acting on the anchored ships. Normally, anchorage areas provide space to allow for free-swinging bow anchoring, since some ships are not equipped with stern anchors. Free-swinging moorings require a circular area having a radius equal to the length of the ship plus the length of the anchor chain (scope of the anchor). The U.S. Navy (1981) has calculated a set of tables giving these required dimensions from which the following approximation can be developed for average 15-m (50-ft-) depth conditions and design ship lengths from 213 to 305 m (700 to 1,000 ft):

$$D/L = 3.0 \tag{9-1}$$

where

D = diameter of anchor swing in feet

L = ship length in feet

This formula assumes that the length of the anchor chain swing circle is six times the depth and that 2.7 m (90 ft) of anchor drag occurs. Large free-swinging anchorages can be expensive to construct and maintain, since sedimentation frequently becomes a problem. Consideration should be given by the designer for the use of fixed mooring dolphins, which can substantially reduce the dredging area costs. Figure 9-2 presents two design anchorage configurations for two ships with free-swinging and fixed mooring situations.

9-4. Jetties and Breakwaters.

a. *Layout.* Entrance channel jetties are usually designed to maintain a stable channel location and depth, control sediment from littoral drift, and reduce wave action in the entrance navigation channel. Some entrances at coasts with high wave action may also include breakwaters in addition to or separate from the entrance channel jetties. The entrance channel alignment should be oriented to reduce channel waves and control sediment movement, keeping in mind the ship maneuvering and control required through waves and crosscurrents. In most cases, two jetties, one on each side, will be needed to keep littoral drift from entering the channel. Jetties are normally aligned parallel with the channel alignment. However, curved jetties may act like a river training system and will help establish a stable deep channel on the outside of the bend. Converging alignments (arrowhead type) often produce unsatisfactory layout solutions because of greater length, no improvement in wave action, and entrance channel meandering. Some general entrance channel layout guidelines follow:

(1) Natural entrance channels in noncohesive (sandy) material are usually unstable.

(2) Parallel aligned twin jetties are preferred.

(3) Curved alignment should be considered if there is significant tidal flow or river discharge.

(4) Straight jetty alignments require closer spacing than a curved alignment to maintain channel depths.

(5) Unequal jetty lengths can cause asymmetric current patterns, making navigation difficult.

Further discussion on entrance channel layout and alternative structures is available in EM 1110-2-2904 and the Coastal Engineering Manual (CEM), Part V, Chapter 5.

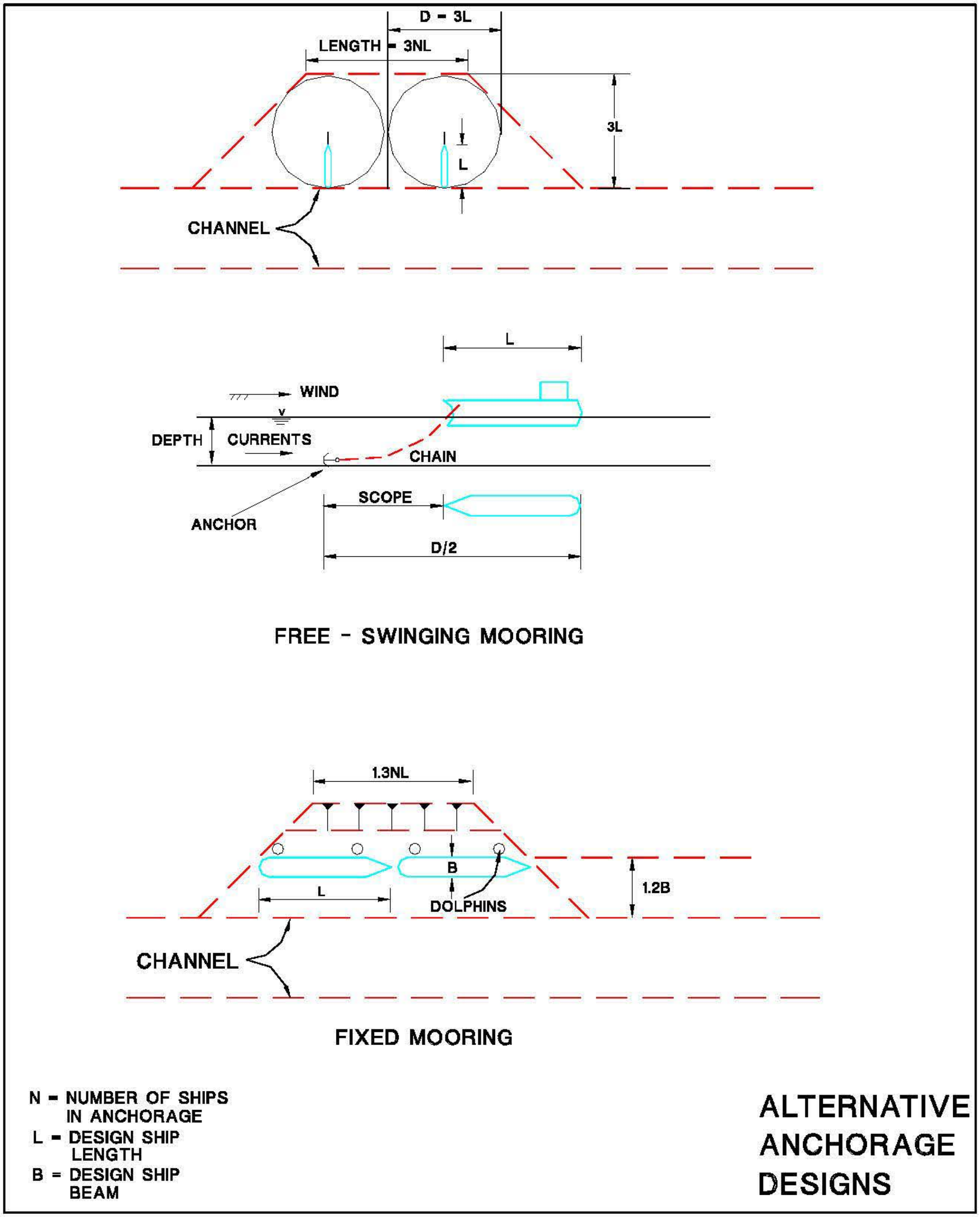


Figure 9-2. Alternative anchorage designs

b. *Spacing.* Determination of the width of the entrance channel should consider navigation difficulties that are frequently encountered in entrance channels from wave action, wind, crosscurrents, and poor visibility. The distance between the toes of the jetties is designed to provide space beyond the channel edges for jetty stability. Consideration of the penetration of wave energy into the harbor should be balanced with the necessary entrance channel width required for safe ship passage. As is the case for proper channel width design, the quality and spacing of the aids to navigation are important considerations also. Harbor entrance channels normally require larger widths than the interior channels as a result of more adverse navigation conditions. Entrance widths in the vicinity of the proposed project improvement should be compared and used in the initial design phase. In most cases, entrance widths equal to the ship length have been found to be satisfactory. Since the ship length-to-beam ratio for most commercial ships is about 1:7, a width of $7B$ may be used for preliminary project design. Spacing in tidal entrances may be governed by tidal flow considerations.

c. *Orientation.* One design criterium to be considered in the layout of jetties and breakwaters is adequate navigation depths in the area to be protected from waves, especially the entrance channel and the harbor interior. To minimize adverse ship motions and wave-generated crosscurrents, the entrance channel should be oriented in the direction of the more severe waves. Bar channels and entrances protected by jetties and breakwaters will require special studies of ship navigation, tidal currents, waves, littoral transport, and shoaling tendencies to determine the optimal design of channel width, cross section, alignment, orientation, and ship response to wave action. Waves aligned with the entrance channel will be reduced in height as they travel between jetties (Melo and Guza 1991a, 1991b). This reduction can be estimated by treating the jetty entrance as a breakwater gap. The inter-jetty propagation distance corresponds to the normal interior distance from the gap, and wave height change can be estimated from standard wave diffraction diagrams. As a general rule, jetties should be long enough to extend beyond the littoral zone so that sedimentation and breaking waves do not impact entrance channel navigation. Additional design details on channel and jetty alignment can be obtained from EM 1110-2-1607. Design procedures on jetty length and type are covered in EM 1110-2-2904. Consideration of hydraulic physical, ship simulator, and mathematical model tests is highly recommended for jetty and breakwater layout to optimize the design.

9-5. Ship Locks and Salinity Barriers.

a. *Ship Locks.* Salinity barriers may be required to control and mitigate the effect of salinity intrusion. A navigation lock is often used as an effective barrier against ocean salinity propagating into freshwater portions of estuaries and canals. General guidelines for salinity barrier design are presented in EM 1110-2-1607. The navigation conditions for ship locks require careful design, especially the lock approach conditions, which should provide adequate distance without waves, turns, and crosscurrents. An additional concern is the density-driven salt water admitted into the lock chamber and thence the upper pool during the lockage of vessels for navigation. Several devices and strategies have been developed to deal with this phenomenon, such as submerged gates on the lock floor, pneumatic barriers, and special design of lock filling and emptying systems. EM 1110-2-1611 and EM 1110-2-1604 discuss navigation and lock design considerations, respectively.

b. *Submerged Barriers.* Barriers can be located in the deeper portions of the navigation channel to reduce salinity intrusion by stopping the deeper, denser saline water's movement upstream. Permanent sills have been considered for installation in the San Francisco Bay to reduce possible saltwater migration into the San Joaquin Delta. A temporary, erodible sill was investigated and implemented in the Lower Mississippi River during the 1988 drought to help protect the freshwater supply for New Orleans (Johnson, Boyd, and Keulegan 1987). The effectiveness of submerged sills and salinity barriers should be investigated and designed with the help of appropriate physical and mathematical models.

9-6. Diversion Works. Diversion works are constructed to separate navigation channels from upland streams and to divert upstream flows. The purpose of the diversion might be to prevent sediment in the stream from shoaling the navigation channel, to limit salinity intrusion into the natural stream channel, or to return upstream flows back to estuarine areas for environmental purposes. Diversion works consist of a dam to close off normal discharges and a canal to convey diverted waters to a neighboring stream, bay, or sea. The environmental and navigational consequences of proposed flow diversion schemes will require intensive study as a result of potentially major changes in water quality and degradation of navigation conditions from crosscurrents and current increases.

9-7. Bridge Clearance.

a. *General.* The clear horizontal and vertical spacing available for navigation at overhead bridges should be sufficient to permit the safe transit of the design ship expected to use the navigation channel under normal operational conditions. The 1972 Waterways Safety Act placed responsibility for establishing bridge clearances with the U.S. Coast Guard. Therefore, initial project design planning of navigation projects involving new or existing bridge crossings should be coordinated with the local Coast Guard District Office, and final design will require Coast Guard approval. The following general guidance applies also to hurricane barriers, power line towers, or other structures that may be a potential obstruction to navigation in a waterway.

b. *Horizontal Clearance.* In general, it is desirable that the horizontal clearance between bridge piers, including bridge fenders, should be equal to or greater than the local channel width. The design should provide for location of bridge piers to cause ship grounding rather than collision with piers or obstructions, which could cause loss of life. Some projects with older bridges built when ships were much smaller than today may have very difficult navigation conditions, sometimes with very small ship clearances. The project planner/designer should study the possibility of upgrading such bridges or other structures to reduce possible navigation hazards. In some cases, smaller distances between bridge piers than desirable may be necessary, depending on local conditions. Each design should consider the following factors:

(1) Navigation traffic density and pattern (one- or two-way).

(2) Alignment and speed of water current.

(3) Risk of collision.

(4) Potential damage from collision, loss of life, hazardous cargo spillage, bridge and ship damage, and interruption to waterway and bridge traffic.

(5) Cost of bridge pier fendering to protect bridge and vessels.

(6) Possible addition of islands around bridge piers.

(7) Navigation span alignment and clearance of other waterway bridges.

c. *Vertical Clearance.* Ship superstructure including radar and radio masts may well be a limiting factor in ship navigation under railroad and highway bridges or other overhead obstructions above waterways and channels. The vertical clearance under bridges is the vertical height between the water level during normal ship transits and the lowest member of the bridge structure over the channel width. In tidal waterways, the water level specified is the mean higher high spring tide elevation. In rivers, some small percent occurrence of water level has been used to specify the water level. A study of the variation of water surface about the higher elevations should be undertaken for important waterway projects to establish vertical clearance (also called air draft).

d. *Bridge Approaches.* The navigation approach to overhead bridges should preferably be straight and normal or nearly normal to the bridge alignment. Crosscurrent alignment and magnitude have a significant effect on navigation conditions and may require an increase in channel width as well as possible channel or bridge realignment. The length of the straight reach of the approach channel on each side of the bridge should be five times the design ship length.

9-8. Training Dikes and Revetments.

a. *Dikes.* In rivers and waterways with high sediment transport subject to shoaling, training structures are frequently required to help maintain deep-draft navigable channel depths during low-water season. Several different types of training dikes have been developed to control navigation channel alignments and maintain adequate channel depths, including spur dikes, vane dikes, longitudinal dikes, and L-head dikes. Training structures are usually designed to constrict the flow at low-water seasons to increase water currents and the natural scouring tendency in the navigation channel. Longitudinal dikes extending along the waterway are often used to help guide or direct currents to reduce shoaling and improve navigation conditions. Dikes are usually constructed of timber pile clusters, stone, or piling with stone fill. Refer to EM 1110-2-1611, *Layout and Design of Shallow-Draft Waterways,* Chapter 7, Section V, for a more thorough discussion of this topic.

b. *Revetments.*

(1) Bank erosion caused by currents or wave wash from navigation is frequently a problem in natural streams and waterways with erodible banks. Protection from bank erosion by revetments should be considered, if required, during project design. Rock riprap and articulated concrete mattress have both been used as revetments to control bank erosion.

(2) The clearance between training structures and navigation channels must be adequate to assure safe navigation. Pilots and captains in charge of ships transiting along channels have a strong aversion to dikes and rock riprap and will keep their ships well away from such structures. It is desirable to locate dikes and revetments to avoid possible damage to ships striking these structures. Careful design and location are especially important in channel curves or turns where ships

are required to maneuver. Design procedures for river and waterway training structures are detailed in EM 1110-2-1611. The principles for the design of bank revetments are explained in EM 1110-2-1601. The location, layout, and orientation of dikes and revetments and the flow, deposition and scour, and impacts on the waterway can be determined best by use of a physical or numerical hydraulic model.

9-9. Hurricane Barriers. Storm and hurricane surges have historically caused major floods and damage in Europe, and the United States' structural barriers located near and across the entrance to rivers, bays, and coastal regions have been proposed, designed, and in some cases built in a number of developed areas. The details of surge analysis are treated in EM 1110-2-1412, which should be consulted for barrier design. The following discussion presents important navigational impacts that should be considered in barrier planning and design.

a. Hurricane and storm surge barriers are normally located as close to the ocean as possible to increase the area of protection inside the river or bay. In most cases, a navigation lock or gap will be required as a part of the barrier. The approaches to the navigation gap or lock should allow for a straight sailing course for a distance equal to five times the design ship length. It is desirable that the design reduces or prevents crosscurrents and wave action in the gap approach to maintain safe navigation. The width and depth of the navigation gap should be designed to allow adequate clearance by normal size ships with due regard for safety of ship transits inside the barrier. To reduce upstream surge transmission, the gap width and depth should be kept as small as possible; thus, there is a need in planning and design to optimize and balance project benefits from flooding reduction with the requirements of navigation.

b. Because current velocities though the navigation gap will be greater than the normal or preproject currents in the waterway, the design should consider whether the user ships can navigate safely through the hurricane barrier. A satisfactory design of the navigation gap and adjacent control gates usually will require the development and use of the appropriate numerical and physical models as well as a ship simulator study. From these studies, an optimum arrangement and barrier location can be developed that will provide for adequate surge protection and safe ship navigation conditions. Model studies can also provide assistance during project construction to reduce any adverse navigation conditions.

9-10. Sediment Traps. Sediment traps or deposition basins are areas in the waterway that are excavated in or near the navigation channel to reduce shoaling in the project navigation channel and manage the sedimentation processes so that the project maintenance dredging is conducted in the most cost-effective manner. Sediment traps have been provided in navigation projects in both estuarine and littoral environments. The effects on navigation from the sediment trap should be considered in the design and trap location for the range of conditions and proposed dredging operations at the sediment trap. For example, the location of a sediment trap on the outside edge of a turn may eliminate the bank cushion effect normally used by pilots to assist in turning the ship. The investigation procedures of sediment traps using physical and numerical models are outlined in EM 1110-2-1607 for estuarine areas. The design procedures to be used in the littoral zone are covered in the *Shore Protection Manual* (1984).

CHAPTER 10

Aids to Navigation

10-1. General. Aids to navigation are used by mariners to determine ship positions and to plan a safe course through a waterway. The proper use of aids requires accurate and up-to-date information on their position relative to the navigation channel, usually involving location on the appropriate nautical charts. Different aids are used to assist in marking harbor entrances, straight channel edges, shoal areas, wrecks and other navigation obstructions, channel centerlines, alternative two-way lanes, and channel turns. Aids include buoys, fixed beacons, lights, sound signals, and electronic systems such as radio beacons, RAdar beaCONS (RACONS), loran, etc. The U.S. Coast Guard is responsible for the design, establishment, and maintenance of all aids to navigation in Federal Interstate waters. The general information provided below is presented to the navigation channel designer to give a brief overview; more details may be obtained in U.S. Coast Guard (1981, 1988a,b) or by contacting the Coast Guard. Figure 10-1 gives two examples of typical ranges and buoys used to mark navigation channels by the Coast Guard.

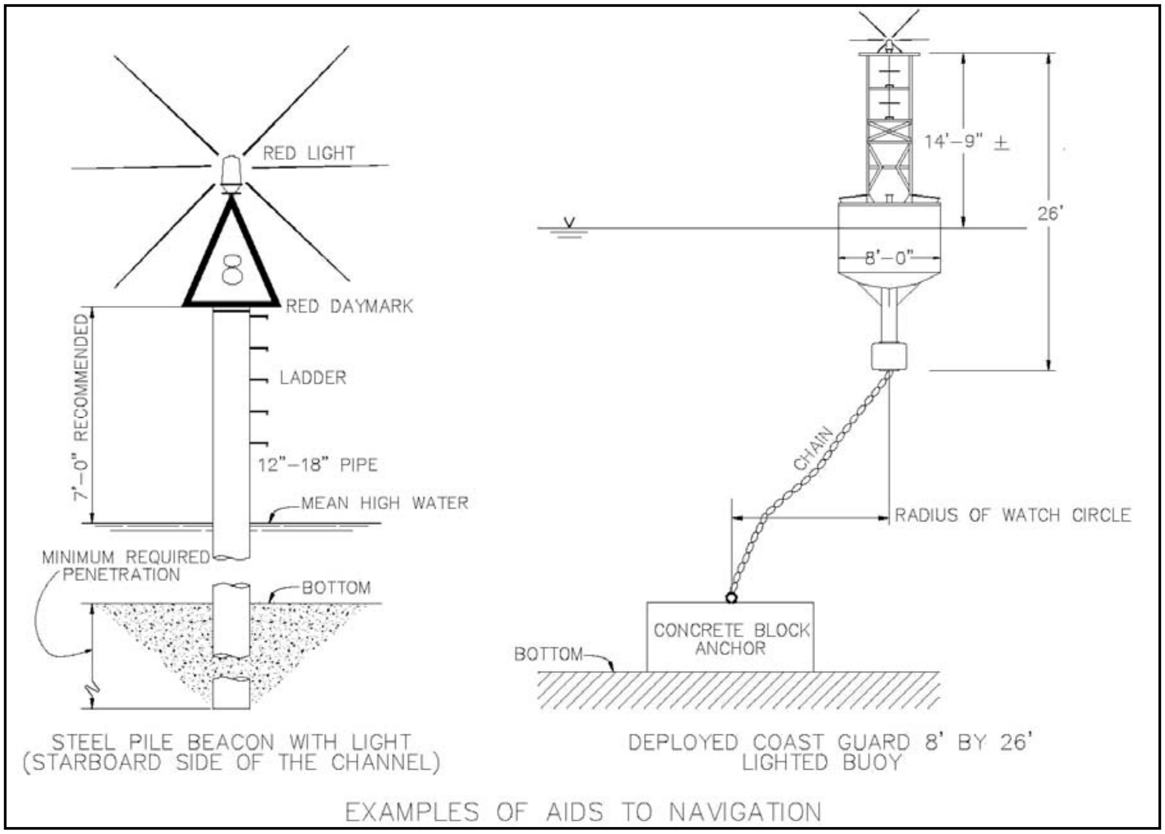


Figure 10-1. Examples of aids to navigation

a. Buoys are floating devices in the water anchored to the bottom with a chain connected to a concrete block. They are located to mark channel boundaries, hazards (such as navigation obstructions, wrecks, or rocks), and channel curves or turns. Some buoys are simple cans and nuns; others are enhanced with lights, sound, radar reflectors, and electronic signals. A unique system of shapes, colors, and numbering or lettering gives the mariner location information and provides enhanced radar reflectivity. Specially designed buoys are used in ice-prone harbors in the Great Lakes and Alaska.

b. Beacons are fixed structures, generally on pilings in shallow water up to about 4.6 m (15 ft). Beacons may be simple visual day beacons with colored, numbered signboards used to mark channels similar to buoys. Other beacons are enhanced and include flashing lights and radio transmitters; the unique marking system for buoys is also used for beacons. In contrast to buoys, which are limited in height above the water surface, beacons can be built to various heights, thus providing greater visibility at a distance.

c. Ranges are pairs of fixed structures usually located beyond and on the channel centerline at one or both ends of straight channel reaches. Some harbor channels include additional range pairs to mark the center of multiple traffic lanes (quarter ranges). Mariners use the front and rear range markers to provide information on lateral ship position in the channel and thus provide a line for the ship to follow. Ranges are usually on shore or in very shallow waters, with the two markers fixed at different heights, the rear marker always higher than the front. Most important ranges include high-intensity lights for visibility during night transits. Sequentially flashing lights, some in color, are used to distinguish ranges.

d. Lights may be located in conjunction with buoys, beacons, or ranges but are also used as additional fixed aids in certain locations. Each light has a unique color and flashing sequence to help in identification during nighttime navigation. Some lights are designed to provide individualized sector coloring over certain portions of their viewing angles for special warnings. Directional lights are used to aid in channel navigation by providing a narrow beam of contrast color along the channel centerline.

10-2. Lateral Aid System. The system of unique aid identifiers used in U.S. Federal waters is nearly uniformly used and is consistent with the International Association of Lighthouse Authorities (IALA). This buoyage system employs an arrangement of laterally located navigation aid colors, shapes, numbers/letters, and light characteristics on each side of navigation channels to provide location information to the mariner. This lateral aid system as implemented in the United States is depicted in Figure 10-2. The system aid sequence is based on the convention of inbound transits from the sea along the navigation channels toward the head of navigation. Generally, this convention conforms to the flood current direction of buoyage.

a. *Colors*. Red is used to denote the right or starboard side of the channel when entering from the sea. Green marks the port or left side of the channel. Red and white vertically striped marker boards denote midchannel or safe water and are used for ranges.

b. *Shapes*. A cone-shaped nun buoy is painted red and marks the right channel side. A cylindrical can buoy is painted green and is positioned on the left side. Ranges are rectangular with the long side vertical.

c. *Numbers*. Aids are numbered from the sea. Even numbers are red and located on the right side of the channel. Green markers are placed on the left side. Ranges are usually given identification letters.

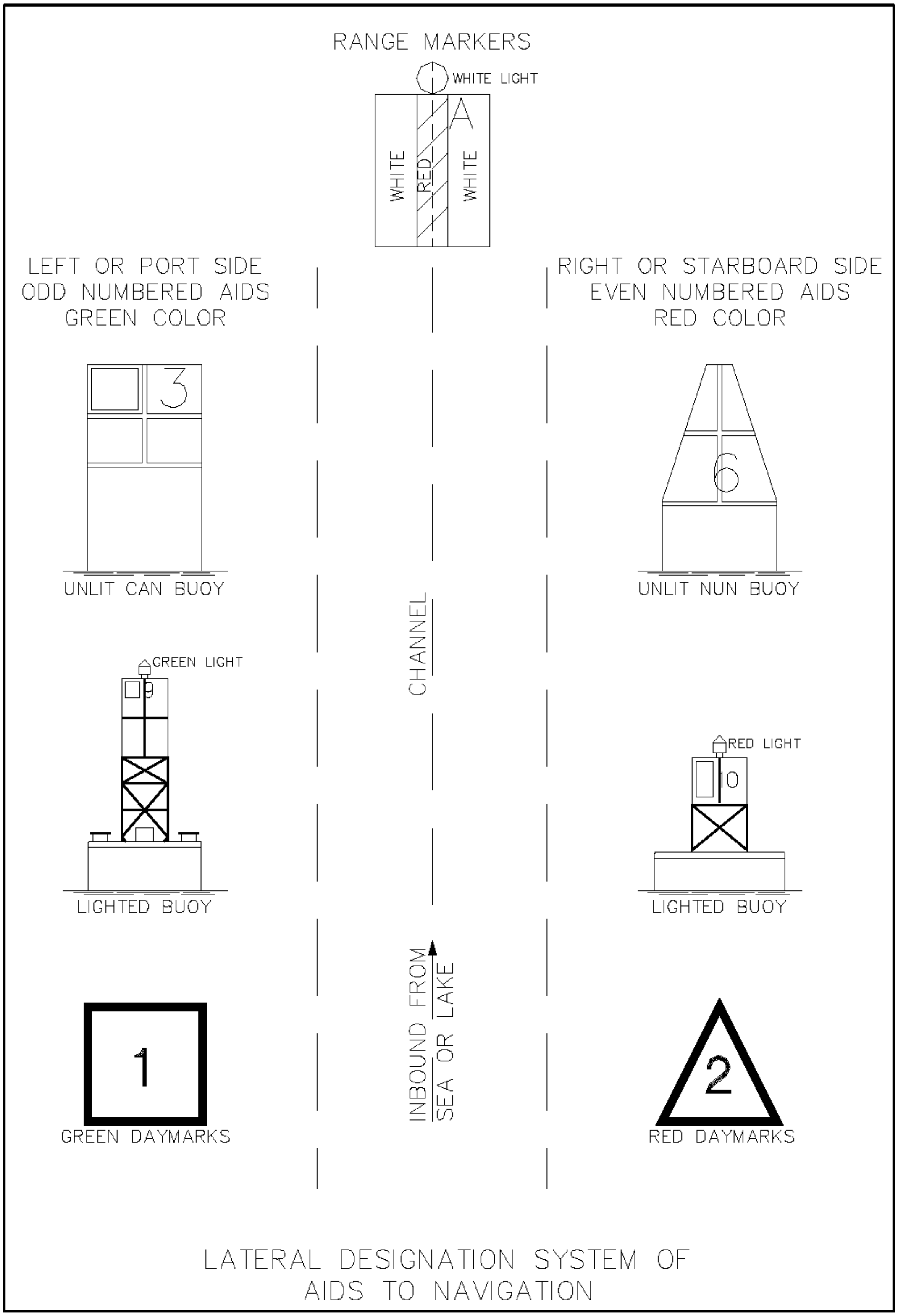


Figure 10-2. Lateral designation system of aids to navigation

d. Beacons. The lateral system also applies to fixed beacons with red triangular markers on the right side of the channels. Green square markers are used on beacons located on the left.

e. Lights. Red lights are also consistent with the system, being used to mark the right side of the navigation channels; green lights signify the left side.

10-3. Seacoast Aids. In addition to harbor channel aids described in paragraph 10-2, the Coast Guard operates an elaborate coastal aid system to help mariners in navigating along the U.S. coastline and in making landfalls from the open ocean. The following two types of aids are used by ship traffic as incoming beacons and departure points by pilots for port calls.

a. Major lights. Each major seacoast port is equipped with one or more primary lights located near the port entrance; this system has replaced most of the lighthouses and lightships. Major lights are high-intensity lights with high reliability located on a fixed structure or tower at heights sufficient to be visible over a long distance. Many of these lights are at heights up to 61 m (200 ft) above the water and are visible up to 40 kilometers (25 miles) away. The structures are often used to collocate other aids to enhance the structure's usefulness with additional electronic devices such as RACONS or radio beacons. Many of these lights are rotating white beacons, although other patterns and colors are also used.

b. Sea buoys. The ocean end of harbor entrance channels is usually marked by one or more special aids called large navigational buoys. These are used as clear designators to help mariners in identifying landfall location from the open ocean. Ships will usually anchor or stand by near entrance sea buoys while awaiting local pilot assistance in navigating from the ocean, across the channel bar, and into a berth in the harbor. Sea buoys provide several additional signals to assist the navigator, generally with a high-intensity light, electronic aids, and a sound signal, such as foghorns, bells, or whistles. Most large navigational buoys are about 12 m (40 ft) in diameter and 9 m (30 ft) or more in height above the water. They are usually located on the centerline of the channel some distance 1.6 to 3.2 kilometers (1 to 2 miles) beyond the end of the channel in deep water with white colors and lights.

10-4. Aid Design.

a. The aids to navigation that are ultimately put in place on a particular navigation channel project are selected after consideration of many factors. The dimensions, alignment, and layout of the project design are affected to an important degree by the aids to navigation. For example, by providing the navigator with better information through more aids to navigation or those with improved accuracy, a new or improved channel could be reduced in width while maintaining an adequate level of safety. It should be possible, therefore, to properly balance the cost and benefits of the aids with the incremental width construction cost. Early consultations with the local Coast Guard district should be undertaken during the channel design process to provide input for the design of the aids.

b. Port regulations and local operational policies can also have important effects on project design. Some of these include navigation traffic controls, vessel speed regulations, limiting some channel reaches to one-way traffic, requiring tug assistance or special steering or propulsion devices, and restricting vessel transits under certain environmental conditions. Regulations requiring certain on-board vessel devices to improve the information available to the navigator also impact channel design. Some of these include radar, depth finders, speed logs, gyrocompass, rate of turn indicators, etc. The availability of a local port VTS may also influence navigation safety and channel dimensions.

10-5. Accuracy.

a. Buoys are subject to deviation about their anchor point, depending upon the depth of water, tidal fluctuations, currents, and winds. Some discrepancy also exists because of uncertainty in precise placement of the buoy. The buoy "watch circle" as shown by a dot or circle on navigational charts is a rough guide to the possible swing of the buoy around the anchor. The reliability of buoys may also be a source of difficulty to mariners because of possible sinking, displacement, or drifting from ramming or dragging by vessels, ice effects, vandalism, and high flooding conditions or waves. Location errors up to two times the water depth are possible.

b. Ranges are probably the best visual aid, being fixed in position, thus providing the high accuracy necessary in ship position alignment. Figure 10-3 shows how ranges are used by mariners to locate their ship position relative to the channel centerline. Location accuracy is dependent on several factors, including length of straight channel reach, width of channel, distance between front and rear range markers, marker height difference, and ship position in the channel reach. Detection distance of range markers is limited due to curvature of the earth and practical height of markers. Visibility in coastal areas can be limited in daytime by fog and haze and at night by background interference from lights and city light glare or glow. This causes a practical maximum length limit on straight channel segments of about 9 to 10 kilometers (5 or 6 miles). Most straight channel reaches are from 3.2 to 4.8 kilometers (2 to 3 miles) in length.

10-6. Aid Arrangement.

a. The spacing and pattern of lateral channel markers (buoys and beacons) have an important impact on the channel design. As a general rule, at least two channel markers should always be visible to the mariner on either side of the channel through a straight channel reach. Because of the normally hazy conditions that prevail at most channels, visibility is often limited to less than 1.5 nautical miles. These two circumstances result in maximum marker spacings of 1.25 nautical miles.; minimum spacing is usually 0.5 nautical miles. Markers can be located along a straight navigation channel in a single-sided, staggered, or gated manner. Simulator research by the Coast Guard has shown the clear superiority of gated markers in straight channel reaches.

b. The minimum requirement is that the inside of all channel turns should be marked. Channel turns can be marked in a variety of schemes, depending on the type of turn, whether cutoff or not cutoff. A cutoff turn would require a minimum of two markers, corresponding to the two changes of inside turn edge. Channel curves can also be marked using various ways. The benefits of providing three markers per turn were also demonstrated using simulation tests by the Coast Guard.

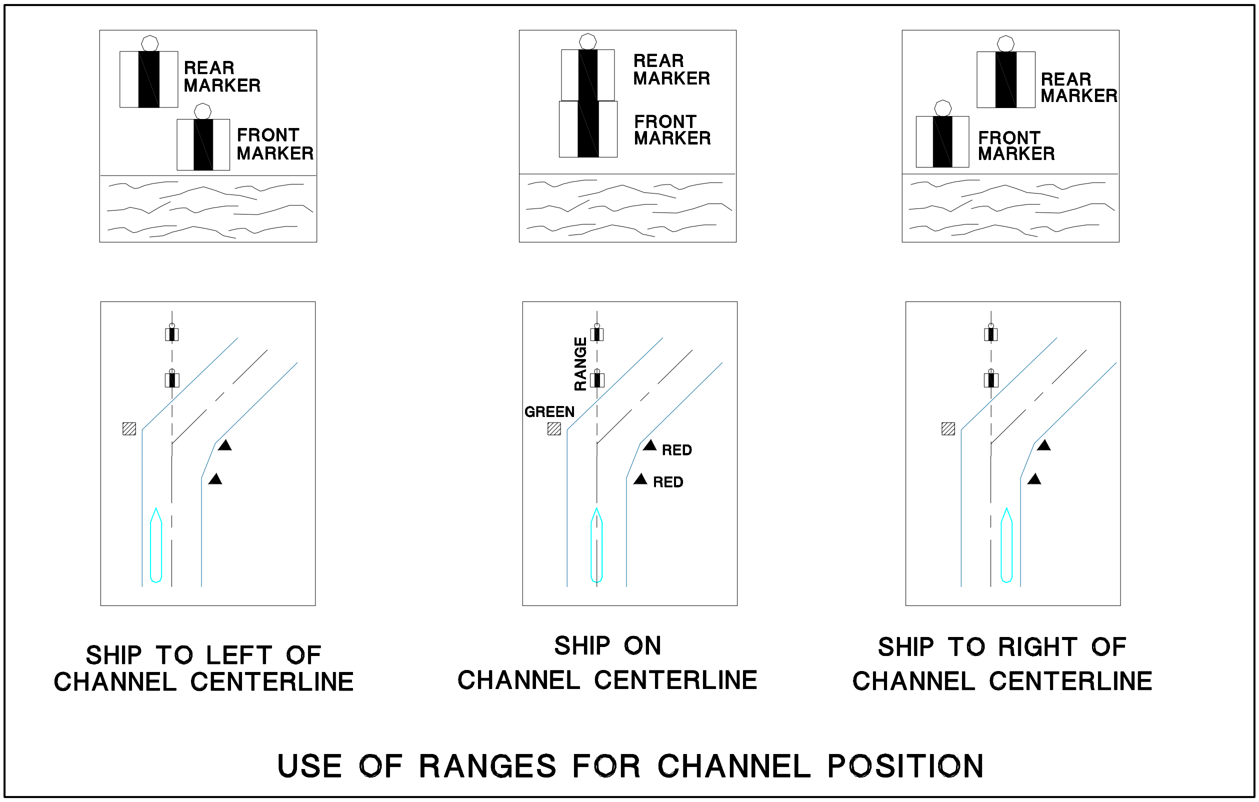


Figure 10-3. Use of ranges for channel position

c. Range markers may be located on both ends of channel straight reaches, or may be located on one end only, relying on a rear view for position location past a turn. Two pairs of range markers are normally used for important channels with strong crosscurrents or wind effects. The accuracy of long channel reaches greater than about 9 kilometers (5 miles) is degraded to a significant degree. The addition of side channel markers (buoys or beacons) to long channel reaches is usually necessary. Redundancy of aids is another important consideration; thus both range markers and side channel markers are used to provide a high degree of reliability.

10-7. Regulations.

a. Navigation in the coastal seas and U.S. waters is controlled by a number of rules and regulations of which the designer should be aware to develop sound engineering designs. The International Rules of the Road (often referred to as the COLREGS) (U.S. Coast Guard 1959) have been agreed to by the seafaring nations under the auspices of the International Maritime Organization (IMO), which is part of the United Nations. These rules have been implemented and agreed to by treaty of the U.S. Government and are part of the Code of Federal Regulations (CFR). Special adaptations have also been made part of U.S. law as pertains to Inland Rules, Great Lakes Rules, etc. Most of the rules apply to specific standards of vessel operation and required equipment. Specific requirements are provided for such activities as designated anchorage areas, lightering zones, regulation of VTS, regulated navigation areas, safety zones, etc. These are explained in detail in the several volumes of the Coast Pilot published by NOAA.

b. Operational rules at particular ports can be used in some instances to improve navigation safety and should be considered as an alternative to channel improvements in some cases. The promulgation of traffic separation schemes to guide inbound and outbound navigation traffic flow is one example of this. These are usually used to mark the approaches to a restricted channel in the ocean port approaches or in the wider, deeper reaches of a waterway or bay. The requirement for local pilotage service is another example of local regulations. States usually have primary jurisdiction in pilot matters; in some localities, the local port authority may exercise responsibility. Some rules are self-imposed by the pilots and may involve maximum ship size limits or tide height and current requirements for ship transiting.

c. The demarcation of port bulkhead lines and pier head lines along a navigation channel is an important function during channel design. The space between the channel limits and the pier head lines is normally used for ships at berth and dredged and maintained by local port authorities. Encroachment into Federal channels by docked ships, sometimes abandoned vessels, is often a problem in some ports. The Corps' review of permit requests should take potential navigation problems and possible channel encroachment into consideration in determining and enforcing permits.

d. Enforcement of applicable rules and regulations is the responsibility of the Coast Guard and is usually delegated to the local Captain of the Port.

10-8. New Technologies.

a. Several new techniques for marking channels and improving navigation safety to replace the more traditional aids to navigation are being studied by the Coast Guard. One of these systems includes the use of satellite-based Differential Global Positioning Systems (DGPS) for accurate (up to 2- to 3-m accuracy) ship location and navigation. The use of electronic navigation charts is another technology thrust area that is also being pursued on the international navigation level. Improved real-time data information systems, especially tides and current data, have been identified by pilots as an important need. Important advances will undoubtedly be made in this area, spurred by the environmental concerns from oil pollution incidents and accidents. These advances will undoubtedly affect operations and channel size requirements.

b. During recent years, two important navigation studies were undertaken in Europe to provide adequate channel access for supertankers to the largest class (up to the 500,000-dwt or Ultra Large Crude Carrier (ULCC) size). These studies were done for the Rotterdam Europort and at the port of Antifer/ Le Havre in France. Accurate ship position data by use of radio electronic navigation aid systems were crucial for keeping channel width to a minimum while maintaining adequate safety. A DECCA navigation chain with a pilot-furnished “brown box” receiver was developed and implemented for Rotterdam. In France, the system was called SAREA and employs an onboard transponder and receiver for use by the pilots. In both cases, strong tidal crosscurrents, wind, wave, and visibility conditions meant a requirement for high-accuracy positioning information. The results proved the safety of the channels and provided an economically viable project that would not have been possible with the required channel widths using standard criteria.

CHAPTER 11

Effects of Ice on Design

11-1. General. In regions where ice formation can be expected, the problems to ship navigation from ice should be considered in project design. Generally, deep-draft ice-prone areas in the United States include the Great Lakes, St. Lawrence Seaway, and Alaska. Ice cover affects the maneuverability of ships, power required to sail, the operation of navigation locks, and the stability of structures. Obviously, navigation ice effects increase with the thickness and extent of coverage of the ice. Some of the problems encountered with ice include larger ship turning radius; greater ship required power, which can increase movement of bottom sediment; ice accumulation on ship bottom increasing effective ship draft; higher loads on structures from moving ice; ice accumulation on lock walls, gates, and operating mechanism; and in some cases, increased vibration in homes and structures near the navigation channel. Ice effects are treated in some detail in EM 1110-2-1612, and by Tuthill (1985) and Tuthill and Carey (1986).

11-2. Design of Channels with Ice. All vessels, but particularly long cargo ships with vertical sides and a blunt bow, have difficulty turning in ice. Since very few prototype tests have been made to determine turning radii in ice, no specific recommendations can be made for channel widths in bends or turning basins when subjected to ice cover. Local conditions of ice thickness and extent of coverage will be necessary to develop adequate channel designs. It is important that turning basins be kept clear of ice to allow ship maneuvers and prevent damage to hulls by ice. It should be noted that conventional commercial ships not specifically designed for ice operation are usually unable to leave the navigation channel through an ice cover once it has been created. Furthermore, repeated transits through the channel may lead to accumulation of brash ice and the formation of underwater ice ridges along the edges of the channel.

Line bubblers have been used with some success in the Great Lakes to mitigate channel ice growth problems. Additional depth might be required for the installation of a bubbler system unless the channel is sufficiently wide to permit the placement of the bubbler line outside of the ship channel. Bubbler systems do not provide ice clearing but do create a line of weakness along which ice breaking is made easier. Channels should be aligned so that navigation can rely on range lights and markers rather than floating navigation aids, which can be covered by ice or displaced by ice movements.

In addition to the navigation impact of ice formation on the surface of the water, under certain conditions ice can accumulate on the bottom of vessel hulls. As a vessel progresses at slow speed through brash ice, pieces become submerged and can be entrained underneath the hull. When these conditions occur, the relative water speed is insufficient to flush the ice. This process is enhanced when the vessel’s bow is sloped or raked, as for a barge on inland waters or when an ocean-going ship is empty. Under extremely cold conditions, the brash ice can become adhered to the hull of an empty or near-empty vessel because of heat loss as the result of air contact through the sparsely loaded hold. In the event that ice forms on the bottom of a vessel, the result would be increased draft and resistance causing maneuvering difficulties.

11-3. Locks. Lock operation during icing conditions can be difficult and time-consuming. Ice buildup on lock walls may reduce the width of the lock chamber to such an extent that it would be too narrow for the ship. Coatings to reduce ice adhesion to lock walls and methods of ice control and removal are covered in EM 1110-2-1612. Consideration should be given to the use of heating devices in or ice-preventive coating on lock walls in the design of new structures or rehabilitation of existing locks. Ice can be prevented from collecting in the miter gate recesses by large-volume air bubblers. Ice in the approach to the lock can be minimized by the placement of an air screen at the upper end of the guide or guard wall. Ice accumulating on the bottom of ships increases their draft, which can present problems in clearing the lock gate sills. Consideration should be given to increasing the depths over the sill and along loading docks in ice-prone areas. When it is not possible to prevent large amounts of ice from entering the lock in front of the ship, it may be necessary to provide a skimmer or water flushing system to remove the ice from the lock before the ship can enter.

11-4. Erosion and Sediment Movement. Studies on sediment movement under ice cover in rivers and restricted channels and studies on the Great Lakes have not been sufficient to indicate any change in the rate of shore erosion resulting from ice. Ice formed on a shore or riverbank could isolate and protect the shore. However, ice formation may cause damage to training and stabilization structures or shore by gouging, removing protective vegetation, or entraining sediment within the ice. Ice cover tends to damp ship-induced bow and stern waves which have relatively short periods. However, ice cover has little effect on relatively long-period water-level fluctuations such as those resulting from drawdown, which can be significant, particularly in restricted channels. Greater power will be required to move a ship through ice, and occasionally a ship will get stuck with its screws turning with maximum power without moving. High power and propeller rotation will tend to increase scour and bottom sediment movement and should be considered, particularly over underwater cable and pipeline crossings.

11-5. Vibration. Reliable reports indicate that there is an increase in the vibration of shore structures near ship channels in winter. The reason for this increase is not known. Preliminary investigations indicate that the energy causing the vibration is primarily from the propellers and not from ice breaking or from pieces of ice hitting each other. Based on some verbal reports that conditions are worse during light snow years, it is probable that the vibrations are transferred through frozen soil structure. Until more observations and measurements are made, no definite recommendations can be made to minimize this problem.

11-6. Mitigation of Ice Problems. Maintenance of navigation in ice-covered channels requires ice breaking, which is the responsibility of the U.S. Coast Guard. Usually this is done with dedicated, specially designed icebreakers. In thin ice (up to 6 in.), normal ships break ice as they move through the channel; however, most commercial ships do not have the hull strength and power to break ice with thickness greater than 15 centimeters (cm) (6 in.). The maritime insurance companies have specifications by which they will underwrite certain ships to operate in varying ice conditions. Small harbor tugs specifically built for ice breaking are required for ice-prone ports. These should have the capability of breaking ice that is at least half the maximum anticipated thickness during a normal winter season. These tugs are expected to operate throughout the season, keeping ice broken up in the channel and turning basin and along docks and assisting ships in the channel and turning basin. The effects of ice can be reduced by using waste heat from power plants and sewage disposal facilities and prohibiting municipalities from disposing of snow in the channel or tributaries. In tidal zones, air screens or ice booms should be considered for intermittent use to prevent ice from entering the channel during rising tide. The drawdown and the amplitude of the bow wave generated by a vessel is a function of ship size, channel blockage, and speed. A surrounding ice sheet will dampen the wave, but the ice may be broken by large drawdown. Broken ice floes could then drift into the navigation channel causing additional difficulties, especially to smaller ships. The broken ice can refreeze into thicker ice, depending on temperature, thus creating more severe channel blockage. If ice breakage extends to the shores, movements of ice floes by wave action and induced currents resulting from subsequent vessel transits may lead to damage of unprotected banks or environmentally sensitive areas. Since the drawdown and bow wave amplitudes decrease rapidly with decreasing ship speed, a minor reduction in vessel speed could avoid or minimize ice breakup and resulting potential ice damages.

CHAPTER 12

Operation and Maintenance

12-1. Operation and Maintenance Plan. A comprehensive plan of how the project will be operated and maintained after construction will be required in support of operation and maintenance (O&M) costs. The following elements are normally included in the O&M plan:

a. Changes and costs. The predicted physical changes with time after construction and the anticipated O&M costs.

b. Surveillance plan. The maintenance plan covers minimum monitoring of the project performance to verify safety and efficiency. Included are type and frequency of hydrographic survey, data collection, and periodic inspection schedule. Hydrographic surveys, beach profiles, tide and wave records, and jetty stability data collection costs are used for O&M budgetary purposes.

c. Project performance assessment. An assessment of the project performance is required based on results of inspections and analysis of comparative surveys to verify design information such as rates of erosion, shoaling, and jetty deterioration and to project changes predicted during the design effort. A comparison of actual O&M costs with predicted cost is required. Coordination with the local pilots, port authority, and other marine interests should be conducted. Plans for a review to determine after-project navigation improvement conditions should be included in the project plans.

CHAPTER 13

Navigation Model Studies

13-1. General. Development of deep-draft navigation projects affected by tides, river currents, and wave effects will in most cases require the use of models and ship simulator studies. Designers and planners should not miss the opportunity for meaningful dredging and cost savings by significant changes in dimensions or layout of navigation channels. Changes in ship type, draft, or size, and modifications to navigation traffic patterns should also be assessed using appropriate models and ship simulator studies. As a part of project feasibility and design, it may be necessary also to provide for some field data gathering of ship maneuvering and wave motion, if warranted. Navigation model studies are used to determine the adequacy of a proposed project improvement plan and to develop possible design modifications to ensure project safety and efficiency and minimize environmental impacts. Figure 13-1 presents a classification diagram of the various study techniques used in navigation project investigations. Physical and numerical models can be used to analyze some of the factors influencing project design and operation.

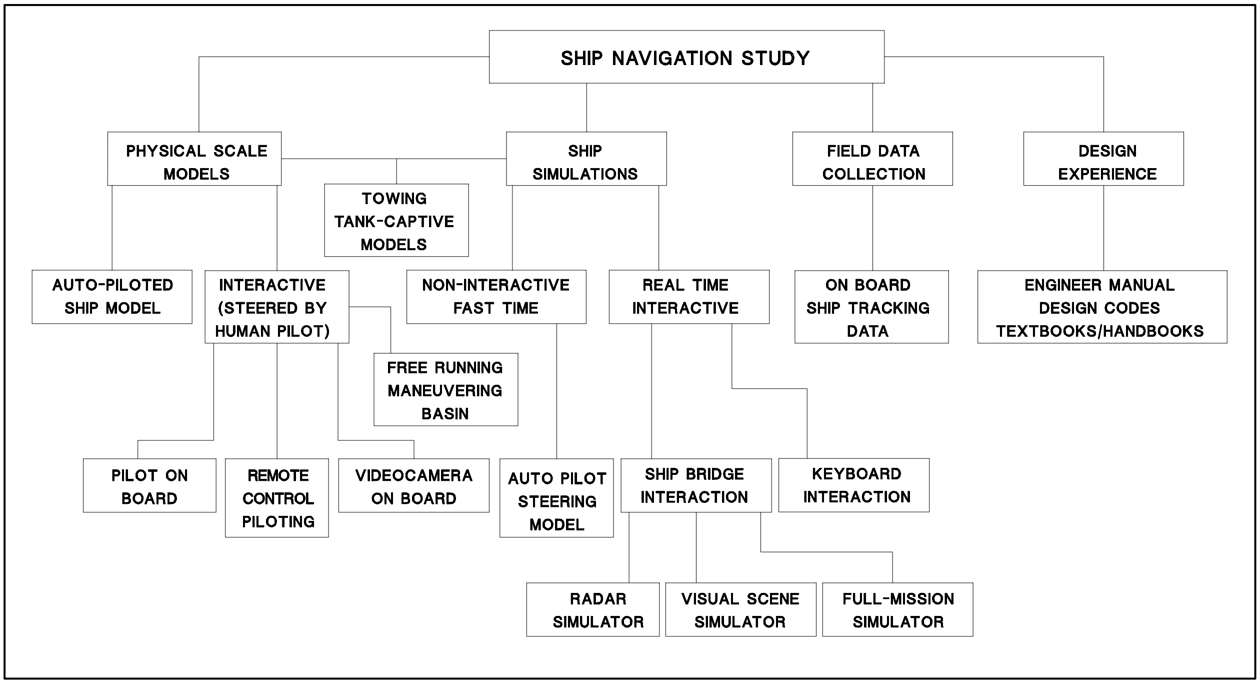


Figure 13-1. Navigation investigation techniques

Because of the complexity of tidal and river currents and effects of wind, waves, sediment movement, etc. on ship navigation, combinations of physical scale models, numerical models, and computer-based ship simulation models are often necessary to resolve proposed project issues. Sediment problems and salinity intrusion in estuarine areas often require extensive field data gathering and modeling efforts to obtain accurate evaluation of the conditions that can be expected with each plan and modification considered. EM 1110-2-1607 gives extensive coverage of needed comprehensive model studies in estuarine areas.

13-2. Physical Models. Physical scale models are used principally to investigate flow patterns where complicated three-dimensional (3-D) effects are important in the study areas of concern. Recent dramatic advances in computer hardware and software have led to a preference to use numerical models to replace and supplement physical model studies. The following types of navigation investigations can be conducted with physical models:

a. Shoaling and erosion characteristics.

b. Salinity intrusion.

c. Wave penetration and harbor response.

d. Jetty design and armor stability.

e. Ship response to waves.

f. Channel width in critical navigation reaches.

g. Tide heights and current patterns.

h. Navigation conditions.

13-3. Numerical Models.

a. *Introduction.*

(1) Numerical modeling is a rapidly developing discipline that can be attributed to the general availability of fast, large-memory computers. A numerical model basically consists of a numerical algorithm developed from the differential equations governing the physical phenomena. All numerical models require the study area to be discretized by a grid or mesh. Furthermore, testing the numerical results against a prototype data set (verification) is highly recommended.

(2) Numerical models may be used to replace or supplement physical models. A study of the following types of investigations with numerical models can:

(a) Provide general circulation patterns for deep- or shallow-draft ship simulator studies.

(b) Determine shoaling and erosion characteristics.

(c) Address dredged material disposal issues and other water quality measures.

(d) Investigate salinity intrusion.

(e) Study wave penetration and harbor response.

(f) Evaluate training structure designs.

(3) Numerous numerical models are available within the scientific community. These models differ in several ways: formulation, governing equations, and user friendliness, to name a few. Some numerical models have the ability to solve hydrodynamics and transport equations simultaneously while others are uncoupled.

(4) The two basic numerical model formulations are finite difference and finite element. Finite difference is the easiest to conceptualize. A finite difference model approximates the calculus differential operators by differences over finite distances. This gives an approximation of the governing equations at discrete points. The finite element model approximates the mathematical form of the solution and inserts it into the exact form of the governing equations. After boundary conditions are imposed, a set of solvable simultaneous equations is created. The finite element solution is continuous over the area of interest.

(5) The governing equations describe the physical processes that are being solved in the model. The dimensionality of the problem is dictated within these equations. These equations describe the physics of the problem. For a hydrodynamic model, these would include items such as friction, density, gravity, rotation of the earth, wind, rain, inflows, and outflows.

(6) The term user friendly is an all-encompassing issue dealing with ease and efficiency of use. It addresses the process of creating a mesh, specifying the parameters within the computational domain, analyzing the solutions, generating presentation and report quality graphics, on-line documentation, and consultation support.

(7) Several models are available within the USACE that have met the test of time. One such model is the TABS-MD numerical modeling system. The multidimensional aspects of TABS-MD have expanded the capabilities of the system such that it has had hundreds of applications within the USACE. TABS-MD has been utilized by a multitude of private consulting firms and universities as well. It has a good reputation and a state-of-the-art graphical user interface that makes it one of the most user-friendly and efficient ways to conduct a numerical model study. Numerous technical reports and papers have been published on TABS-MD applications, the most recent of which are listed in Appendix A.

b. TABS-MD Numerical Modeling System.

(1) The TABS-MD is a collection of several generalized finite element models and pre- and post-processing utility programs integrated into a multidimensional numerical modeling system. TABS-MD is suitable for use in solving hydraulics behavior, sedimentation, and transport problems of rivers, reservoirs, wetlands, estuaries, and bays. Examples of past use include predicting flow patterns and erosion in a river reach constricted by a cofferdam, evaluating sedimentation rates in a deepened navigation channel (both riverine and estuarine), determining the impact of flood control structures on salinity intrusion, developing recommendations for a safe and cost-effective navigation channel design, and defining flow and sedimentation impacts to wetlands.

(2) The system is designed for use by engineers and scientists who are knowledgeable of the physical processes that control behavior of waterways, but who may not be computer experts.

TABS-MD offers a complete range of model study functions, including map digitization, mesh generation, modeling, and graphical display of numerical model results.

(3) TABS-MD is currently operational on a wide variety of computer platforms, ranging from super computers to personal computers (PC). The numerical models and the utility programs are written in FORTRAN-90. Plans are underway to modify the models to take advantage of parallel processor environments.

(4) The system is maintained by the ERDC/WES and includes two hydrodynamic models: RMA2-WES and RMA10-WES. In this context, the term hydrodynamic modeling is a general term intended to denote a body of water with a free surface such as a river. The first fundamental decision, prior to conducting a numerical model study, is to classify the study area in order to choose the appropriate numerical model. RMA2-WES is an appropriate choice for a far-field problem whose study area may be modeled with a two-dimensional (2-D) depth-averaged approximation. Otherwise, the modeling effort must employ RMA10-WES to incorporate the 3-D aspects. TABS-MD permits an efficient numerical approach by incorporating multiple dimension concepts within a given mesh domain. For instance, an RMA2-WES application may use economical one-dimensional (1-D) calculations in some areas and 2-D calculations within the primary area of interest. An RMA10-WES application may use any combination of 1-, 2-, and 3-D calculations with or without the transport options. The modeling effort can reach a high degree of complexity and computational burden with 3-D computations.

(5) Two sediment transport options are available with the TABS-MD system. SED2D is a 2-D finite element model that solves the convection-diffusion equation with bed source-sink terms. These terms are structured for sand or cohesive sediments. Cohesive deposited material forms layers, and bookkeeping allows layers of separate material types, deposit thickness, and age. SED2D uses the hydrodynamic solution generated by the RMA2-WES model. RMA2-WES and SED2D are uncoupled; therefore, a new geometry must be cycled back to RMA2-WES when the bed deposition and erosion patterns begin to significantly affect hydrodynamics. Work is ongoing to upgrade SED2D to accommodate all features of RMA2-WES, such as 1-D and marsh/wetland calculations. The other sediment transport option is to couple the sediment transport with the hydrodynamic calculation by using RMA10-WES. RMA10-WES includes a single-class fine-sediment transport with an associated layered bed with distinct densities and erodibilities for each layer. Changes in bed elevation are made during computations and are accounted for in the continuity equation.

(6) There are two water quality transport options within TABS-MD as well. RMA4-WES is a 1-D and 2-D finite element model with a form of the convective diffusion equation with general source-sink terms. The model may transport and route up to six constituent substances, with or without decay. The model accommodates a mixing zone outside the model boundaries for estimation of reentrainment. RMA4-WES uses the hydrodynamic solution generated by the RMA2-WES model. RMA10-WES has the option to couple temperature, salinity, and/or sediment transport with the hydrodynamic calculations.

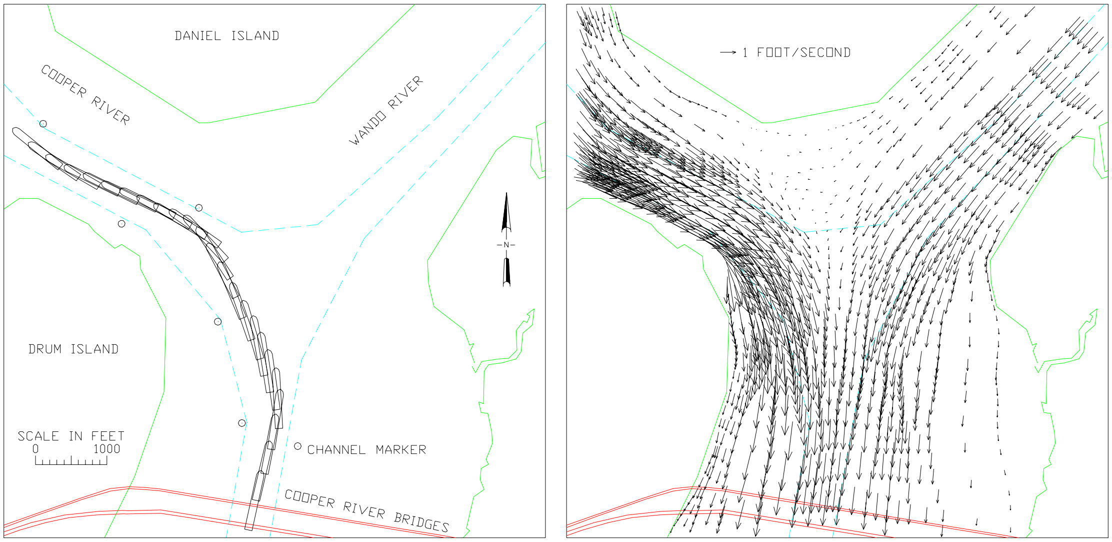
(7) A recent research effort was conducted at ERDC/WES to provide guidelines and help field offices conduct hydrodynamic numerical models to address both deep-draft and shallow-draft issues. The work emphasized RMA2-WES hydrodynamic applications since all

navigation studies involve that aspect and most of the field offices have access to personal computers or workstations capable of running 2-D simulations. Furthermore, the ERDC/WES ship simulator typically uses the RMA2-WES solution as input to define the currents for the simulator (Figure 13-2).

c. *Example Navigation Applications Using RMA2-WES Solutions.*

(1) *Charleston, SC, Estuary*. The study was undertaken to evaluate and optimize proposed improvements including deepening the navigation channel from 12 to 14 m (40-45 ft), realigning and/or widening several fairways along a 8-kilometer (5-mile) stretch of the estuary, and locating a proposed seven-berth container terminal. The RMA2-WES simulation was conducted to provide currents to the ERDC/WES ship simulator for several time-steps on both the ebb and flood portions of a spring tidal cycle. Figure 13-2 shows the ERDC/WES ship simulator response track plot corresponding with one set of velocity vectors computed by RMA2-WES for the Drum Island reach of the study area. The study was an iterative process between the RMA2-WES hydrodynamic model, the ship simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 13-3.

(2) *Redeye Crossing near Baton Rouge, LA, along the Lower Mississippi River*. The study was undertaken to evaluate the effect of river training structures on vessels (both ships and tows) transiting the Redeye Crossing Reach. Studies included a TABS-MD RMA2-WES hydrodynamic model, the ship/tow simulator model, and a SED2D sediment transport model. Figure 13-4a and b show the ERDC/WES tow simulator response track plot corresponding to one set of velocity vectors computed by RMA2-WES using the secondary flow corrector. Figure 13-4c shows the computational mesh used by the TABS-MD models. The study was an iterative process between the RMA2-WES hydrodynamic model, the s hip simulator model, and the SED2D sediment transport model, as indicated by the flowchart in Figure 13-3.



a. WES ship simulator track plot b. RMA2-WES hydrodynamic solution

Figure 13-2. The Cooper River, Charleston, SC channel realignment study

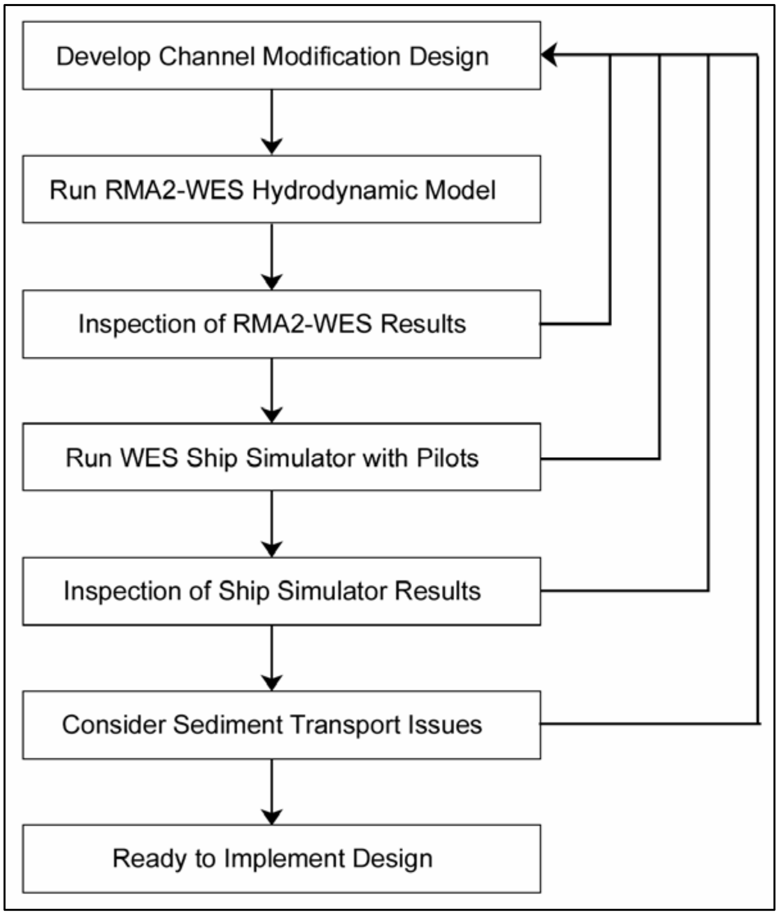
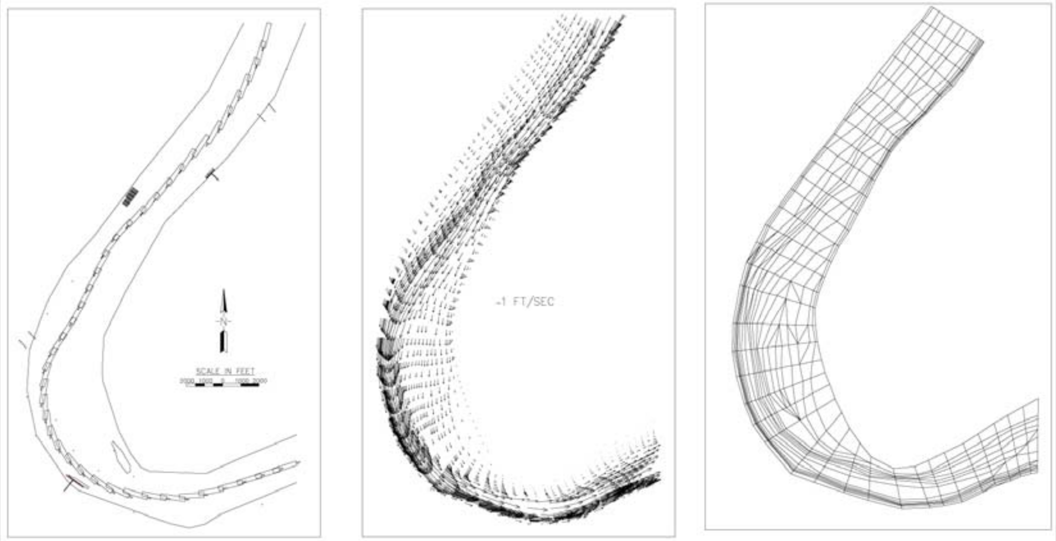


Figure 13-3. Typical events and feedback loops involved in ERDC/WES ship simulator study



a. ERDC/WES tow simulator track plots

b. RMA2-WES hydrodynamic solution

c. Numerical model computational mesh

Figure 13-4. Redeye Crossing of the Lower Mississippi River *d.* *RMA2-WES Hydrodynamic Model.* RMA2-WES is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with Manning's equation, and eddy viscosity coefficients are used to define the turbulent exchanges.[1] A velocity form of the basic equation is used with side boundaries treated as either slip or static. The model has a marsh porosity option as well as the ability to automatically perform wetting and drying. Boundary conditions may be water-surface elevations, velocities, discharges, or tidal radiation. Both steady and unsteady free-surface calculations for subcritical flow problems can be analyzed.

(1) *RMA2-WES governing equations.*

(a) The generalized computer program RMA2-WES solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The forms of the solved equations are:

$$\begin{aligned}
& h\frac{\partial u}{\partial t}+hu\frac{\partial u}{\partial x}+hv\frac{\partial u}{\partial y} \\
& -\frac{h}{\rho}\left(E_{xx}\frac{\partial^2 u}{\partial x^2}+E_{xy}\frac{\partial^2 u}{\partial y^2}\right) \\
& +gh\left(\frac{\partial a}{\partial x}+\frac{\partial h}{\partial x}\right) \\
& +\frac{gun^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2} \\
& -\varsigma\ V_a^2\cos\Psi-2h\omega v\sin\Phi=0
\end{aligned} \qquad (13\text{-}1)$$

$$\begin{aligned}
& h\frac{\partial v}{\partial t}+hu\frac{\partial v}{\partial x}+hv\frac{\partial v}{\partial y} \\
& -\frac{h}{\rho}\left(E_{yx}\frac{\partial^2 v}{\partial x^2}+E_{yy}\frac{\partial^2 v}{\partial y^2}\right) \\
& +gh\left(\frac{\partial a}{\partial y}+\frac{\partial h}{\partial y}\right) \\
& +\frac{gvn^2}{\left(1.486h^{1/6}\right)^2}\left(u^2+v^2\right)^{1/2} \\
& -\varsigma\ V_a^2\sin\Psi+2\omega hu\sin\Phi=0
\end{aligned} \qquad (13\text{-}2)$$

---

[1] Recent improvements to the hydrodynamic model allow the user to employ automatic parameter assignments for roughness and turbulent coefficients as the velocity field changes during a time varying simulation.

$$\frac{\partial h}{\partial t}+h\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \qquad (13\text{-}3)$$

where

h = depth (meters (feet))

u,v = velocities in the Cartesian directions (meters/second or feet/second)

x,y,t = Cartesian coordinates and time (meters/second or feet/second)

ρ = mass density of fluid (mass/unit volume) (kilograms/meter^3 or slugs/feet^3)

E = Eddy viscosity coefficient,
for xx = normal direction on x axis surface,
for yy = normal direction on y axis surface,
for xy and yx = shear direction on each surface

g = acceleration because of gravity (meters/second^2 (feet/sec^2))

a = elevation of bottom (meters or feet)

n = Manning's roughness n-value$\left(\frac{\text{sec}}{\text{m}^{1/3}}\text{ or }\frac{\text{sec}}{\text{ft}^{1/3}}\right)$

1.486 = conversion from SI (metric) to non-SI units

ζ = empirical wind shear coefficient

V_a = wind speed (meters/second or feet/second)[2]

ψ = wind direction (radians)[1]

ω = rate of earth's angular rotation (1/sec)[1]

φ = local latitude, Coriolis (radians)[1]

Equations 13-1, 13-2, and 13-3 are solved by the finite element method using the Galerkin Method of weighted residuals. The elements may be 1-D lines, or 2-D quadrilaterals or triangles, and may have curved (parabolic) sides. The shape functions are quadratic for velocity and linear for depth.

(b) Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form.

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[2] At this point in the equation, there are the units for consistency. User input units may vary.

$$f(t) = f(0) + at + bt^c \quad t_0 \leq t \leq t_0 + \Delta t \tag{13-4}$$

This is differentiated with respect to time and cast in finite difference form. Letters *a, b,* and *c* are constants. Experiment has shown that the best value for *c* is 1.5 (Norton and King 1977).

(c) The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson non-linear iteration. The computer code executes the solution by means of a front-type solver, which assembles a portion of the matrix and solves it before assembling the next portion of the matrix.

(d) RMA2-WES is based on the earlier versions (Norton and King 1977) but differs in several ways. It is formulated in terms of velocity (v) instead of unit discharge (vh), which improves some aspects of the code's behavior. Other differences from the earlier versions include the following:

- Employs new numerical solution algorithms.
- Permits wetting and drying of areas within the mesh.
- Permits wetlands to be simulated as either totally wet/dry or as gradually changing wet/dry states.
- Permits specification of turbulent coefficients in directions other than along the x- and z-axes.
- Accommodates the specifications of hydraulic control structures in the network.
- Permits the use of automatic assignment of friction and turbulent coefficients.
- Permits input in either non-SI or SI units.

(e) Additionally, a numerical corrector for secondary ("bendway") flow has been incorporated into the RMA2-WES model as a result of deep- and shallow-draft research and applications.

- Incorporated a secondary flow ("bendway") corrector.
- Improved the RMA2-WES documentation and provided resolution guidelines.
- Provided an on-line point-and-click documentation capability on the PC.
- Incorporated a documentation icon within the graphical user interface on the PC.

(2) The principle of bendway correction.

(a) The secondary flow (or "bendway") corrector was added to the RMA2-WES model. The modified program, designated as version 4.35, solves a transport equation for streamwise vorticity and converts it to accelerations due to secondary currents. These additional accelerations result in improved predictions of the traditional depth-averaged velocity calculations. Their effect is to reduce velocities on the inside of river bends and increase them on the outside of bends. The modeler may activate or deactivate the secondary flow corrector as required for its application. This enhancement permits RMA2-WES to be successfully used for some study areas that otherwise would have required the 3-D model.

(b) The theoretical basis of bendway correction was developed for the depth-averaged finite difference numerical model, STREMR (Bernard and Schneider 1992).

(c) The bendway correction is accomplished by first solving an additional equation for the transport of streamwise vorticity. Vorticity is a measure of rotation of flow. Streamwise vorticity at a point is equal to the velocity of the fluid about the axis in the streamwise direction of flow. Streamwise vorticity is in the vertical plane perpendicular to the direction of flow and is related to the radial accelerations that cause the helical flow pattern.

(d) The transport equation for streamwise vorticity is

$$\begin{aligned}\frac{\partial\Omega}{\partial t}+u\frac{\partial\Omega}{\partial x}+v\frac{\partial\Omega}{\partial y}&=\frac{A_s\sqrt{C_f}\,|\vec{u}|^2}{Rh\left(1+9h^2/R^2\right)}\\ &-D_s\sqrt{C_f}\,\Omega\frac{|\vec{u}|}{h}+\frac{1}{h}\nabla\left(vh\nabla\Omega\right)\end{aligned} \tag{13-5}$$

where

Ω = streamwise vorticity

A_s = 5.0

C = friction coefficient

h = water depth

$|\vec{u}|$ = magnitude of the velocity vector

R = local radius of curvature

D_s = 0.5

Units of vorticity are sec^{-1}.

(e) The additional shear stress caused by the secondary, helical flow is calculated from streamwise vorticity at each node. The components of this shear stress are added to the other terms (friction, slope, Coriolis) in the governing equations.

e. RMA2-WES Documentation. With the technological advancements of the computer industry and the evolution of computational algorithms, it was evident that published documentation could be quickly outdated. To address the evolution of the “art” of numerical modeling, a living approach to documentation was selected. The RMA2-WES "*DOC-TO-HELP*" hypertext documentation is regularly updated and available for download from the World Wide Web (WWW). After downloading it to your PC, you may view the on-line documentation on any PC running windows. The WWW address for the documentation: *http://chl.wes.army.mil/software/tabs/docs.htp*

f. *Graphical User Interface.* All USACE and ERDC/WES employees performing surface water analyses for the USACE may obtain a copy of SMS, the Surface Water Modeling System graphical user interface, developed by Brigham Young University (BYU). This graphical user interface was first made available in 1989 and has evolved to its present release. SMS is fully compatible with the TABS-MD suite of models and with many other surface water models. To obtain a copy of the SMS interface, download the proper executable for your computer and complete the request form available from the WWW at this address: *http://chl.wes.army.mil/software/sms*

13-4. Ship Simulations.

a. Increasingly, navigation studies of deep-draft channels are being tested for design with ship simulators. A block diagram of the ERDC/WES ship simulator is presented in Figure 13-5. Shiphandling simulators have the distinct advantage over scale models in allowing for testing using human piloting in real-time rather than reduced Froudian time scaling. The inclusion of the local professional pilot in the channel project design process has proved distinctly advantageous in developing a safe and optimum channel. Simulators may be viewed as a special case of numerical models, using one or more dedicated computers and appropriate display equipment and providing real-time interactive input and output during testing. As depicted schematically in Figure 13-6, an appropriate ship simulator includes models of a ship, the navigation channel, the currents, the wind, the visual scene, the radar image, tugs and thrusters, the ship bridge controls, and typical bridge instruments. The simulator can be used with human piloted control in real-time or an autopilot, which follows a track-keeping function for fast-time tests. The ship model must be complete and realistic with appropriate ship hull dynamics; engine thrust; control surface hydrodynamics; cross-term interactions; bank, shallow water, currents, wind, and wave effects; and tug, bow, and stern-thruster forces.

b. The visual and radar models depict the changing scene in enough detail to enable the pilot to determine his location and the rate of motion. The pilot has full access to visual cues and instrumentation information and controls normally available to him as is available onboard the real ship. The visual scene and radar scene include the details of the navigation aids and realistic cultural features often used to pilot ships. The channel model produces the effects on the ship that will cause the ship to respond to the channel similar to the way it does in real life using detailed description of the currents, channel banks, and underkeel clearance throughout the channel test scenarios. For passing situations, accurate modeling of ship force and moment interaction effects must be reproduced. The environmental factors such as wind, currents, and waves cause perturbations on the ship, which are crucial to realistic channel design studies.

c. A block diagram showing the method of operation in real-time simulation is given in Figure 13-7. A more complete description of the ERDC/WES ship simulator and details of study techniques with several project channel design applications are presented in Appendix C.

13-5. Field Data Collection. In some situations, navigation problems can be most expeditiously investigated using onboard instrumentation to measure ship data. An example of this was the extensive 2-year effort to collect ship motion data at the Mouth of the Columbia River to develop data for channel design in very high-wave environment (Wang et al. 1980). The introduction of satellite-based DGPS provides the accuracy required to give ship position data accurate enough to give useful ship navigation channel design guidance. In conjunction with the Houston Ship Channel simulator study, DGPS field data on ship meeting and passing in the 400-ft-wide channel were collected that proved very valuable in channel design.

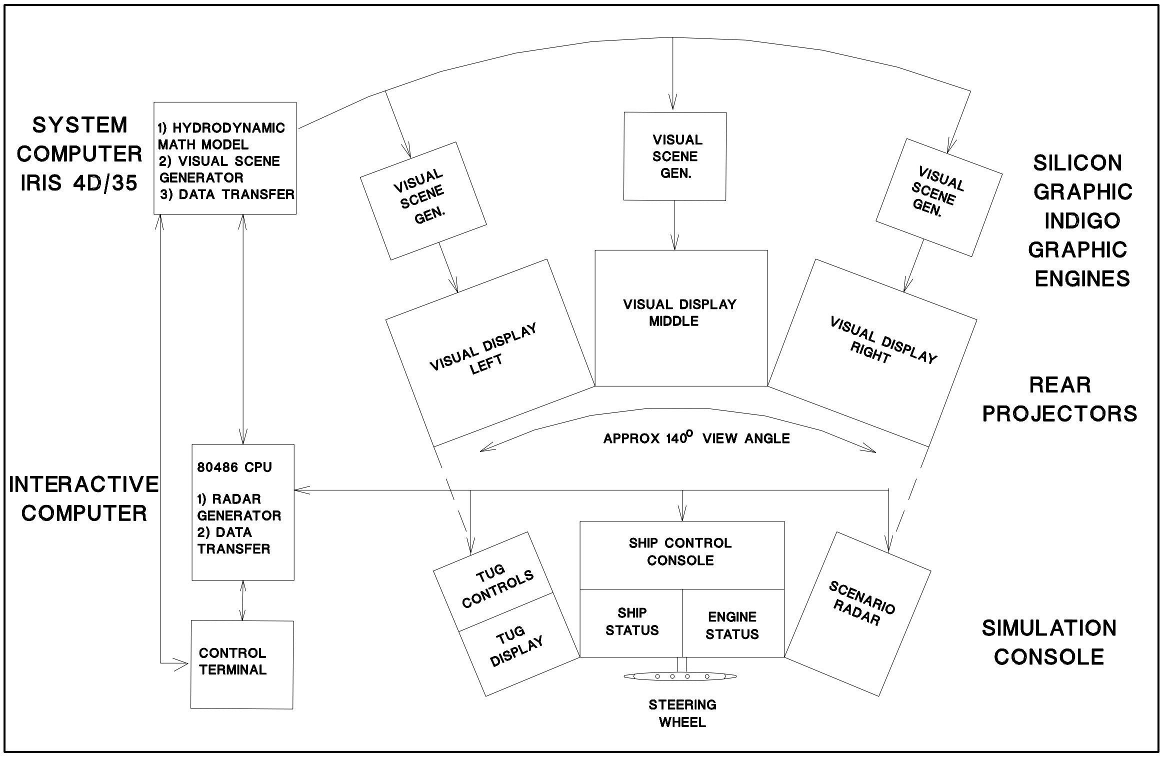

Figure 13-5. WES ship simulator system

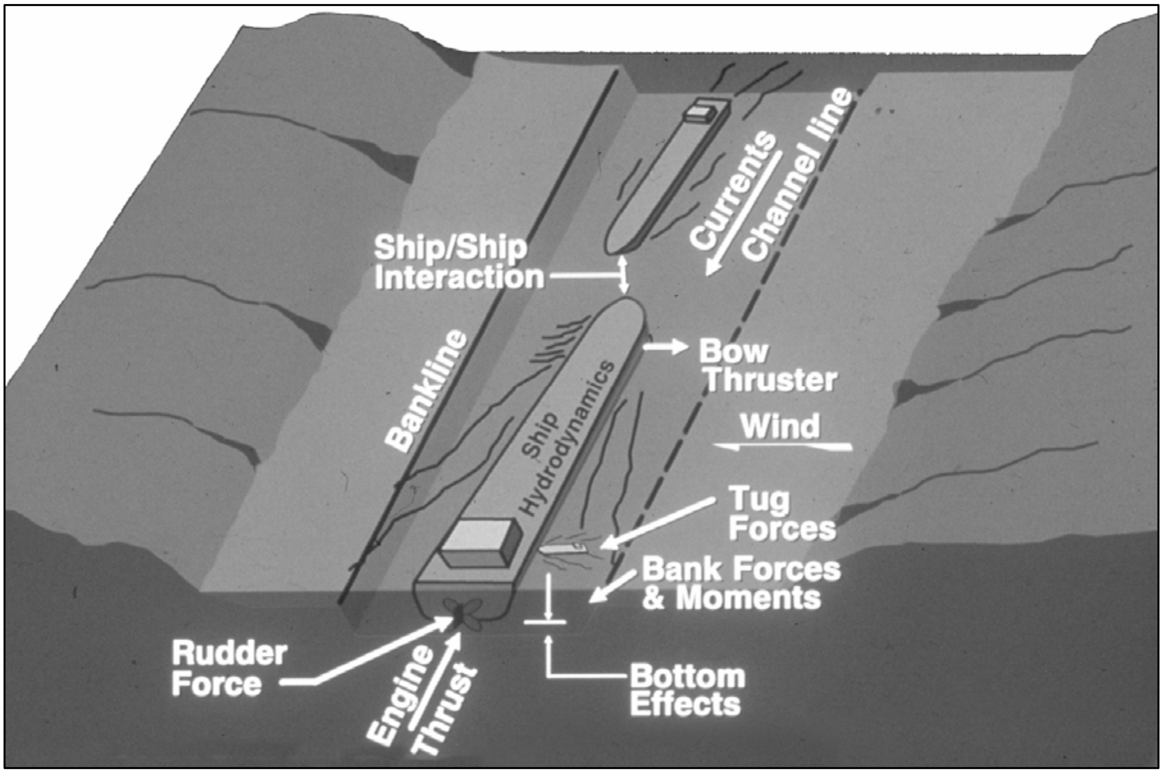

Figure 13-6. Ship simulator forces and effects

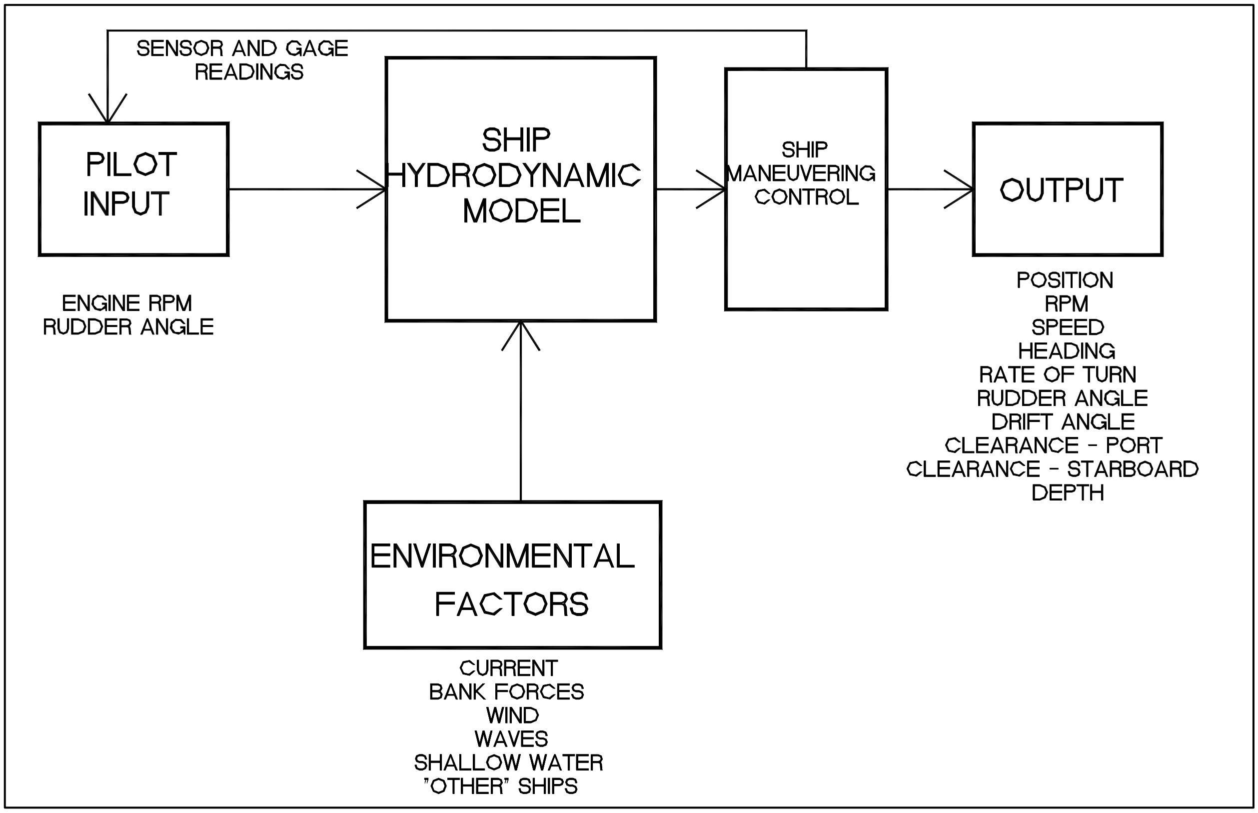

Figure 13-7. Real-time simulation

APPENDIX A

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EM 1110-2-1202
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EM 1110-2-1502
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Hydraulic Design of Navigation Locks

EM 1110-2-1607
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EM 1110-2-1611
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APPENDIX B

Conversion Factors and Constants

B-1. Introduction. Table B-1 presents conversion factors for units of measure commonly used in the study of navigation. Table B-2 presents standard physical constants and properties.

Table B-1
Conversion Factors

Multiply	By	To Obtain
	Length	
feet	0.3048000	meters
miles (British nautical)	6,080.	feet
miles (Int. naut.)	6,076.1155	feet
miles (U.S. statute)	5,280.	feet
miles (U.S. statute)	1.609344	kilometers
miles (U.S. statute)	1,609.347	meters
fathoms	6.	feet
meters	3.2808399	feet
kilometers	3,281.	feet
miles (International nautical)	1,852.	meters
kilometers	1,000.	meters
yards	0.91440	meters
	Area	
square meters	10.76391042	square feet
	Volume	
cubic feet	28.31685	liters
barrels (U.S. oil)	42.	gallons (U.S.)
barrels (U.S. oil)	158.9873	liters
cubic feet	7.4805195	gallons (U.S. liquid)
liters	0.0010000	cubic meters
gallons (U.S. liquid)	3.785412	liters
	Velocity	
knots	1.6878099	feet per second
knots	1.8532	kilometers per hour
knots	1.1507794	miles (U.S. statute)/hour
knots (international)	0.514444	meters per second
feet per second	1.09728	kilometers per hour
miles (U.S. statute) per hour	1.4666667	feet per second

Table B-1 (Continued)

Multiply	By	To Obtain
miles (U.S. statute) per hour	1.609344	kilometers per hour
meters/second	2.2369363	miles (U.S. statute)/hour
	Weight	
kilograms	2.2046225	pounds
tons (long)	2,240.	pounds
tons (short)	2,000.	pounds
tons (metric)	1,000.	kilograms
tons (short, 2,000 pounds)	907.1847	kilograms
tons (long, 2,240 pounds)	1,016.047	kilograms
pounds (avdp)	0.4535924	kilograms
tons (long)	1.0160469	tons (metric)
tons (metric)	2,204.6226	pounds (avdp)
tons (metric)	2,679.2289	pounds (apot, troy)
	Power	
horsepower	550.	foot-pounds per second
horsepower (550 foot-pounds per second)	745.7	watts
Btu (International Table)/second	1,055.056	watts
foot-pounds/second	1.355818	watts
	Force	
pound (force)	4.448222	newtons
kilogram (force)	9.80665	newtons
ton (force) (long)	9,964.016332	newtons
	Energy	
foot-pound	1.355818	joules
Btu (International Table)	1,055.056	joules
Btu	777.649	foot-pounds
	Pressure	
pounds per square foot	47.88025964	newtons/square meter
pounds per square foot	47.88025964	pascal
pounds per square inch	6,894.757	newtons/square meter
atmosphere	101,325.0	newtons/square meter (pascals)

Table B-1 (Concluded)

Multiply	By	To Obtain
	Mass	
slugs	14.59390	kilograms
slugs	32.1737	pounds (avdp)
slugs/cubic foot	515.379	kilograms/cubic meter
	Unit Weight	
pounds per cubic foot	16.0184633	kilograms per cubic meter
pounds per cubic foot	157.087460	newtons/cubic meter
grams/cubic centimeter	62.427961	pounds per cubic foot
	Angles	
radians	57.295779531	degrees
radians	57° 17' 44.80625"	degrees
degrees	0.017453292519943	radians

Table B-2
Standard Physical Constants and Properties

Multiply	By	To Obtain
	Gravitational Acceleration	
International standard value (sea level, 45-deg latitude)	32.1737 ft/sec^2	9.80665 m/sec^2
	Water Properties (59 °F, 3.5 percent salinity)	
	Fresh	Salt
Density, slugs/ft^3	1.9384	1.9905
Density, kg/m^3	999.00	1,025.87
Unit density, lb/ft^3	62.366	64.043
Unit volume, ft^3/long ton	35.917	34.977
	Air Properties (59 °F, sea level)	
Density, slugs/ft^3	0.002378	
Unit density, lb/ft^3	0.076509	

APPENDIX C

Ship Simulator Applications to Waterways Design — Lessons Learned

C-1. Introduction. The ERDC/WES Ship and Tow Simulator has been used to study over 30 navigation channel projects since 1983. Most of these studies have involved design issues of required channel geometry and alignment for adequate ship safety and maneuverability. Simulator results and recommendations have been well received by the professional pilots and the design engineers of the U.S. Army Corps of Engineers Districts.

We present an overview of the ERDC/WES Simulator and the study methodology. Selected simulation application test results are reviewed, and some generalized design guidance is presented. A research effort to address some of the simulator limitations is outlined.

The use of computer simulation modeling of ship and tow maneuvering was started at ERDC/WES in the 1970's (Ankeny et al. 1978, Huval and Pickering 1978). Physical scale models had been in routine use for assessment of navigation, however, for a number of years (Franco and McKellar 1966). The availability of the WES Simulator for use in waterway and port design was announced in 1983 (ETL 1110-2-289, 1983). The simulator is used for both ship and pushtow (towboats and barge flotillas) studies, sometimes both on the same project, as required.

C-2. Simulator Description. The ERDC/WES Simulator includes models of a ship or tow, the navigation channel, the currents, the wind, the visual scene, the radar image, tugs and thrusters, the ship or towboat bridge controls, and typical bridge instruments. The simulator can be used with human piloted control in real-time (Figure C-1) or an autopilot, which follows a track-keeping function for fast-time tests. The autopilot has a "look-ahead" capability to anticipate a channel turn. The ship model is complete with hull dynamics; engine thrust; control surfaces; cross-term interactions; bottom effects; bank effects; current effects; wind effects; ship/ship interactions; and tug, bow, and stern thruster forces. The simulator system is shown in Figure C-2.

The visual and radar models depict the changing scene in enough detail to enable the pilot to determine his location and the rate of motion. These details include formal navigation aids and realistic cultural features often used to pilot ships. The channel model produces the effects on the ship that will cause the ship to respond to the channel similar to the way it does in real life using a detailed description of the currents, channel banks, and underkeel clearance throughout the channel. These factors are the outside perturbations that act on the ship and are crucial to realistic channel design studies.

The pilot, as seen in Figure C-3, has full access to visual cues and instrumentation information and controls normally available to him on board the real ship. The use of professional pilots from the area being simulated may be the most important factor and a primary reason for conducting a simulation study. Simulations are used to bring the skills and judgment of the pilot into the waterway design process and to determine the limits of the ship maneuvering characteristics in the specific navigation channel environment. Simulation studies are normally conducted as comparative studies in which one alternative channel design can be compared against a base (usually existing) condition or another design.

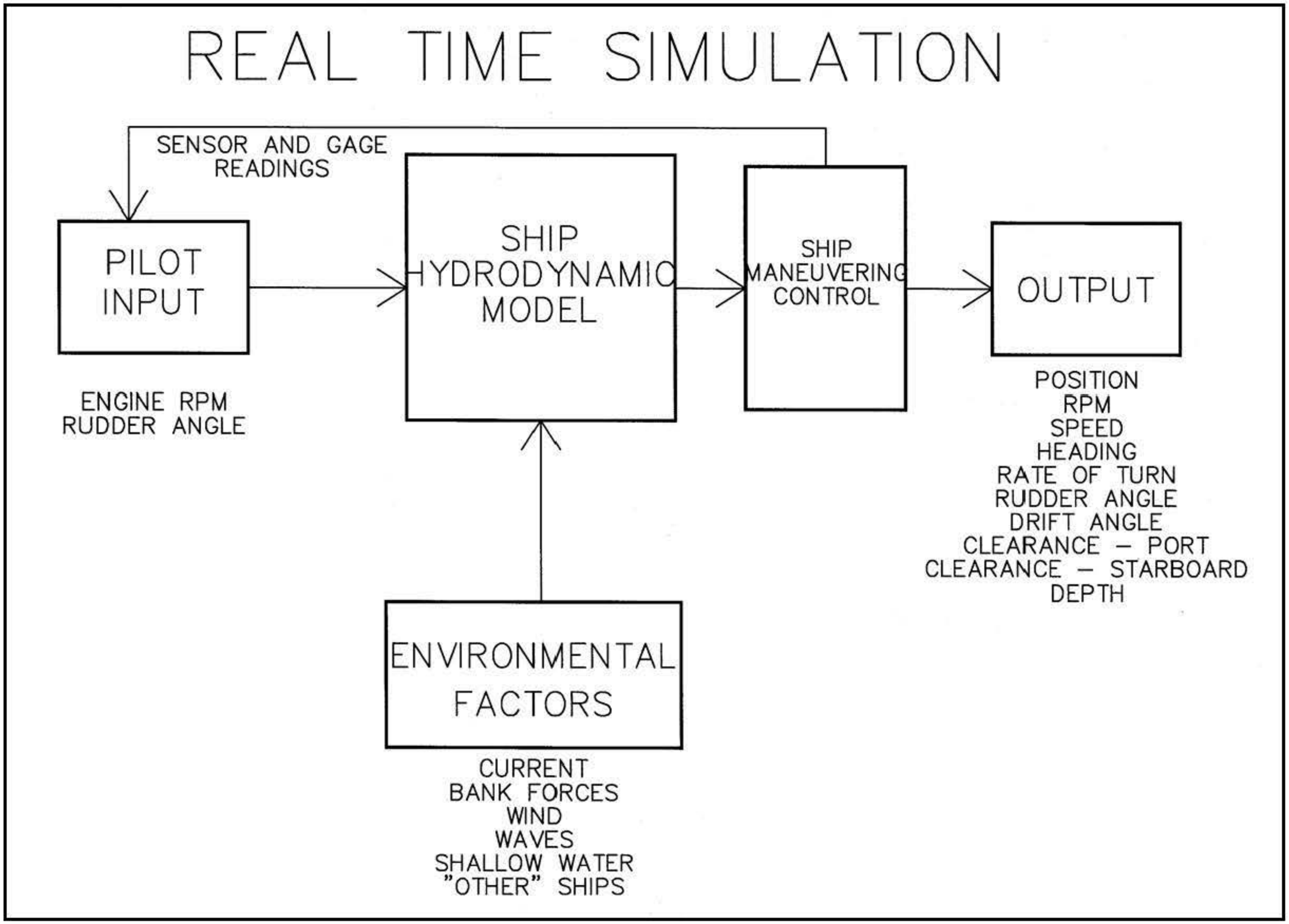


Figure C-1. Real-time simulation

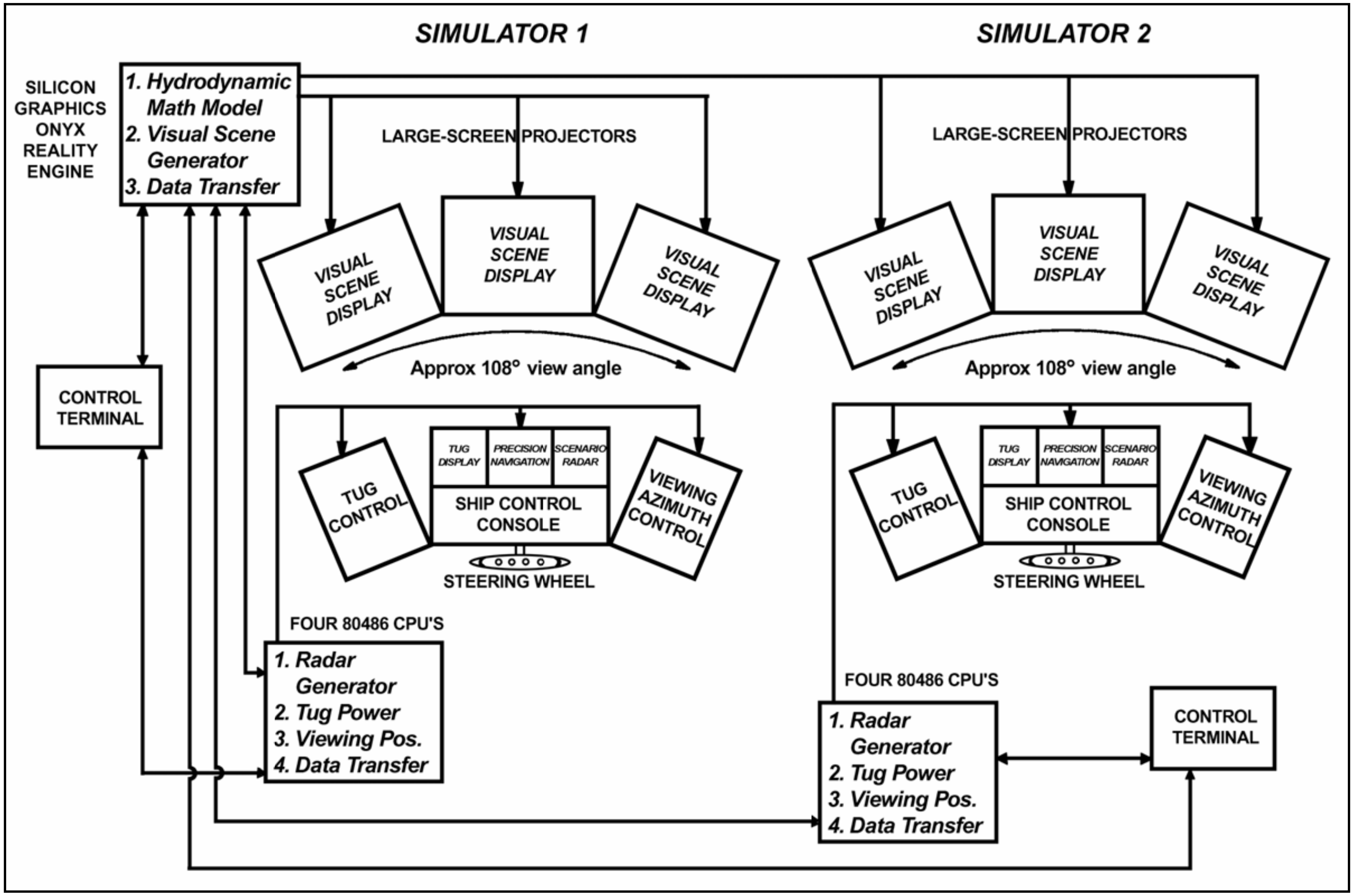
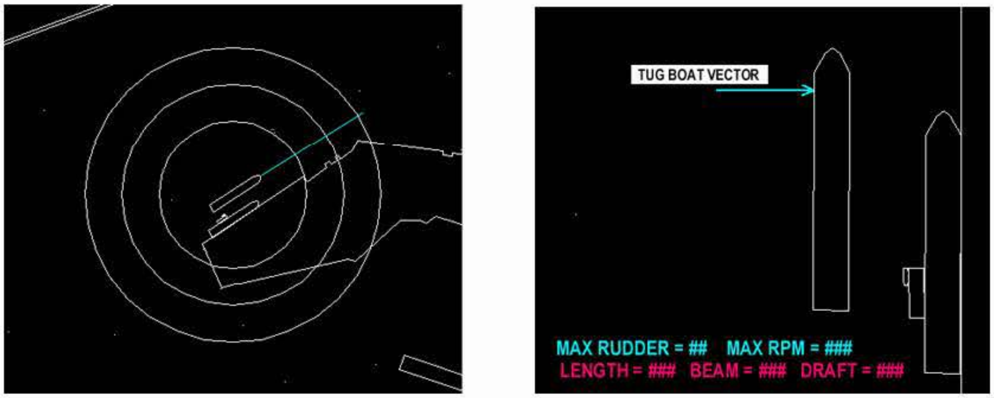


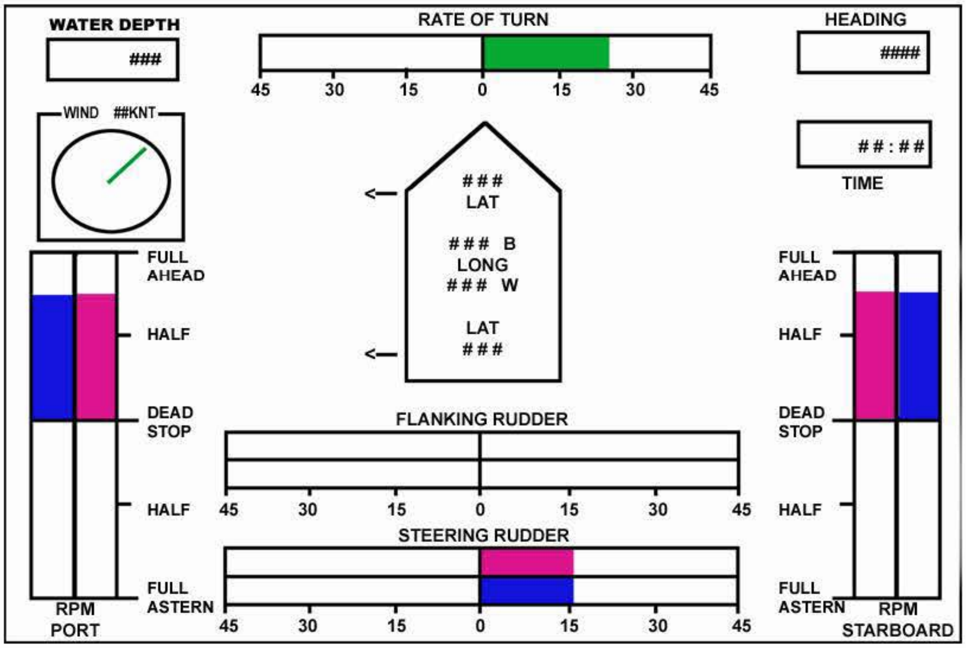
Figure C-2. ERDC ship simulator system

Simulator Visual Scene



Simulator Variable Radar Screen

Simulator Fixed Radar Screen



Navigation Parameters Screen

Figure C-3. Ship/tow Simulator visual scene and instrumentation

C-3. Study Methodology. Simulation studies can be used during different phases of waterway or port improvement projects. The earlier the simulation is introduced during project development, the more influence it can have on optimizing the design. At the reconnaissance level, a simulation study can identify the truly superior alternatives, eliminate the poor ones, and identify the required maneuvering areas. The same is true in the feasibility stage but with more detail. When the design has basically been set, a simulation study can refine and optimize the channel dimensions and alignment features and establish operational procedures. A simulation study “localizes” the navigation requirements; the local conditions are used to develop a final design. If operational problems exist or new operations are being considered, the simulation model can define the level of improvement and safety of the alternative designs.

Definition of the problem to be studied is important and must include a full understanding of the important issues and all of the ramifications, especially the range of ship operations and limitations, local pilotage, and environmental conditions. Navigation conditions for simulator testing have to be selected with care. Normally, reasonably high levels of wind and current conditions are used.

The modeling of the river or tidal currents is expensive and time-consuming; but it is an extremely critical part of most studies. Finite element mathematical modeling of the currents provides the most accurate and flexible modeling in many cases. There have been, unfortunately, several examples in the past of current modeling on a grid spacing that was larger than the channel width. How can current patterns at channel turns be resolved on such a grid? At least five or more grid points are included over the width of the channel in the ERDC/WES Simulator.

It is also important that the currents be accurately modeled in the simulator. Some simulator models are limited in the ability to represent the spatial distribution of currents. Accurate definition of current patterns across and along the channel is required for adequate simulation. The ERDC/WES Simulator allows eight depth and velocity stations over the channel width and interpolates between definition points along and across the channel.

C-4. Applications.

a. J. F. Baldwin II Long Wharf.

(1) Study description. One of the first studies (Huval et al. 1985) conducted resulted in major savings of construction costs and reduced dredging quantities requiring disposal. This study involved deepening a channel from deepwater in San Francisco Bay to the Richmond Long Wharf facility, a major oil terminal on the west coast of the United States (Figure C-4). The project improvement called for deepening from 35 to 45 ft to allow 150,000 deadweight tons (dwt) tankers to go directly to the terminal rather than to lighter, smaller tankers in the bay, always risking an oil spill. Questions were raised about the safety of the larger tanker approaching the terminal in the maneuvering area and the approach channel width required. Maneuvers depend on the phase of the tide, flood, or ebb, when the docking occurs; pilots approach the dock while stemming the tide. Tidal current data were developed from special measurements on the San Francisco Bay scale model.

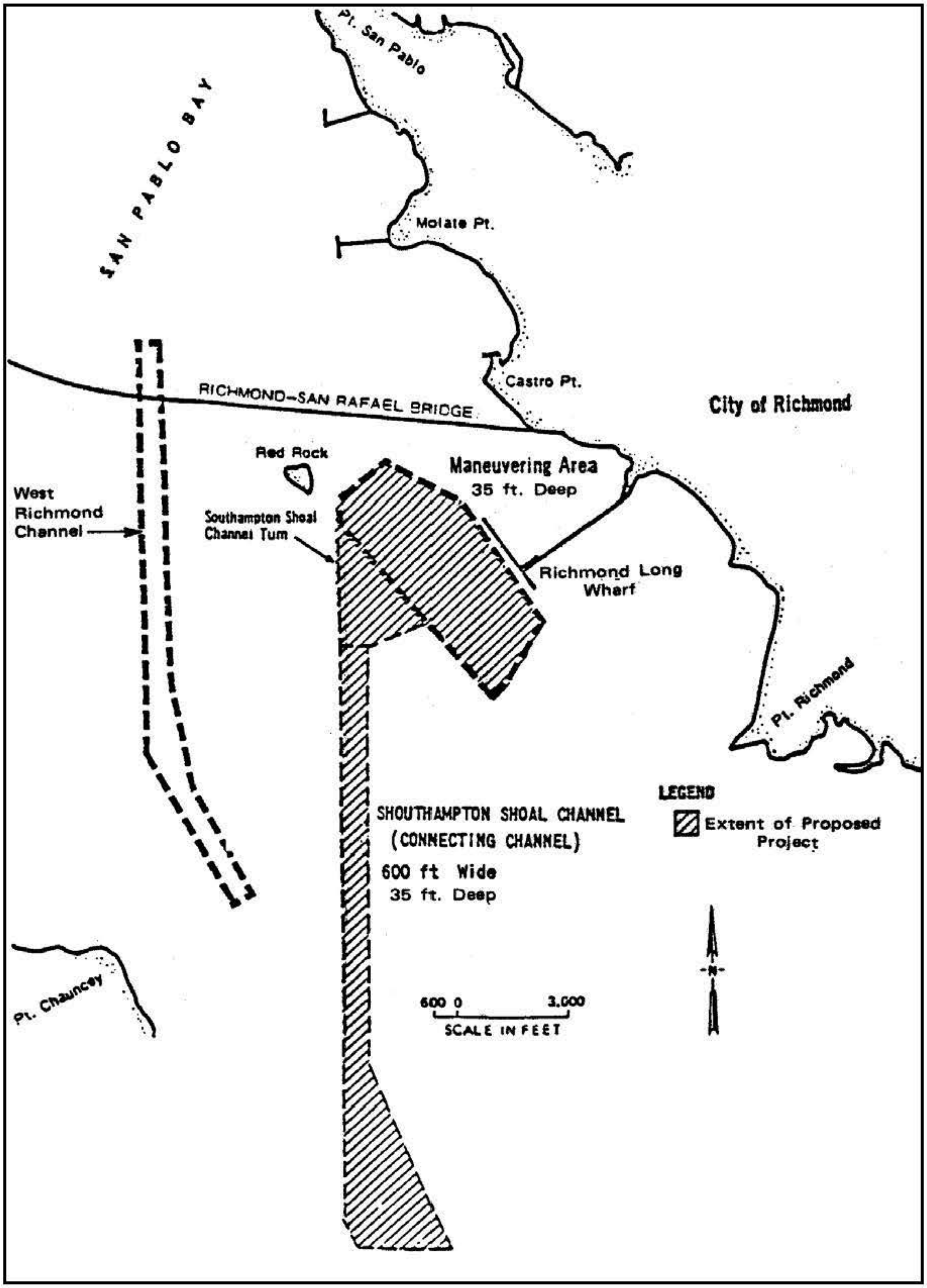


Figure C-4. Connecting channel from San Francisco Bay to Richmond Long Wharf facility

Project construction was imminent. Early tests in the WES Simulator indicated that the proposed 600-ft approach channel width was required because of strong crosscurrent and reduced ship forward speed. Docking approach maneuvers did not take as much room as expected. As a result of a reanalysis of test results and a second set of simulations, the area of the maneuvering area was reduced significantly, resulting in a savings of $1.8 million and 1.43 million cu yd of dredging. The project cost is estimated to be $12.8 million and the simulator study cost was $110,000.

(2) Lessons learned. The simulator model was a very good representation of the real world. Engineers can get a good feel for the navigation problems from simulation tests and develop adjustments in the design. Local pilots are very important to a successful study, which must include their skills, experience, local knowledge, special operations, cooperation, and coordination. Simulation provides a means to develop or enhance a consensus on the design between the planners, project managers, engineers, pilots, port authorities, and terminal operators. Optimizing a design can help reduce environmental impacts and project opposition and environmental mitigation costs. It is never too late to adjust the design; even after construction, the project can be corrected if a navigation or maintenance dredging problem exists.

b. *Grays Harbor.*

(1) Study description. Grays Harbor (Figure C-5) is another example that demonstrated the benefits of simulation studies (Hewlett et al. 1991). This project consists of two portions, the outer harbor in open bay water and the inner harbor or river portion. The project involved deepening and widening the navigation channel to allow timber ships that are presently calling to be loaded to a greater draft and thus operate more efficiently. The channels were to be deepened from 30 to 38 ft and the outer channel widened from 350 ft to 400 ft throughout. Pilots were brought in from the local area early in the study and the District sponsor was actively involved. Physical scale model data from a previous study were used but the model was not available to allow special data collection as in the previous case. It was found that the pilots routinely took the ships beyond the limits of the existing authorized as well as the proposed, deepened channels into naturally deep areas. However, they reported that the existing 350-ft-wide channel deepened to 38 ft provided more control than the widened channel, as a result of higher bank forces. They preferred the narrower channel; however, there had to be some adjustments at the channel turns to allow for the wide swing of the ship and the transition from locally widened areas to the confined 350-ft channel (Figure C-6). Savings in dredging volume, environmental impact (impact on crabs), and project costs were $2 million.

The interior portion involved ship maneuvering in a river environment, with one large bend and a narrow channel with high banks. Here the point current measurements from the scale model became limited and not always available where data were needed. Bank effects on the maneuvering ships became significant. A narrow railroad bridge span (125 ft) was to be increased to 185 ft by bridge replacement and redesigning the timber fendering on another nearby highway bridge. Could larger ships than the current limit of 80-ft-beam, 30,000-dwt timber ships call the terminal at the head of the channel for greater benefits? With adjustments to the channel design upstream of the highway bridge, the simulations showed that with ships up to

100-ft-beam, 50,000 dwt, could safely transit through the modified bridges. The benefits from the nearly doubled cargo greatly outweighed project costs.

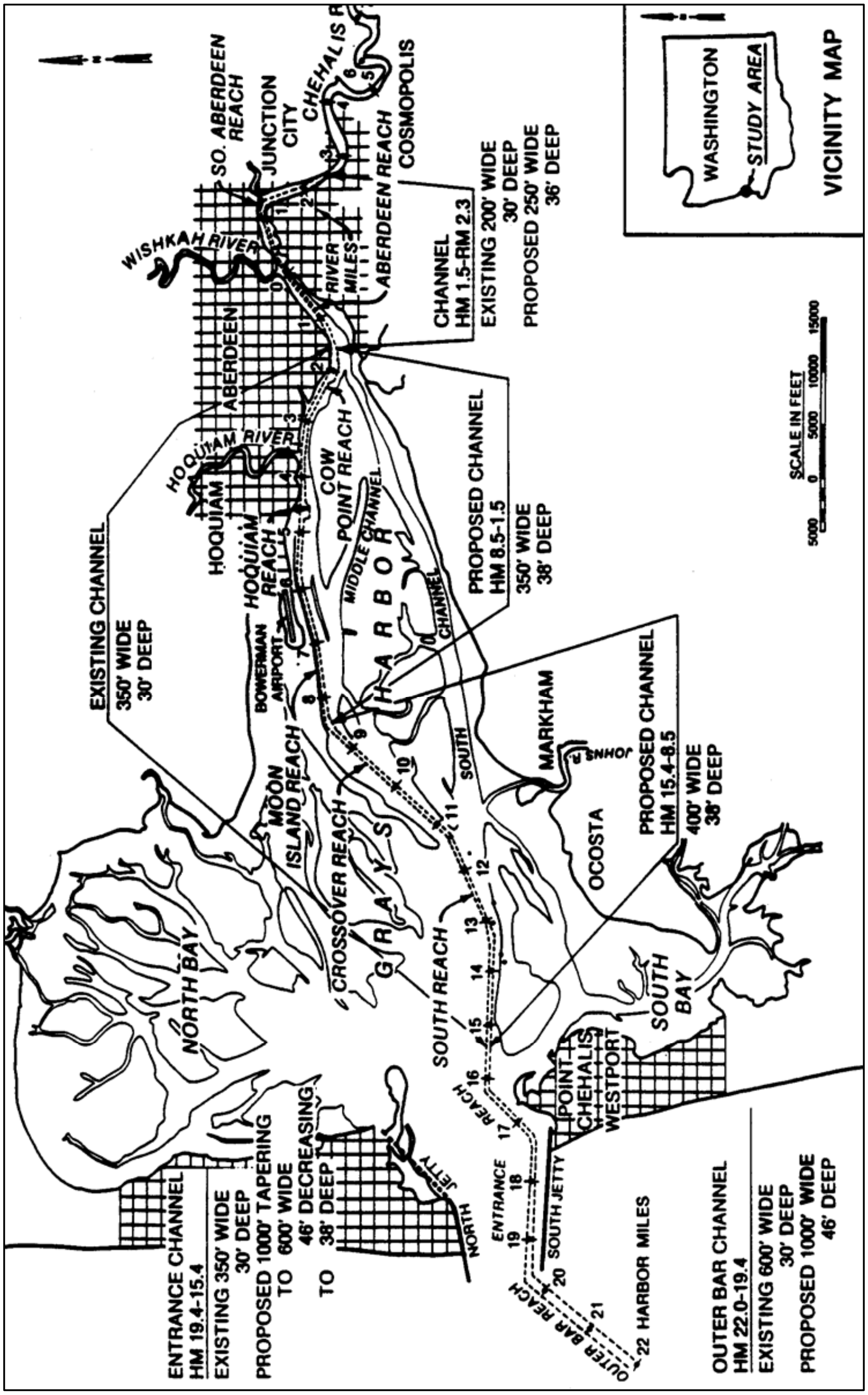


Figure C-5. Grays Harbor

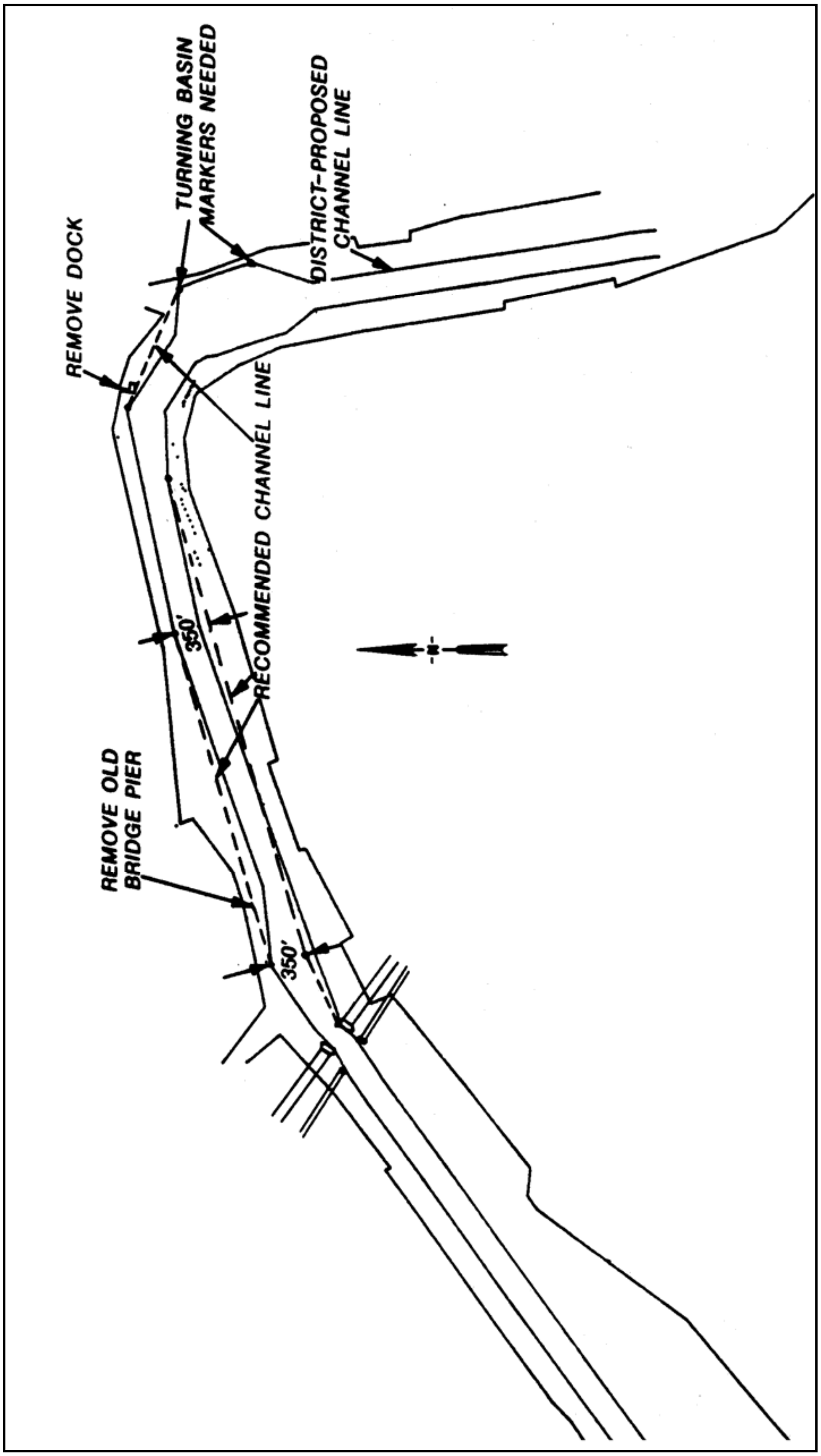


Figure C-6. Grays Harbor, recommended channel alignment

(2) Lessons Learned. Major project savings can be obtained by applying the simulator. The pilots suggested improvements; project engineers and managers were deeply involved and provided valuable feedback and interaction. The simulation study identified a potential problem for inbound transits not recognized by the engineers that required additional local channel widening. Point measurements from physical scale models do not provide adequate current pattern data needed for accurate simulations. Testing alternative channel design widths can identify improvements in navigation conditions, sometimes indicating that increased width is not always beneficial. The simulation study allowed the identification of additional project benefits for the proposed project.

c. *Bridge Relocation Study*.

(1) Study Description. A ship simulation study was conducted to determine the appropriate span increase for the Gilmerton Bridges in Portsmouth, VA. Docking pilots from the project site traveled to Vicksburg to maneuver the simulated vessels through several proposed fender layouts. The existing span width was 125 ft. The simulations revealed that a minimum of 150 ft was required and that the widening should be on the west side only. The design was approved by the pilots and the Norfolk District engineers.

(2) Lessons Learned. Vessel simulations can be used to evaluate proposed bridge span locations and width. Simulation of several span widths will assist in selection of the safest and most economically attractive alternative. Also, possible changes to the navigation channel and channel markings can be examined.

d. *Project Site Screening*.

(1) Study description. Simulation can be used in the early phases of navigation projects to include and define navigation requirements, even at the reconnaissance study level. A recent towboat simulation study of 13 potential navigation lock sites resulted in 22 different specific design alternatives on an inland waterway. Because of the many sites and flow combinations, a simplified river current model was used. The study allowed the ranking of the alternative design combinations based on piloted navigation qualities in a way never before possible. In the past, lock site navigability was considered in the design based on engineering judgment as to suitability. Real estate and foundation considerations usually governed lock site location, rather than the project purpose of navigation and its related factors, hydraulics, and channel alignment. From this study, it was clear that some sites were much better navigationally than others; the 22 alternatives were easily ranked into three categories: 6 were recommended, 5 were feasible, and 11 were unacceptable.

(2) Lessons learned. While river currents are important for towboat simulation, it is possible in some cases to develop an adequate current pattern without modeling in detail, particularly where the channel configuration will dominate navigation considerations. Navigation can and should be considered with the simulator early in the project so that major navigation hazards resulting from a poor choice of lock location can be avoided.

e. Port Jersey Channel.

(1) Study description. Not all simulator studies result in project savings from the originally planned design. The Port Jersey channel project (Figure C-7) called for deepening from the present 35 ft to the proposed 41 ft to allow fully loaded, 106-ft-beam, 950-ft-long containerships to call at the port. Several channel widths were being considered, including one 350-ft-wide plan, which would considerably reduce the present available width. The entrance into the design channel requires the ship to turn almost perpendicular to the flood or ebb tidal currents. During an inbound run, the ship experiences high (2.5 knots) crosscurrents, small currents in a semiprotected channel between shoals, back to high crosscurrents, and finally minimal currents in a fully protected and confined channel. A car carrier terminal with moored ships alongside near the entrance further complicates the navigation conditions.

The simulation study (Thevenot et al. 1996)showed the 350-ft-width design should not be seriously considered. In fact, a significant increase in width is recommended from the originally considered design (Figure C-8). Some of the docking tug company pilots had difficulty adapting to the new, deeper, but narrower channel condition. They tried to use several different strategies for turning and reducing speed. The available tugs could not be used to control the ship in the 25-knot wind and strong tidal currents.

(2) Lessons learned. Safety considerations dictated a wider channel than originally planned due to the severity of local environmental conditions. Backing large ships is difficult, particularly in currents. Sometimes the operational limits may have to be adjusted, e.g., the ships may not be able to come in under high wind and currents. In some cases, it may be desirable to consider high-accuracy ship positioning information, such as in the 1,250-ft turning basin, as an alternative to size increases.

f. Oakland Harbor Navigation Study.

(1) Study Description. The Port of Oakland and the Inner and Outer Harbors are located on the eastern side of the San Francisco Bay in the Counties of Alameda and San Francisco, California (Figure C-9), Navigation problems arise from the shear or cross currents at the entrance of Inner and Outer Harbors (Figure C-10), and the size of the two harbor's turning basins (Figure C-11). A deepening project to take the channel to –50 ft was proposed to accommodate the Extended K-class containership, to reduce tidal-caused delays associated with containership passages, and to increase navigational safety.

The most critical aspect of the deepening project was the Inner Harbor Turning Basin. Real estate concerns not only limit the size of this turning basin; but would also prefer for the size to be reduced. After lengthy validation time to ensure that the simulator was acting correctly in this critical area, the final study showed that although the turning basin could not be reduced; the pilots would be able to maneuver the new design vessels in the existing dimension basin (Figure C-12).

(2) Lessons Learned. Turning basin design based only on a multiple of a design ship length cannot be generalized without including site-specific considerations. Sometimes changes in turning basin layout can be made using the simulator and local pilots to accommodate

concerns without sacrificing navigational safety. However, these site-specific results cannot necessarily be applied to another location, even in the same port.

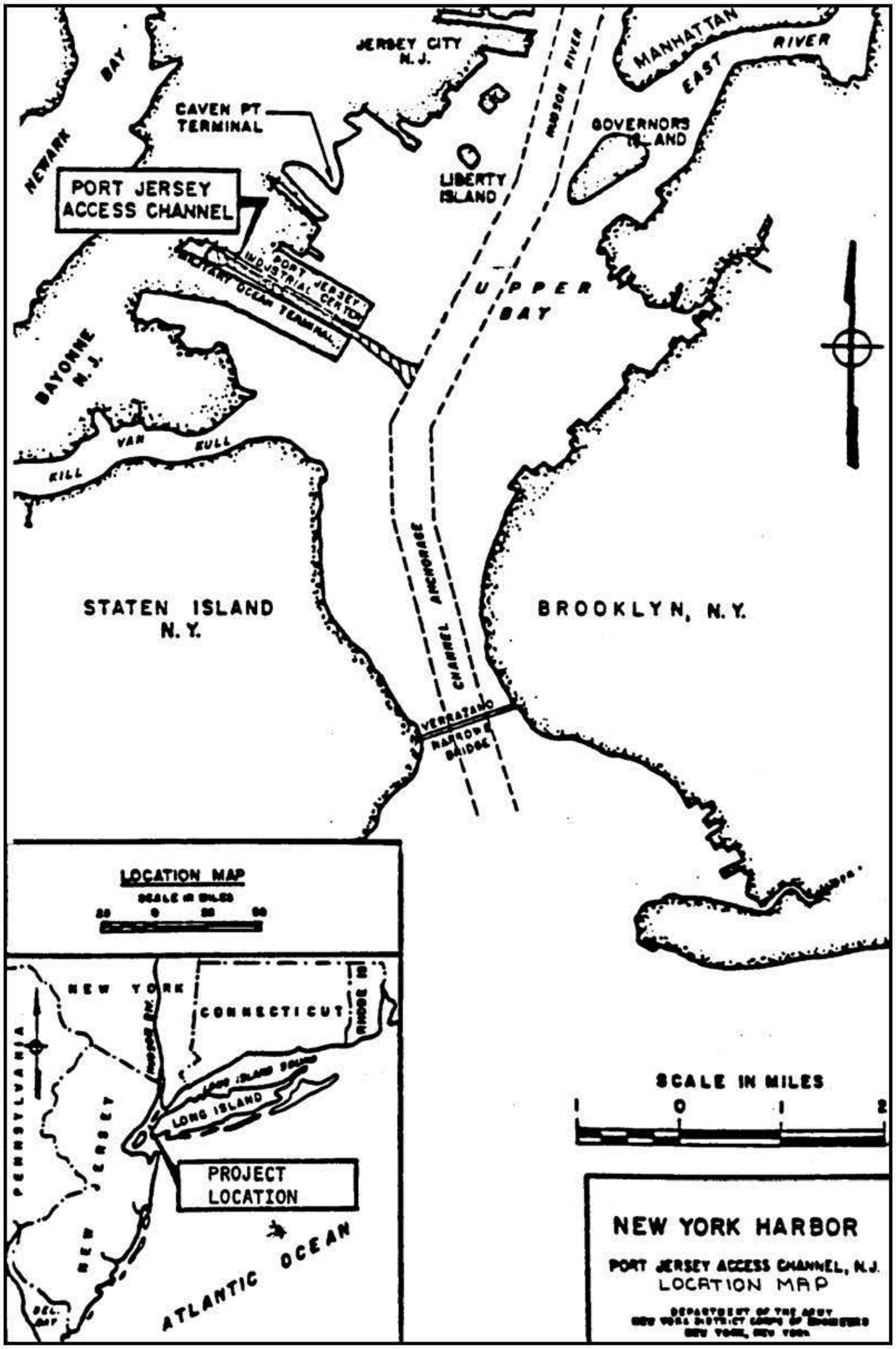


Figure C-7. Port Jersey location map

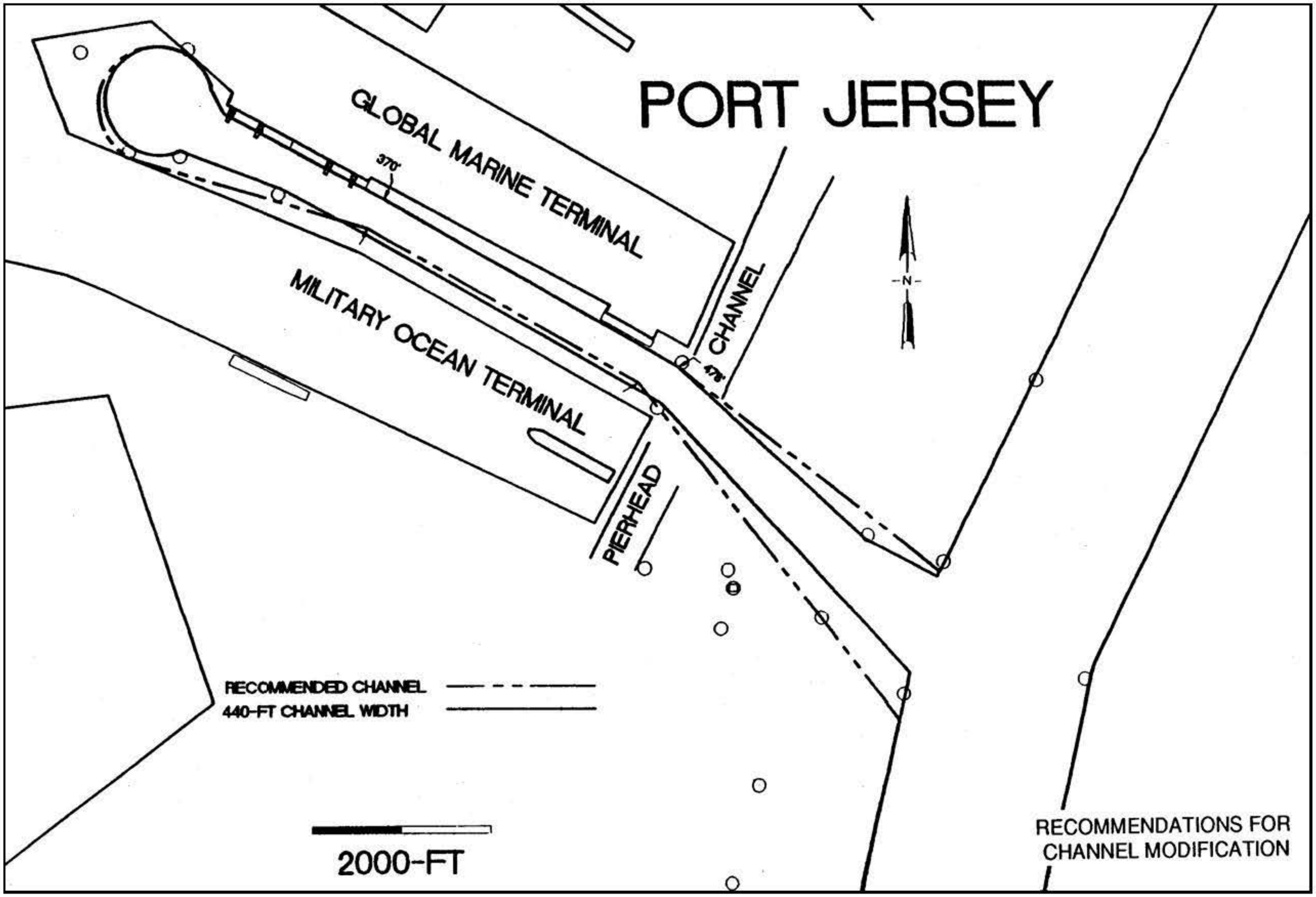


Figure C-8. Port Jersey channel modification recommendation

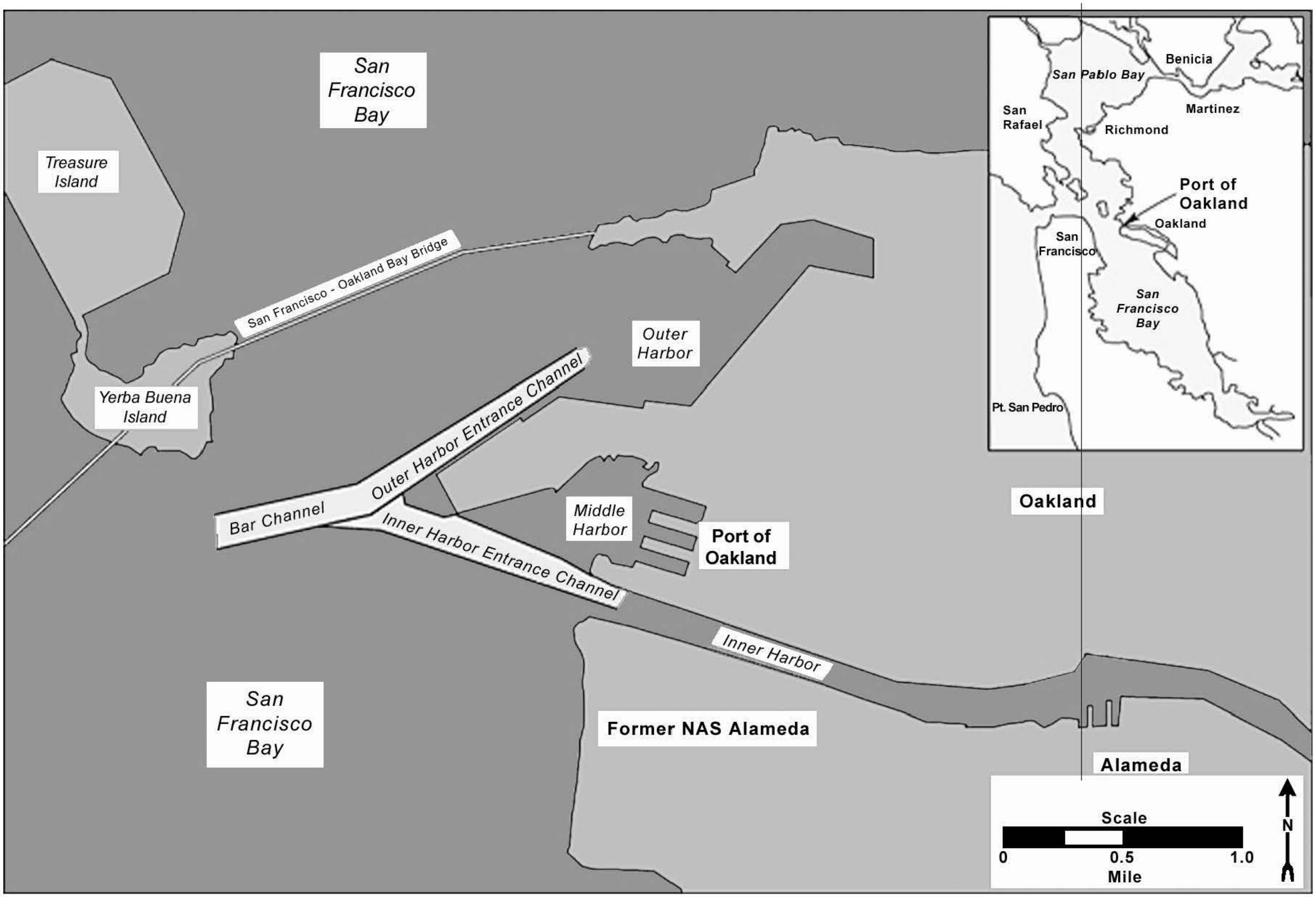


Figure C-9. Oakland Harbor location map

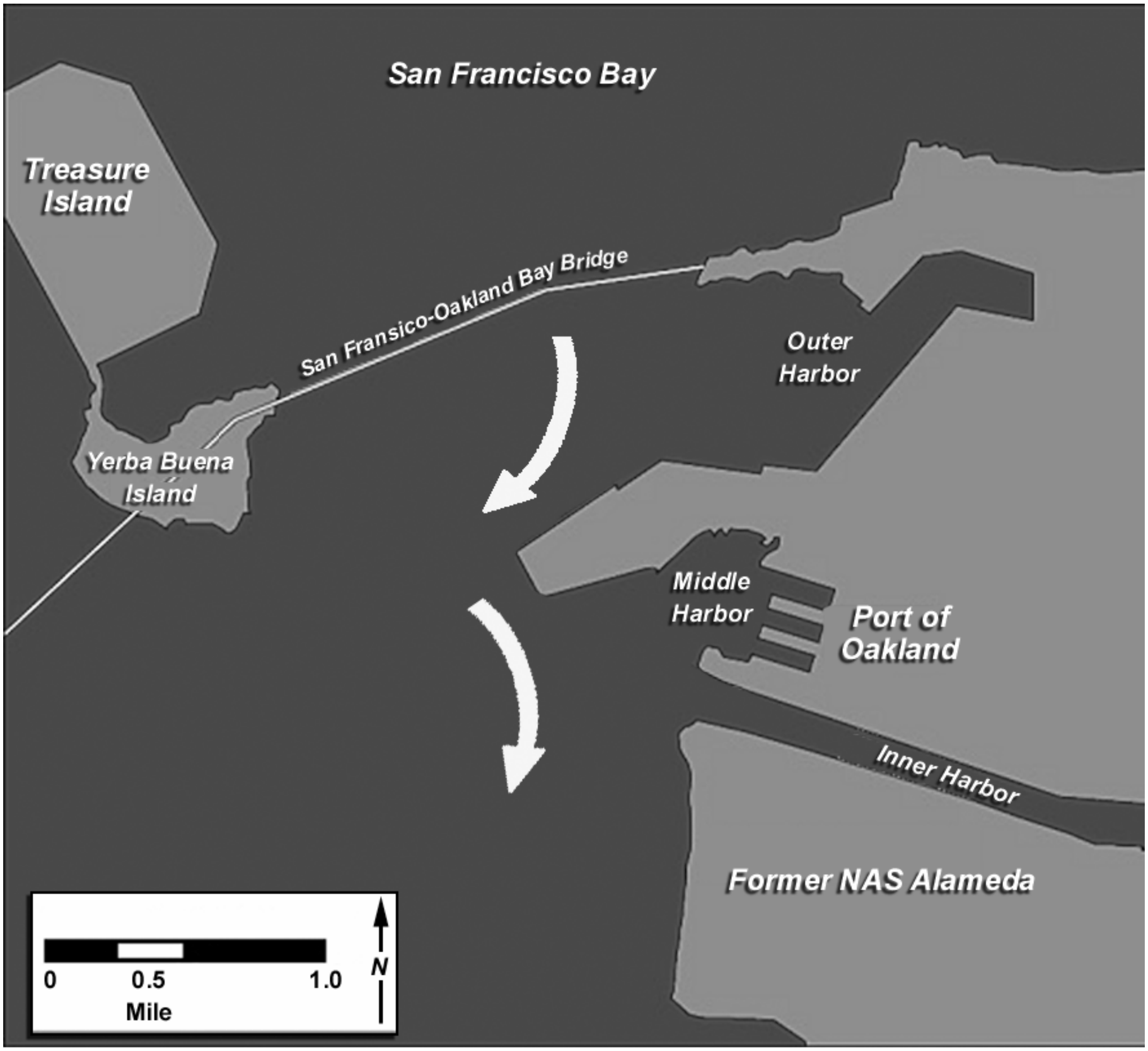


Figure C-10. Oakland Harbor – location of shear currents

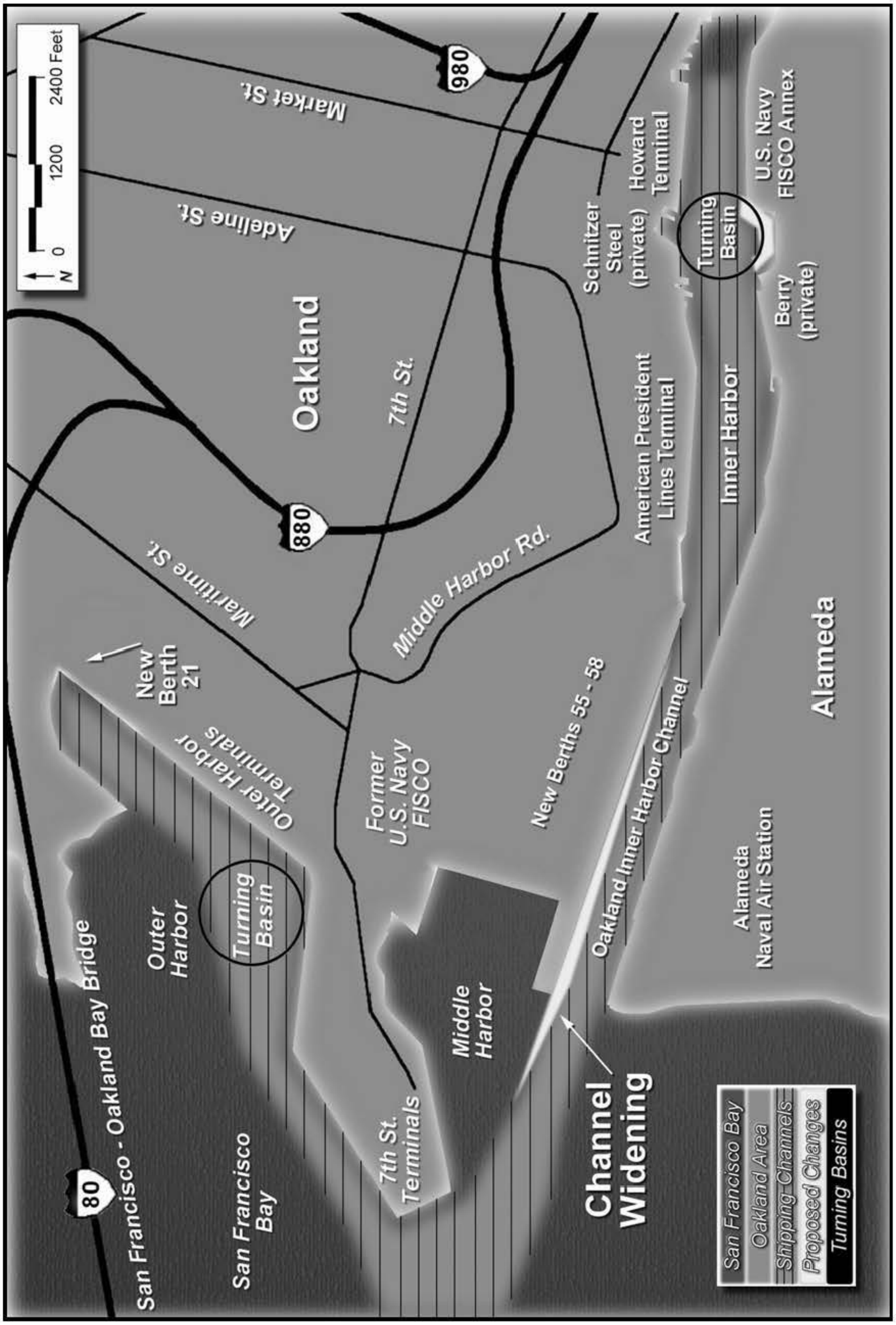


Figure C-11. Oakland Harbor – location of turning basins

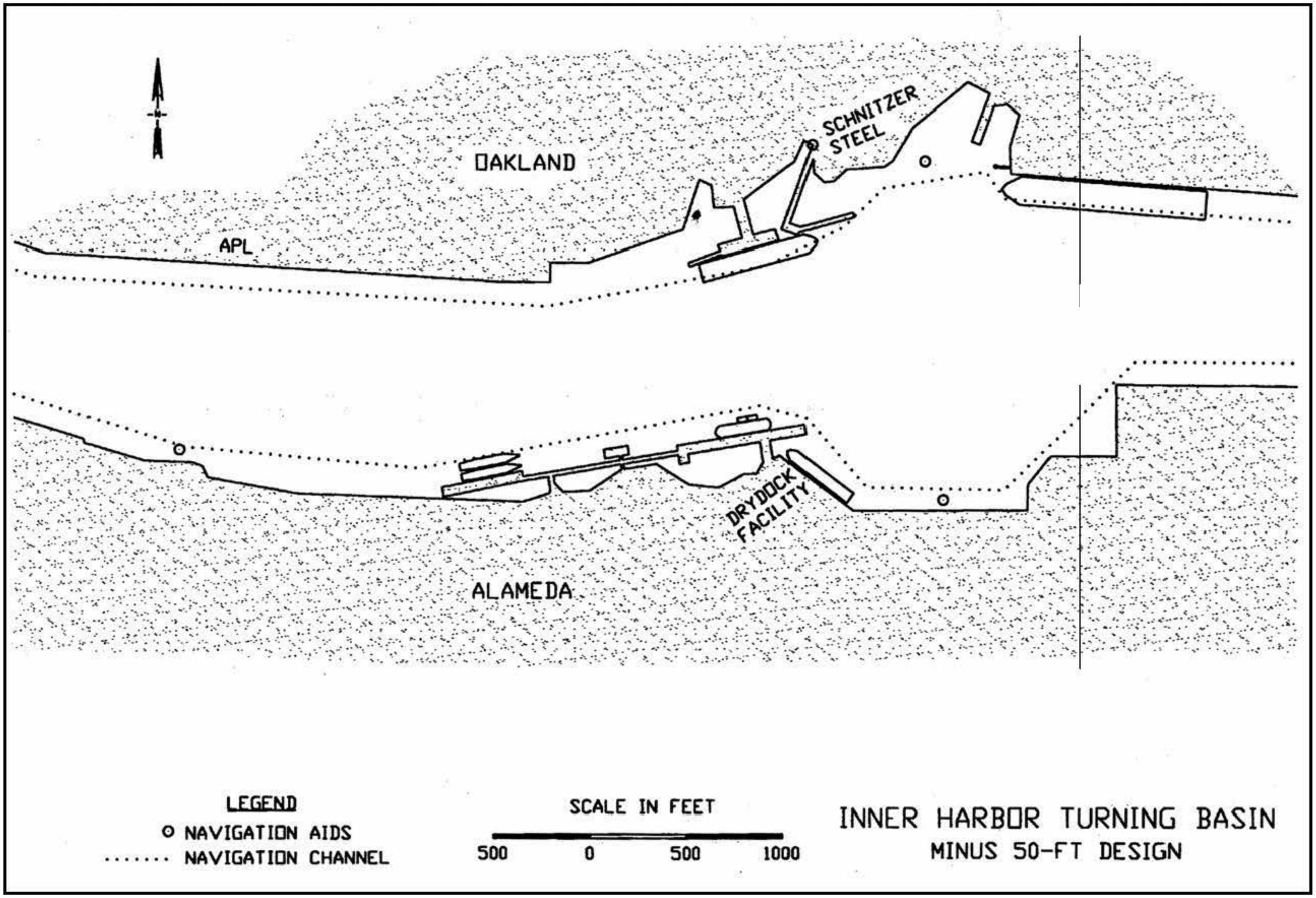


Figure C-12. Oakland Harbor Navigation Study, recommended design for Inner Harbor turning basin *g. Sacramento Ship Channel.*

(1) Study description. Cost sharing by local port authority project sponsors for navigation improvements has introduced new factors to consider into design. In fact, financial considerations, such as port revenues, can determine which, or even whether, projects will be built by the Federal Government. The Sacramento River Deepwater Channel is a project that became critical because of the high cost and marginal local port authority financing. Ninety percent of the project cost was in the man-made canal portion. This involved deepening the project from 30 to 35 ft and widening the channel from 200 to 250 ft.

Through ship simulation tests, substantial design changes were developed for the deeper channel. By widening the turns to 250 ft and providing transitions from the widened turns to the existing 200-ft-width channel, the pilots could maintain the same level of ship control as they had in the unimproved 30-ft channel. This resulted in a savings of about $20 million.

(2) Lessons learned. Ship simulation tests in highly constricted canals can be conducted but require more subjective pilot and engineer judgment. Published bank effect models of ship forces and moments are inadequate; the study led to improved modeling of the canal bank effects on the maneuvering ship. The man-made trapezoidal canal cross section had changed substantially due to local scouring. The bank effects model had to account for changing canal cross sections, which was important to realistic ship simulations.

C-5. Simulator Limitations. Bank and shallow water effects and modeling techniques are presently not well defined. More towing tank testing is needed for these important areas, especially in the range of realistic ship and channel dimensions.

Validation of ship simulation studies depends largely on the local pilot's evaluation. An improved method for obtaining validation of simulator models would go a long way to increase acceptability of channel design studies.

A lack of a generally accepted measure of safety by simulator operators is another important present limitation.

Simulation models presently all assume passive ship effects, even when the ship presence influences the flow field, such as lock approaches. Ships meeting and passing in highly restricted waterways (the so-called Texas Chicken maneuver) is another example of important ship/flow field/ship interaction. More experimental and theoretical studies are needed to quantify and develop math models of highly interactive maneuvering situations.

C-6. Conclusions. Published channel design criteria are very conservative. Channel width, turning basin, and turn widening designs can all be less than the required dimensions, provided a simulator study is used to verify the design.

Ship simulator study results have been used by ERDC/WES to substantially decrease project costs and reduce dredging material volumes on many navigation projects throughout the United States.

Channel design can be localized using a simulator to the specific project requirements. Channel size can be localized as required by simulator test results, providing width increases only where needed.

In some cases the simulator tests have resulted in improved safety and efficiency of the navigation project.

Simulator studies can be costly and time-consuming; the benefits in most cases, however, are far greater than the costs and result in safer channel designs.

Smaller, less expensive, studies (desk-top studies) can be designed to explore potential benefits and indicate the need for more extensive investigation of specific project areas.

Engineering design of navigation channels can be accomplished in a cost effective manner with limited ship simulators having modest visual scene display and bridge equipment. Accurate modeling of the ship, currents, and channel effects is important for successful channel design studies.

Simulation studies should be initiated early in the project planning process and preferably conducted in an iterative manner to ensure that an optimum design has truly been achieved.

C-7. Acknowledgements. The success of the ERDC/WES Ship Simulator would not be possible without the highly capable and dedicated team conducting the studies. We appreciate their efforts.

The tests described and the resulting data presented, unless otherwise noted, were obtained from research conducted under the Navigation Hydraulics Research Program of the United States Army Corps of Engineers and specific project studies for the respective District offices by the ERDC/WES, Vicksburg, MS. Permission was granted by the Chief of Engineers to publish this information.

C-8. References.

ETL 1110-2-289
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APPENDIX D

Ship Simulator Scope of Work

D-1. Introduction. A checklist for navigation study design and a sample Scope of Work (SOW) for a case study are included. The SOW is an example of how a study plan can be prepared and what it would contain. The SOW should be designed to fulfill the specific needs and desires of the project design office for the navigation simulation study. The checklist may be helpful in the preparation of a new simulation study to ensure all items that should be considered in the study are included.

D-2. Checklist for Navigation Study Design.

a. *When can a ship simulation study be used?*

(1) Reconnaissance study.

(2) Feasibility study.

(3) General design memorandum.

(4) New construction design.

(5) Modification of existing channel, turning basin, anchorage area, etc.

(6) Federalization of a privately developed channel.

(7) Operational issues.

(8) Permitting decisions.

(9) Maintenance operations.

(10) Accident reconstruction.

b. *What is the project purpose?*

(1) Channel modification.

(a) Widening
(b) Narrowing
(c) Deepening

(2) Construction of new channel.

(3) Bend widening.

(4) Turning basin construction or modification.

(5) Anchorage construction or modification.

(6) Overhead bridge construction/replacement/ modification.

(7) Risk analysis.

(8) Alternative plan selection.

(9) Development of project design.

(10) Confirmation of project design.

(11) Navigation problem identification.

(12) Resolution of safety problems.

c. What should be modeled in the study?

(1) Existing conditions.

(2) Designs and alternative(s).

(3) Critical navigational conditions.

(a) Currents
(b) Wind
(c) Bank suction
(d) Channel geometry
(e) Traffic
(f) Tug assistance

(4) Navigational concerns.

(a) Increased vessel size
(b) Increased vessel draft
(c) New types of vessels in the channel
(d) Safety problems at specific locations
(e) Change in traffic operation
(f) Possible elimination of tidal restrictions
(g) Possible elimination of tug handling requirements

d. What information is required to perform a study?

(1) Environmental description of existing conditions.

(a) Channel bathymetry
(b) Wind data
(c) Currents – magnitude and direction
(d) Channel geometry and markers
(e) Existing vessel operational procedures

(2) Environmental description of new design conditions.

(a) New channel bathymetry
(b) Wind data
(c) Modified currents – magnitude and direction
(d) New channel geometry and markers
(e) Proposed vessel operational procedures

(3) Vessel(s) descriptors.

(a) Length overall (LOA)
(b) Beam (B)
(c) Draft (T)
(d) Handling characteristics
(e) Bow/stern thrusters.
(f) Special rudders
(g) Engine propulsion

e. *What type of channel is being studied?*

(1) Open water entrance.

(2) Fresh/saline/brackish water.

(a) Possible salinity wedge
(b) Vessel draft changes
(c) Three-dimensional currents

(3) Shallow draft.

(4) Deep draft.

(5) Turning basin.

(6) Anchorage.

(7) Canal.

(8) River.

(9) Lock approach.

(10) Bed material and geometry.

(a) Flat
(b) Natural alluvial
(c) Sand/sand waves
(d) Rock
(e) Coral

(f) Mud
(g) Fluff
(h) Hazardous material

f. *What type of vessel traffic?*

(1) One-way only.

(2) Two-way.

(3) Meeting and passing.

(4) Overtaking and passing.

(5) Tug assist.

(6) Other vessels: Recreational, ferries, small push-tows.

g. *What is the project vessel type?*

(1) Bulk carrier.

(2) Containership.

(3) Roll-on/roll-off (RO/RO).

(4) Car carriers.

(5) Tanker.

(6) Ferry.

(7) Etc.

h. *Possible sources of information for design vessels?*

(1) Tow tank tests.

(2) Sea trial data.

(3) Estimated model.

(4) Adjusted model from a geometrically similar ship.

i. *Visual conditions to be used in testing?*

(1) Daytime.

(2) Nighttime.

(3) Fog/Haze conditions.

(4) Radar-only navigation.

j. *Are structures affecting the navigation conditions?*

(1) Bridge(s).

(2) Lock.

(3) Anchorage/mooring cells.

(4) Dikes.

k. *What pilotage should be used?*

(1) Autopilot.

(2) Engineering/Scientists.

(3) Professional, licensed pilots.

(4) Local licensed pilots.

(5) Bar pilots.

(6) Docking.

(7) Tug pilots.

l. *What analysis of the data is required?*

(1) Track plots.

(2) Pilot survey, questionnaires, and comment.

(3) Ship control parameters.

(a) Rudder
(b) Shaft RPM
(c) Heading
(d) Rate of turn
(e) Speed
(f) Drift Angle

(g) Tugs
(h) Bow/Stern Thrusters

(1) Channel Parameters.

(a) Vessel clearance: Port and starboard
(b) Swept path of vessel
(c) Percent of channel used by vessel
(d) Heading of vessel relative to channel bearing

m. What reporting requirements are desired?

(1) Monthly progress.

(2) Financial.

(3) Special problem.

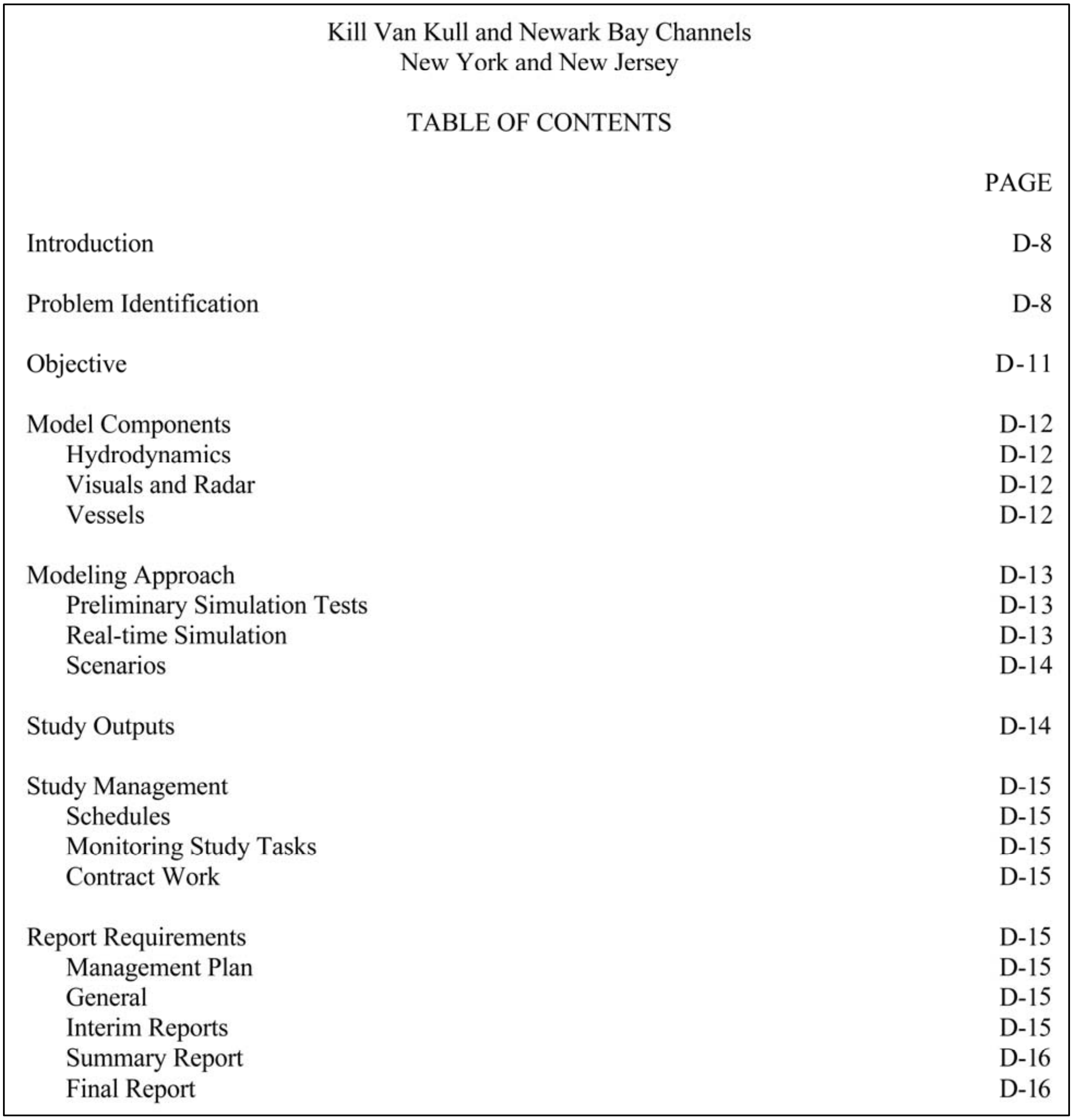
(4) Preliminary results.

(5) Draft final.

(6) Final.

(7) Executive summary.

D-3. Example Scope of Work. Figure D-1 provides the table of contents for the following example SOW, with page numbers in the table of contents referring to pages in this example.



Kill Van Kull and Newark Bay Channels
New York and New Jersey

TABLE OF CONTENTS

Figure D-1.

KILL VAN KULL AND NEWARK BAY CHANNELS
NEW YORK AND NEW JERSEY
SCOPE OF WORK
SHIP SIMULATION MODELING

Introduction

1. The study area, consisting of the Kill Van Kull, Newark Bay Channels, and a section of the Arthur Kill Channels, is located west of the Upper New York Bay along the border of New York and New Jersey. The Kill Van Kull, an 800-ft-wide channel approximately 4 miles in length, extends from Constable Hook to Bergen Point, New Jersey, connecting the Upper New York Bay to Newark Bay. The Newark Bay Channels, stemming north from the junction of the Kill Van Kull and Arthur Kill at Bergen Point, service the busy port authority terminals at Port Newark/Port Elizabeth and continue farther north, connecting with the Passaic and Hackensack River Channels. The North of Shooters Island, Elizabethport and Gulfport reaches of the Arthur Kill Channel, 500 to 600 ft wide and approximately 3.2 miles in length, extend west and south from the western end of the Kill Van Kull in Newark Bay.

Problem Identification

2. The problems associated with vessel navigation within the existing projects are related to the existing available channel depths. The existing 35-ft channel depth requires that the larger vessels enter the channel less than fully loaded, forcing tankers to perform costly lightening operations in the deeper areas within the Upper New York Bay and containerships to arrive at port underloaded, thereby increasing the shipping costs. The predicted trend is not for larger ships, but for an increasing number of the existing vessels deeper laden. The increased traffic in the already congested channels, combined with complex currents, sharp bends, and limited maneuvering areas have dictated the need for modifying the existing Federal navigation projects. The recommended modifications to the existing projects are developed in the “General Design Memorandum, Kill Van Kull and Newark Bay Channels, New Jersey and New York,” June 1986, (Reference 1) and the “Feasibility Study, Arthur Kill Channel, Howland Hook Marine Terminal, Staten Island, New York,” March 1986 (Reference 2), and shown in Figures D-2 and D-3. These modifications include deepening the Kill Van Kull and Newark Bay channels to 44-ft MLW and the Arthur Kill to 40-ft MLW. In addition to deepening the channels, critical locations of historical trouble spots will be widened. However, since there is a possibility that the Kill Van Kull channel will not be constructed to the authorized depth, but may be left at the Phase I depth of 40 ft, the channel dimensions should be determined for this condition. The ship handling conditions will likely be more difficult for this condition, since the velocities in the channel will probably be higher and the underkeel clearance will be minimum, assuming containership drafts do not change significantly. Thus, this more critical condition (Phase I) will be evaluated in the simulation study, and these results will also be applied to the 44-ft depths in the Kill Van Kull.

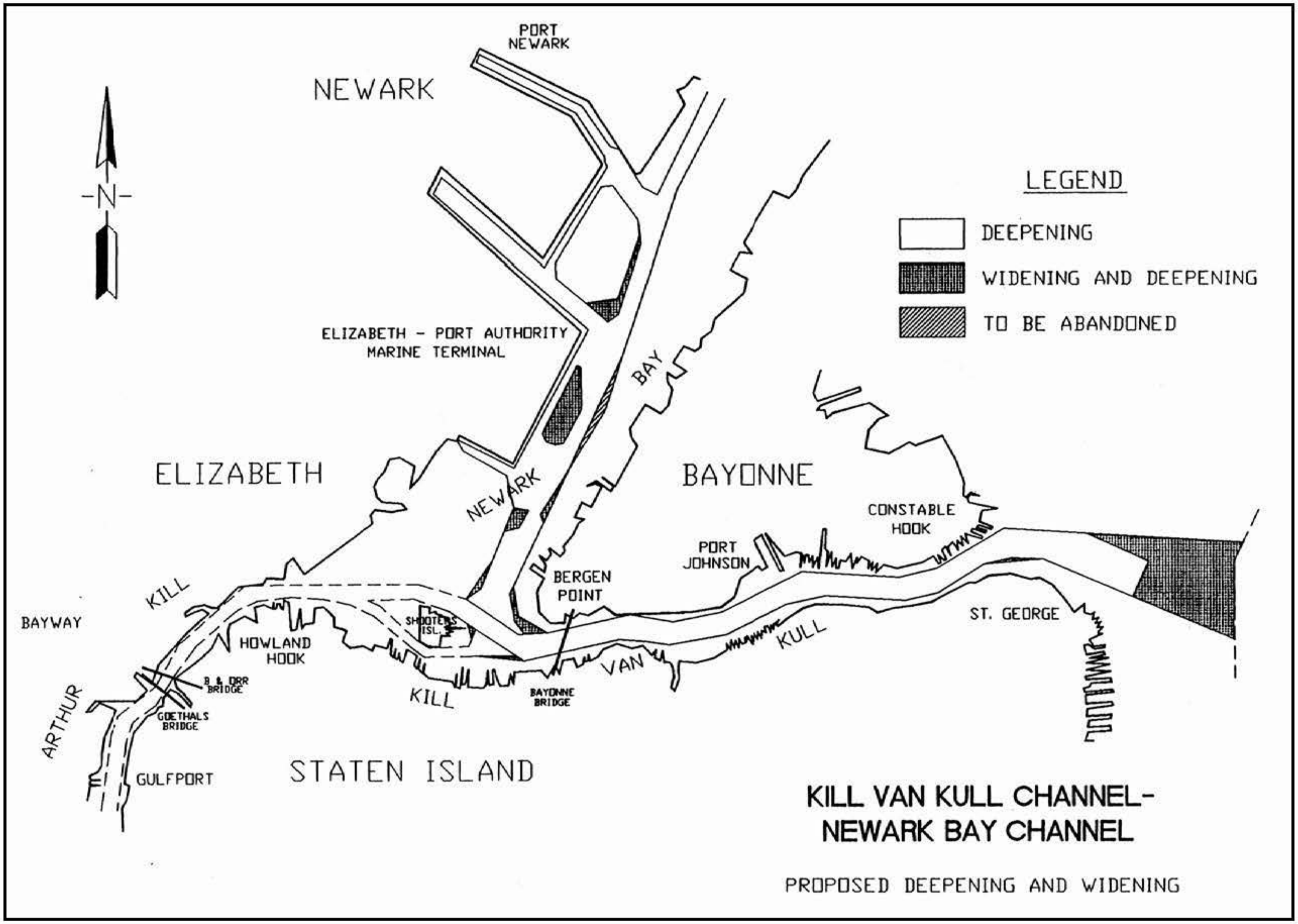


Figure D-2. Kill Van Kull and Newark Bay Channels – Study Area

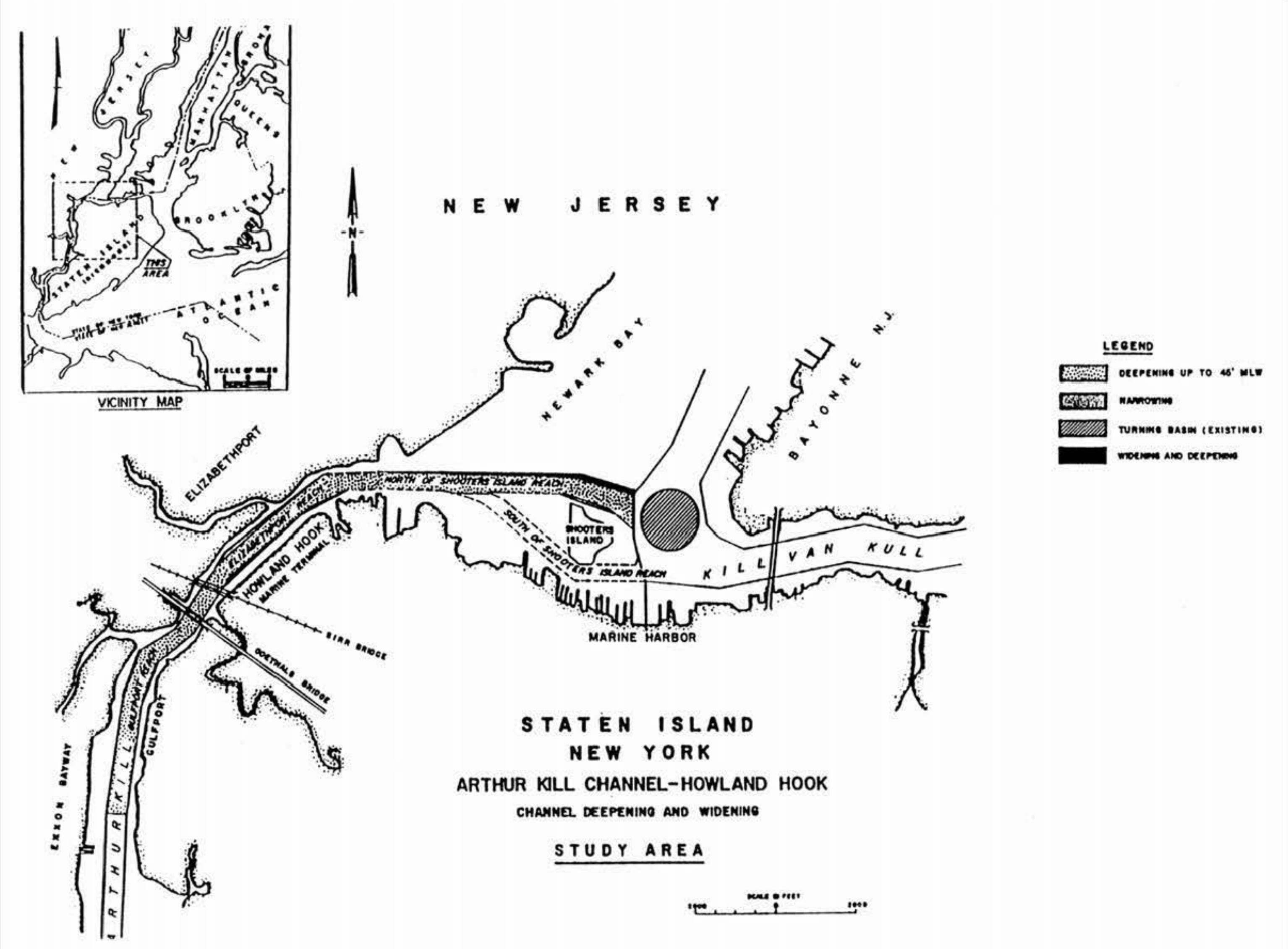


Figure D-3. Arthur Kill Channel and Howland Hook Terminal – Study Area

Objective

3. The objective of this simulation study is to aid in the refinement of the widths of the recommended channel improvements and also to assess the impact of the proposed improvements on the safety and efficiency of the deep-draft waterborne commerce within the study area. In order to obtain these objectives, the ship simulation study will evaluate vessel movement throughout the entire study area with particular concentration on the following locations:

a. The entrance to Kill Van Kull.
b. The Bergen Point Bend.
c. The Port Elizabeth Maneuvering Area.
d. The Newark Bay Channels.
e. The North of Shooters Island Reach.
f. The Staten Island R.R. and Goethals Bridge.

4. The entrance to the Kill Van Kull is the site of complex traffic patterns where two-way deep draft traffic is combined with crossing ferry traffic and shallow-draft tug/barge units through a 60-deg bend forming a complex three-way traffic situation. Deep-draft vessels reduce speed when entering the Kill Van Kull; some vessels pick up their tug escort at this location. The proposed improvements in this reach require widening the entrance of Kill Van Kull to a maximum of 2,000 ft. Simulation at this location should simulate two-way tanker traffic through the bend with the center lane blocked to simulate the presence of a shallow-draft tug/barge combination and crossing ferry traffic. Normal rules of the road will be observed in the test procedure.

5. The Bergen Point bend at the junction of the Kill Van Kull and Newark Bay channels is a sharp 127-deg bend hampered by complex and varying currents formed by the confluence of three channels. The existing channel width is inadequate for two-way deep-draft traffic, forcing an oncoming vessel to hold in the channel until the bend is clear. As a result, this bend has historically been the site of many accidents. In addition to through traffic, the Bergen Point bend also serves as a turning basin for containerships to turn and back down the Arthur Kill. The proposed improvements require widening the bend to a maximum of 2,200 ft to accommodate two-way (deep/shallow) traffic. Simulation at the Bergen Point bend should include the following scenarios: two-way traffic (container and tug/barge), two-way container traffic with one vessel holding just outside of the bend until the bend is clear, and a containership and/or tanker entering the bend from Kill Van Kull turning around and backing into the Arthur Kill.

6. The Newark Bay channels serve the busy Port Newark/Port Elizabeth terminals and the Passaic and Hackensack Rivers. Two-way deep-draft traffic is common throughout most of the channels where channel dimensions permit. In addition to the two-way traffic, many vessels turn around and back into the Port Newark and Port Elizabeth Channels when docking. The proposed improvement of the main channel includes widening to 800 ft. Simulation in the Newark Bay Channels should include a container vessel entering the Bay from Kill Van Kull, passing an outbound vessel near the Newark Bay Middle Reach and turning into the Port Newark Channel.

7. The construction of the Port Elizabeth maneuvering area (maximum width 1,570 ft) would permit vessels to turn around within the Port Elizabeth Pierhead area, and create a safe area for

vessels to hold within Newark Bay while awaiting berth. Simulation within this area should include turning a containership and backing the ship into the Port Elizabeth Channel.

8. The Arthur Kill is a narrow confined channel whose dimensions are dictated by the existing width between the banks of the waterway. Traffic patterns in this channel vary with the width of the channel. The North of Shooters Island reach of the Arthur Kill experiences two-way deep-draft traffic, often with one of the vessels backing down from Bergen Point to the Howland Hook Marine Terminal. The remainder of the Arthur Kill experiences two-way traffic (deep-draft or shallow/deep) along the straight sections. One-way traffic is the general rule in the sharper bends. The proposed improvements include widening of the North of Shooter Island reach to 600 ft (800 ft at the junction of Kill Van Kull). Simulation in the Arthur Kill should include an inbound tanker proceeding from the Anchorage Channel through the Kill Van Kull and Bergen Point to the Gulfport terminal, meeting the various passing situations as described above.

9. The Staten Island R.R. Bridge and the Goethals Bridge span a 500-ft- wide section of the Gulfport reach of the Arthur Kill. Immediately south of the bridges, two sharp bends (19 and 45 deg) create a hazardous approach to the bridges. North of the bridges and south of the bends, the channel widens to 600 ft. Simulation of one-way traffic (tanker) might identify possible realignment of the approach sections to lessen the severity of the bend-bridge combination.

Model Components

10. Hydrodynamics. In order to determine the hydrodynamic forces affecting vessel navigation, a two-dimensional (2-D) vertically integrated, finite element model will be developed. The grid will have sufficient resolution within the channel areas to define lateral as well as longitudinal currents. The hydrography/ topography should be based on current hydrographic/topographic data such as channel sounding, NOAA navigation charts, etc. These data have previously been developed for the New York Harbor model study at U.S. Army Engineer Research and Development Center (ERDC)/U.S. Army Engineer Waterways Experiment Station (WES). The model will be verified for tidal propagation and current velocities throughout the numerical grid using available field data as well as physical model data. Field data have been collected for the previous New York Harbor and Kill Van Kull model studies. No additional hydrodynamic field data collection is expected.

11. To represent the improved conditions with the proposed channel, the existing hydrography above the project depth will be deepened to the project depth. Those areas naturally deeper will remain so. Bank conditions along the existing and proposed channels will be defined so that bank effects on vessels will be modeled.

12. Visuals and Radar. In addition to the hydrodynamics, a physical representation consisting of a visual scene and radar image will be developed to guide the pilots through the real-time simulation of the vessel transits. The visuals and radar should display all buoys, ranges, landmarks, prominent channel features, and obstructions normally used by pilots as aids-to-navigation. Traffic ships will also be displayed in the visual scene and radar image.

13. Vessels. The deep-draft design vessels to be modeled in the study are containerships and tankers in the “Pan-Max” class with a maximum beam of 106 ft. In addition to the deep-draft

vessels, a tug/barge combination is to be modeled to represent shallow-draft traffic. The dimensions of the three design vessels are presented in Table D-1 below.

Table D-1

			Static Draft	
Type	Length, ft	Beam, ft	Existing	Improved
Container	944	106	30	36
Tanker	880	106	30	35
Tug/barge	330	75	20	20

The actual loaded drafts should include the appropriate underkeel clearances (trim, density, and squat) as defined in References 1 and 2.

14. In addition to the individual vessels above, the study should model the tankers and containerships with tug assistance when required. The number, placement, type, and size of tugs will be coordinated with the local pilots. Tug assistance may be modeled as a force on the ship with controlled direction and magnitude.

15. It is understood that models of these vessels have been previously developed and are currently available. Modifications required are expected to include variation in draft.

Modeling Approach

16. The scope of testing is being limited to two project channels. The existing channel will be the base condition. The plan condition will include both Kill Van Kull and Arthur Kill projects deepened to the Phase I depths of 40 ft as designed and approved by the New York District. In addition, the hydrodynamics of the Kill Van Kull deepened to 44 ft will be evaluated. No testing of a channel condition in which only one project is completed and the other is not, e.g., build Kill Van Kull and not Arthur Kill, is included in this scope of work. Any consideration of these options may require additional testing.

17. Preliminary Simulation Tests. Because of time and cost limitations, preliminary tests will be limited to checking out the simulator setup. In order to identify the most critical conditions to be used in the real-time simulations, discussions with the local pilots will be conducted to determine the appropriate tide stages, wind conditions, and vessel traffic conditions that create the most severe navigation conditions. These preliminary simulations will be conducted in lieu of auto-piloted fast-track analyses since auto-piloted tests are not practical for the high degree of maneuverability required in the project channels.

18. Real-time Simulation. Upon determination of the worst conditions, the selected conditions will be tested using real-time simulations piloted by local pilots, with a visual “view-out-the-window” scene, a simulated radar image, and operating with the ship's console with appropriate ship controls and instruments. It is expected that these tests will include piloting by experienced New York Harbor pilots (Sandy Hook Pilots and/or McAllister Tugboat Pilots). The tests will determine if the proposed channel is too small, too large or near the optimum dimension and proper alignment. This will be based upon being able to maintain adequate control of the vessel, sufficient clearance from

the channel edges and distance between the ships being passed. Passing situations will be set up to occur at several places, including bends and straight sections. The passing situations will be evaluated based on positions and orientations obtained from individual transits through the channel reacting to a meeting traffic ship by maintaining location within a passing lane. It is anticipated that the above test procedure will be refined, based on pilot consultations.

19. Scenarios. Tests will be conducted for both existing and improved channel dimensions (width and depth). In general, simulations should reflect existing traffic situations discussed briefly above and in detail in U.S. Army Engineer District, New York, “General Design Memorandum, Kill Van Kull and Newark Bay Channels, New Jersey and New York,” June 1986, and U.S. Army Engineer District, New York, “Feasibility Study, Arthur Kill Channel, Howland Hook Marine Terminal, Station Inland, New York,” March 1986. It is expected that the tests can be divided into two sets - Kill Van Kull/Newark Bay and Kill Van Kull/Arthur Kill. Runs for the Kill Van Kull/Newark Bay tests should include but not be limited to a containership entering the Kill Van Kull from New York proceeding north through Newark Bay and turning into Port Newark; a containership transiting Kill Van Kull, holding at the Bergen Point bend for an outbound vessel to pass, proceeding into Newark Bay, turning around in the Port Elizabeth maneuvering area and backing into Port Elizabeth Channel; and an outbound container vessel leaving Port Elizabeth through the Bergen Point bend into Anchorage Channel. To simulate emergency conditions, a run should be made with a containership loosing power entering the Bergen Point Bend and being guided through the bend using tug assistance only.

20. Runs for the Kill Van Kull/Arthur Kill tests should include but not be limited to a containership entering the Bergen Point bend, turning around and backing down the Arthur Kill to Howland Hook; a containership exiting from Howland Hook through Kill Van Kull straight through Bergen Point; a tanker entering Kill Van Kull, proceeding straight through Bergen Point and continuing through the Arthur Kill to Gulfport with the appropriate passing situations; and a tanker exiting from Gulfport through Bergen Point and out Kill Van Kull.

21. Tug assistance would be required to be available for all transits, turning and backing maneuvers.

22. Location of critical passing situations will be identified by the local pilots.

23. Environmental conditions, such as winds and visibility, will be determined upon discussions with pilots and analysis of available data.

Study Outputs

24. In order to determine the effectiveness of the proposed channel improvements, the data outputs of the model study should include but not be limited to the following:

a. Vessel position relative to the channel boundaries, bridges, and passing vessels.
b. Vessel control measures, e.g., rudder used, drift angles, etc. for various tests.
c. Pilot's assessment of the test conditions.

25. The format of the output, method of analysis of output data, and the specific variables to be evaluated will be determined prior to the initiation of the study.

Study Management

26. Schedules. The preliminary results for the Arthur Kill reaches are required by 30 December 1987; results for the Kill Van Kull and Newark Bay reaches are required by 30 September 1988. Changes in the proposed schedule must be approved by the New York District in advance.

27. Monitoring Study Tasks. It is the intention of the New York District to carefully monitor the hydrodynamic and simulation modeling described in this SOW. Monthly progress reports will be submitted through the first of each month due 15 calendar days later. The monthly progress reports will cover:

a. Accomplishments since the previous report.
b. Progress to date.
c. Preliminary study results.
d. Expected accomplishments for next month.
e. Existing and adherence to schedule.
f. Anticipated problems and consequences.
g. Recommendation for study changes, if necessary.
h. Funding allotted and spent to date.

28. Coordination meetings will be held as agreed upon by the New York District and ERDC/WES. It is anticipated that approximately three meetings will be held; however, this is dependent upon study needs.

29. Contract Work. The ship simulation portion of this study will be conducted by Tracor Hydronautics, Inc., using the Computer Aided Operations Research Facility (CAORF) under the guidance of ERDC/WES. Tracor is a partner in the privatized operation of CAORF. Contracting will be performed under an existing contract with Tracor. This facility was chosen because a model of New York Harbor exists and can be readily modified and because it is located near the project site and the local pilots that would be involved in the study.

Report Requirements

30. Management Plan. Prior to the initiation of work, a management plan will be submitted to detail the procedures and methodologies, assumptions, and test schedule.

31. General. Reports on the ship simulation model studies will present study results, explanations of study procedures used, and interpretations of study results. Published formal reports, except routine progress reports, will conform to requirements of ER 1110-1-6 relating to identification of proprietary matters, key sheets, and statement prohibiting use of the report for promotional purposes.

32. Interim Reports. In an effort to reduce costs and save time, separate interim reports will not be required. However, the information normally presented in these reports (a brief description of

study results and problems encountered, one to two typed pages written in a form that will be of use to lay personnel with supporting documentation) will be included in the Monthly Progress Report following the completion of each subtask of Tasks 1, 2, and 3.

33. Summary Report. A draft summary report will be prepared for use by the New York District in a form that will be of use to both technical and lay personnel. Its purpose is to provide the District with sufficient information to be incorporated into the documentation to both higher authority and interested private organizations. The report will clearly describe the study aspects such as, methodology and procedures, hydrodynamic model verification, ship simulation study results, and conclusions. The draft summary report need not be more than 20 pages and will be completed 2 months after completion of the testing. The District will review the report and return the draft for revisions (if required) within 30 days from receipt of District’s comments.

34. Final Report. A final report will be prepared for the ship simulation model study. The document will contain a complete discussion and analysis of the technical studies. A draft of this report accompanied by a suggested distribution will be submitted to the New York District Engineer for approval prior to publication.

APPENDIX E

Sample Wave-Induced Ship Motion Calculation for Tankers Using the Kimon Method (1982)[1]

E-1. Below are listed the appropriate factors required for wave-induced ship motion calculation using the Kimon method.

a. Mean draft: Vessel mean draft (ft).

b. Roll period: Observed or calculated vessel deep water natural roll period (sec). If unknown, 10 sec is a good estimate.

c. Pitch period: Observed or calculated vessel deep water natural pitch period (sec). If unknown, 10 sec is a good estimate.

d. Vessel speed: (knots).

e. Wave period: (sec).

f. Mean wave height: (ft).

g. Relative wave heading: Head seas: 0 deg; Bow seas:± 45 Beam seas: ± 90 deg; Quartering seas: ± 135 deg; Following seas: 180 deg.

h. Water depth: (ft).

i. Channel length: nautical miles.

E-2. The following is a sample calculation for a 250 KDWT tanker.

a. Mean draft: 49 ft (given).

b. Roll period: 10 sec (given).

c. Pitch period: 10 sec (given).

d. Vessel speed: 3 knots (given).

e. Channel length: 3 nm (given).

f. Vessel deadweight: 279,700 long tons (given).

g. Water depth: 55 ft (given).

h. Wave period: 10 sec (given).

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[1] Kimon, P. M. 1982. "Underkeel Clearance in Ports," Report No. EII.17TM.82, Exxon International, Tanker Dpt-R&D, Forum Park, NJ.

i. Mean wave height: 3 ft (given).

j. Relative wave heading: 90 deg (given).

k. Wave period/Roll period: 1.0.

l. Wave period/Pitch period: 1.0.

m. Water depth/Ship draft: 1.12.

n. RMS response for 200 KDWT tanker in 1-ft seas (Figure E-1): 0.57 ft.

o. RMS response for 200 KDWT tanker at given wave ht: (Line 8 H Line 13): 1.7 ft.

p. Displacement response ratio (Figure E-2): 0.9.

q. RMS response for given vessel (Line 15 H Line 16): 1.5 ft.

r. Period of encounter (Figure E-3): 10 sec.

s. Number of wave encounters (Line 5/Line 4 * 3600/Line 18): 360.

t. Wave encounter multiplier (Figure E-4): 4.6.

u. Wave allowance for underkeel clearance (Line 17 H Line 20): 6.9 ft.

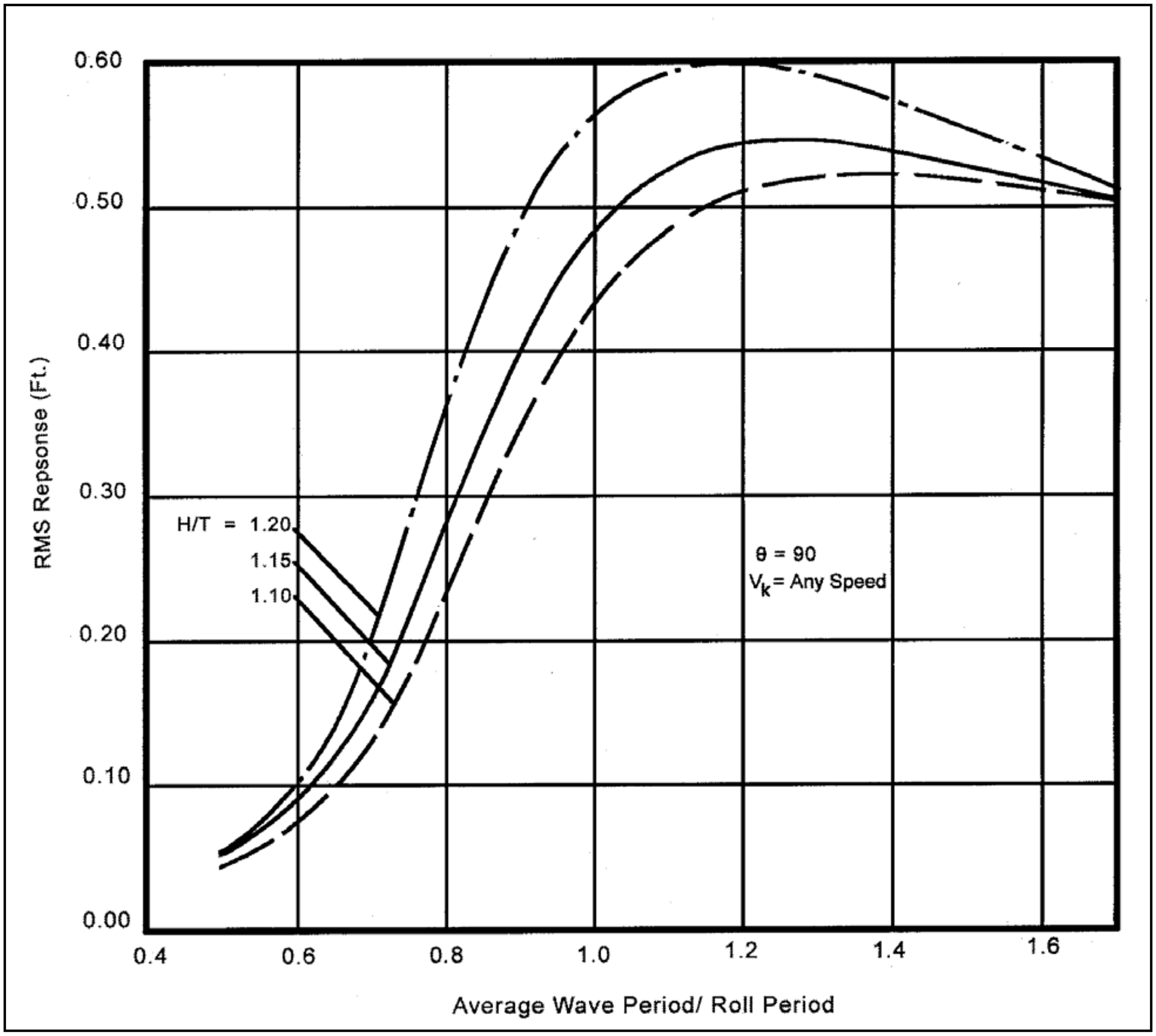

Figure E-1. Beam sea response, V_k = any speed

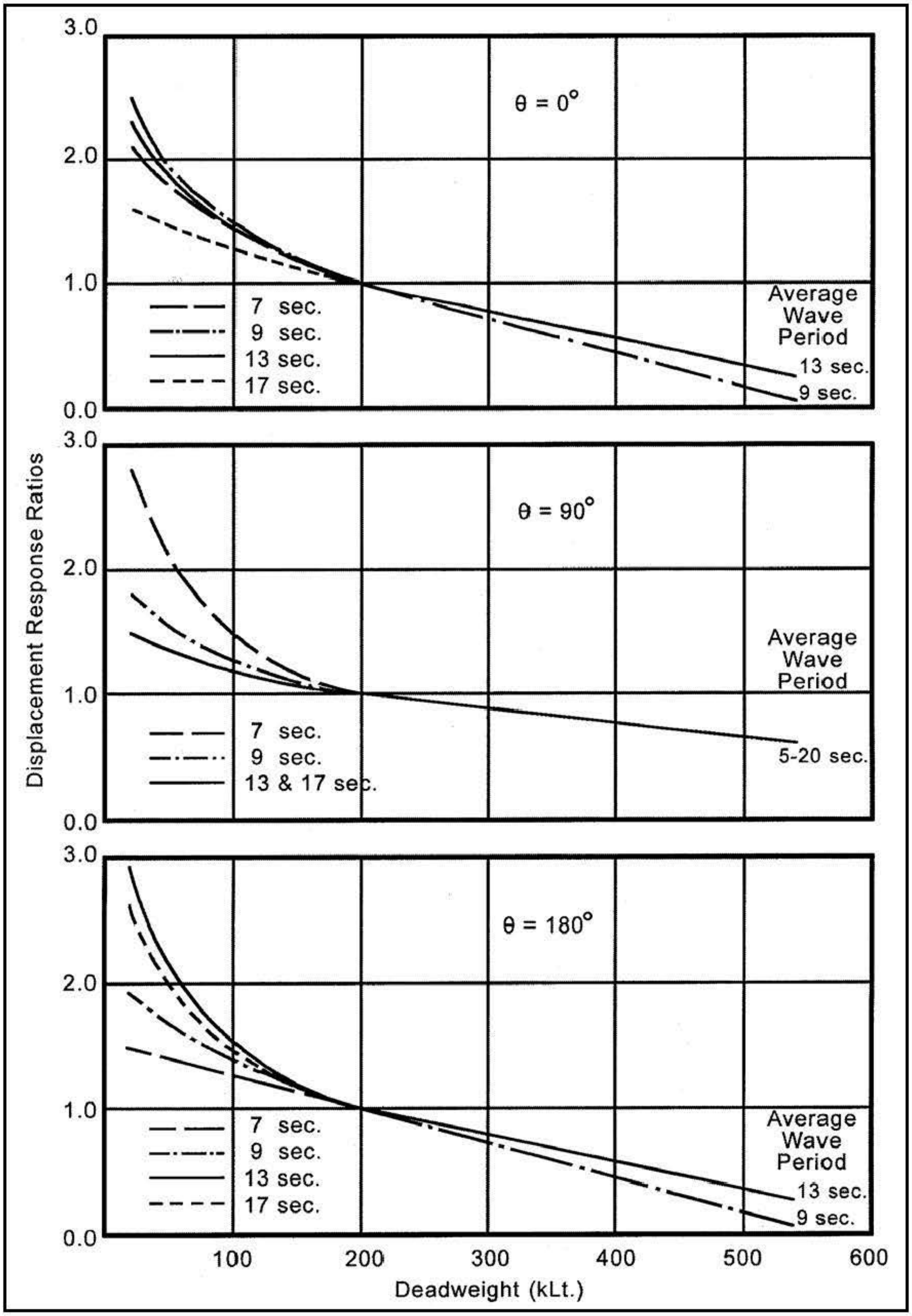

Figure E-2. Displacement response ratios

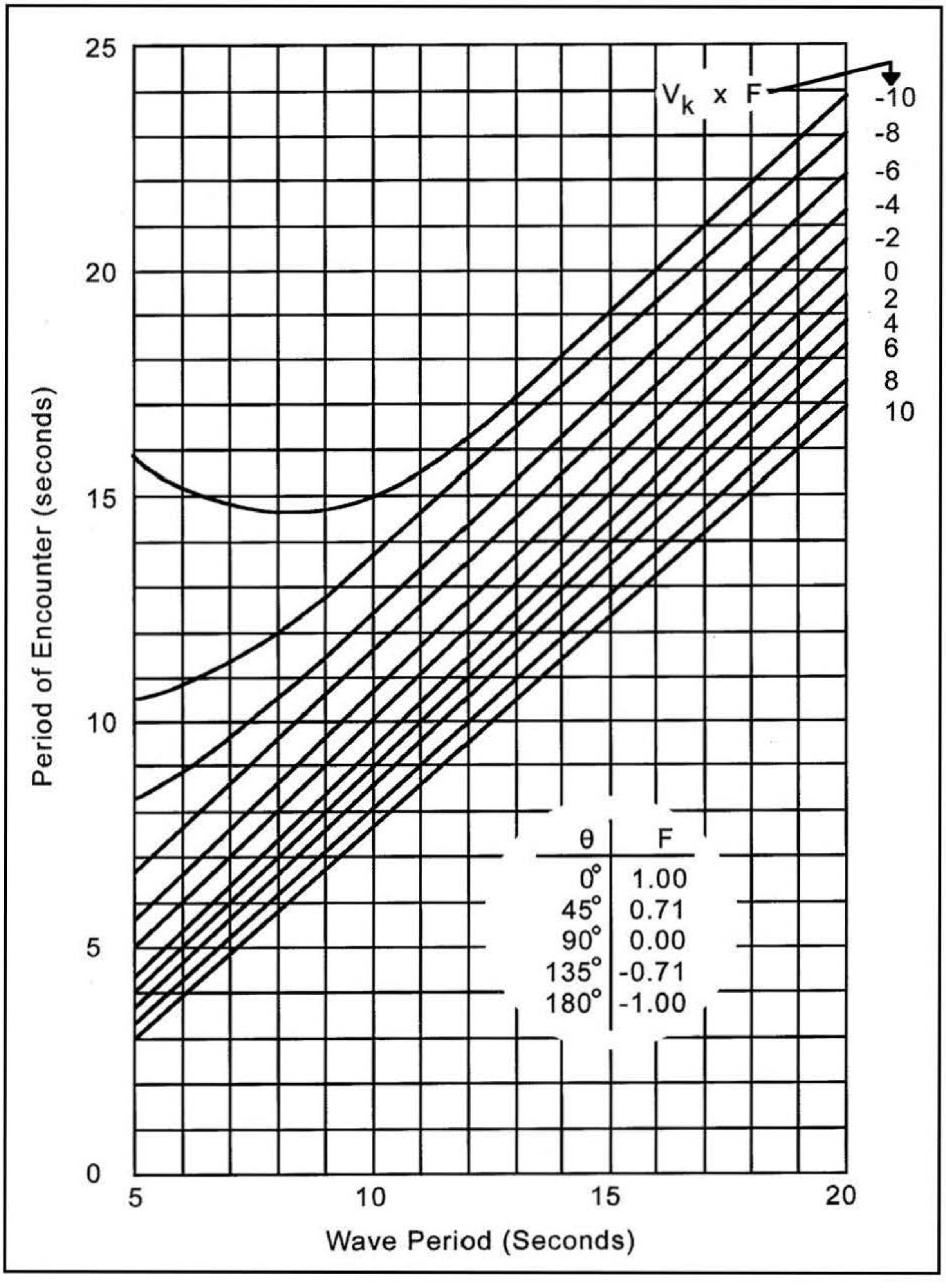

Figure E-3. Wave encounter period

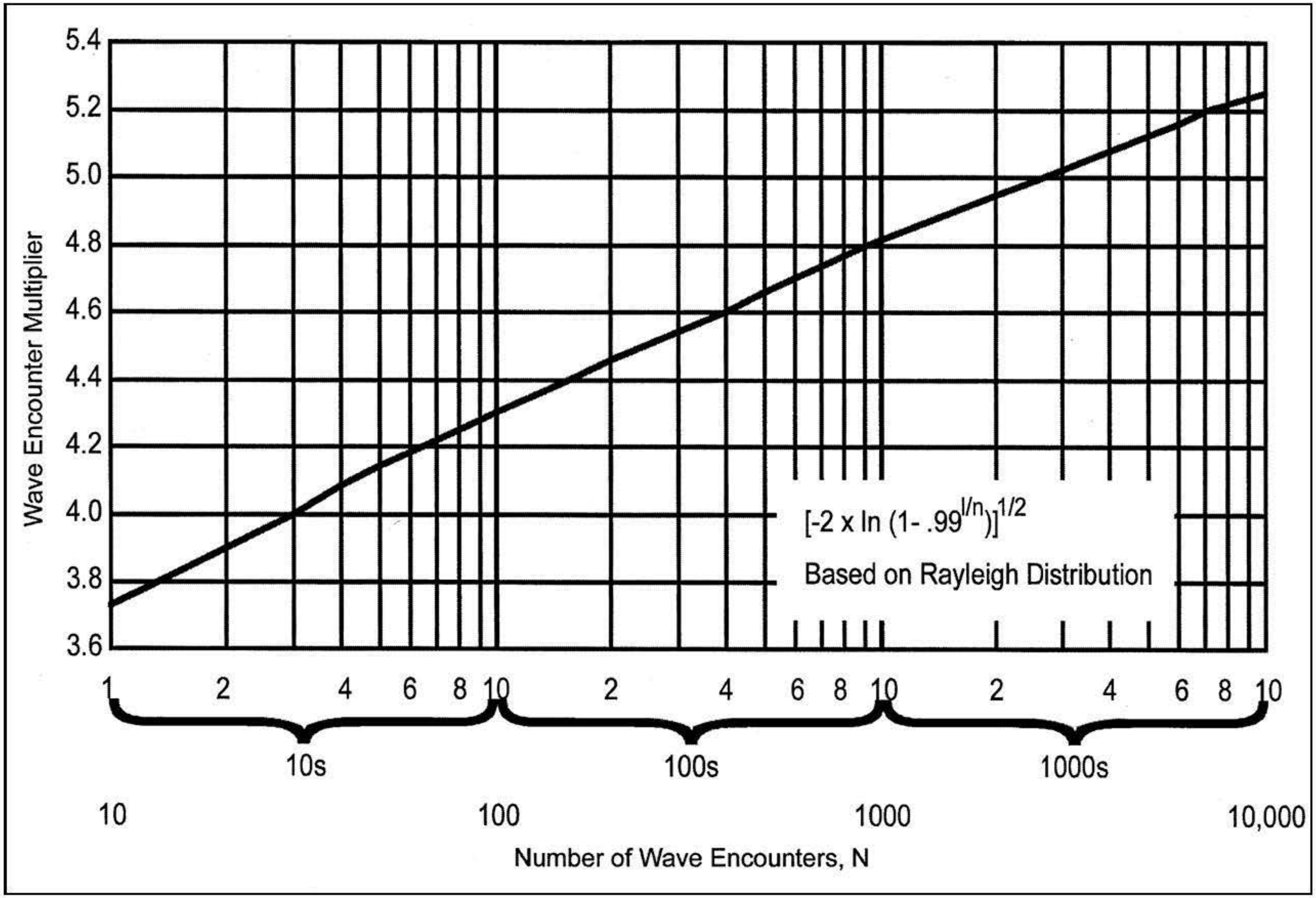

Figure E-4. Wave encounter multiplier

APPENDIX F

Notation

Symbol	Units	Term
A_c	sq ft	Cross-sectional area of the navigation channel from the free surface to the bottom.
A_s	sq ft	Cross-sectional area of the wetted ship, usually equal to the beam times the draft.
B	ft	Beam of the ship; maximum ship width at the design waterline, usually the molded beam.
B_d	ft	Beam of the design ship.
B_t	ft	Beam of the traffic ship.
B_R		Channel blockage ratio, cross-sectional area divided by the ship cross-sectional area.
C_B		Ship block coefficient; the ratio of the ship displaced volume to the length times beam times draft.
C_S		Ship coefficient of slenderness, length over volume of displacement to one-third power.
C_z		Ship sinkage coefficient, characteristic of hull form, empirically measured as about 1.5.
C_Θ		Ship trim coefficient, characteristic of hull form, empirically measured as about 1.0.
d	ft	Channel cross-section mean depth.
D	ft	Diameter of anchored ship swing; size of single anchored ship “watch circle.”
F_{P}		Froude number based on ship length. Ship speed over the square root of length times g.
F_h		Froude number based on channel depth of water; ship speed over the square root of depth times g, the acceleration of gravity.

F_L		Schijf limiting Froude number in a canal, based on one- dimensional squat theory.
g	ft/sec^2	The acceleration, as a result of gravity, approximately 32.2 ft/sec/sec.
$\overline{GM_l}$	ft/sec^2	Longitudinal metacentric height.
$\overline{GM_T}$	ft/sec^2	Transverse metacentric height.
h	ft	Depth of water in a navigation channel from the water surface to the bottom.
h_b	ft	Depth of water at which waves break.
H	ft	Wave height, the vertical distance from the wave crest or peak to wave trough; generally, significant wave height.
H_o	ft	Deep water significant (Average of the highest 1/3 waves) wave height.
H_2	ft	Translated local significant wave height.
k		Relationship of transverse radius of gyration to the ship's beam.
k_1		Relationship of longitudinal radius of gyration to the ship's length.
L, L_{BP},	ft	Alternative notations for ship.
L_{PP}		Length between perpendiculars; common definition of ship length.
L_{OA}	ft	Ship length definition based on overall length dimension from the farthest point on the ship bow to the aftermost point on the stern.
L_{WL}	ft	Ship length definition based on length at the ship design waterline.
N		Number of ships at anchorage for use in anchorage size design.
p		Probability of exceedence.
P	ft	Penetration of ship hull below the still water line in response to wave action.
P_{avg}	ft	Average bow or stern excursion during a transit.
P_{max}	ft	Maximum ship excursion ship due to heave, pitch, and roll.
$P_{(p)}$	ft	Average bow or stern excursion with a probability of (1-p) of not being exceeded.

P_{tot}	ft	Total ship vertical penetration resulting from waves below the still water surface.
R	ft	Radius of navigation channel curve, from channel centerline to center of curvature.
T	ft	Ship draft; vertical distance from the loaded ship waterline to the keel; usually, the molded ship draft.
T_e	sec	Encounter period.
T_θ	sec	Natural roll period.
T_ϕ	sec	Natural pitch period.
T_w	sec	Water wave period.
U	knot	Ship return velocity; in canal squat analysis, the speed increase of the water between the ship and channel sides above the ship speed.
U_L	knot	Limiting return velocity at the Schijf limiting speed.
V	knot	Ship speed in the axial ship direction; the speed of the ship in the surge direction.
V_s	knot	Ship service speed; the design sustained sea speed of a ship, normally rated at 80 % of full engine power.
W	ft	Navigation channel width; topwidth of canal section in squat analysis.
W_1	ft	Channel bottom width for one- way ship traffic.
W_2	ft	Channel bottom width for two-way ship traffic.
V	ft/sec	Ship speed.
V_L	knot	Schijf limiting ship speed in squat analysis.
z	ft	Ship sinkage (vertical drop of ship center of gravity) when underway in shallow water.
$z_{\max}$	ft	Total vertical ship motion resulting from sinkage and running trim; ship squat in shallow water.
Z	ft	Approximate maximum ship squat for low ship speeds.

Z_s	ft	Schijf squat based on one-dimensional canal theory.
Z_w	ft	Ship heave response due to wave action.
Z_L	ft	Ship squat at the Schijf limiting ship speed.
δ	deg	Deflection angle at navigation channel turn.
λ	ft	Water wave length; the horizontal distance between adjacent wave crests in the direction of wave advance.
λ_o	ft	Deep water wave length.
λ_2	ft	Translated local wave length.
μ	deg	Encounter angle.
π		The ratio of the circumference to the diameter of a circle; approximately 3.14159.
Θ	rad	Trim angle of ship, positive is bow up.
ΔW	ft	Local increase in channel width at a turn.
Δ	tons	Weight displacement of a floating ship, usually given at design draft; normally equal to the weight of salt water displaced.
∇	cu ft	Volume displacement of a ship; equal to volume of salt water displaced by the floating ship.

GLOSSARY

Notation

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Θ	rad	Trim angle of ship, positive is bow up.
ΔW	ft	Local increase in channel width at a turn.
Δ	tons	Weight displacement of a floating ship, usually given at design draft; normally equal to the weight of salt water displaced.
∇	cu ft	Volume displacement of a ship; equal to volume of salt water displaced by the floating ship.

Terms

Abeam
To one or both sides of a vessel; at right angles to the vessel centerline.

Advanced Maintenance
Overdepth maintenance dredging to provide a greater channel depth or width than authorized in areas of high shoaling rates. The purpose is to increase the time interval for dredging cycles and thus decrease overall project cost.

Aft
Near, toward, or at the ship stern.

After Perpendicular (AP)
The vertical line perpendicular to the ship keel line through the intersection of the ship design water line and the after side of the rudderpost or sternpost.

Afterbody
The portion of the ship hull aft or abaft of amidships.

Ahead
Moving in a forward direction; as opposed to astern.

Aids to Navigation
Markers with known charted positions located and designed to enable mariners to avoid dangers and fix their positions. Examples are buoys, ranges, and electronic aids.

Amidship
(a) In the center of a vessel; in the vicinity of the ship hull midlength. Midway between the forward and after (fore-and-aft) perpendiculars (FP and AP).
(b) In ship piloting, the order to bring the rudder to the zero angle position on the vessel center line.

Amplitude
The maximum value of a fluctuating or oscillating (usually periodic) variable or quantity from the mean value. For a harmonic sinusoidal water wave, the amplitude is one-half the wave height.

Anchor
A heavy device, usually of metal, fastened to a chain or line to hold a vessel in position. Also applied to hold any other floating object, such as a buoy. Anchors hold by weight and by digging into the sea bottom.

Anchorage
A customary, suitable, and usually designated area in a harbor set aside for vessels to anchor and await berthing space, repairs, etc. A sheltered area in a harbor reserved, legally or by custom, for anchoring vessels. Usually designated by the U.S. Army Corps of Engineers and depicted on appropriate nautical charts.

Answer
To move in response to a rudder movement, as a vessel yawing to port when given left rudder. A ship is said to answer to the helm when the rudder position is changed.

Astern
The movement of a vessel in a backward direction; opposite of ahead.

Athwartship
Across the ship, at right angles to the fore-and-aft hull center line; across a vessel from side to side.

Authorized Channel Depth
The depth of a Corps navigation project as authorized by Congress and as presented in the appropriate design documents. The water depth usually available in an official Federal channel referred to a local datum, such as mean lower low water (mllw).

Automatic Pilot
A vessel steering system designed to maintain a course from feedback information on ship course deviation, ship location, and other ship data, and provide compensating rudder changes to minimize course deviation.

Azimuth
The horizontal, clockwise angular arc from the north reference point to some other object or point, such as the ship's heading.

Ballast
Additional weight (usually water) placed in the vessel hull to provide static stability and improve maneuverability. Usually provided in unloaded vessels; a ship "in ballast" is an unloaded vessel.

Bar
A submerged embankment or shoal area of usually sandy material extending partly across the entrance channel into a harbor where wave effects are important. Bar pilots are locally licensed to guide ships from the open sea through the bar and into the harbor.

Basin
A comparatively large excavated space at a dock or in a waterway or channel, configured to permit the turning or other maneuvering of vessels to enter a dock or berth or depart from port.

Bathymetry
The measurement or portrayal of the underwater portion of navigation channels, coastal areas, or ocean topography; typically, a map of a region with depths and contours shown over the area.

Beacon
A fixed aid-to-navigation marker located on the edge of a channel or in shoal water for use by mariners.

Beam
One of the three principal dimensions of a ship; the width of a vessel in a transverse horizontal direction at its widest point, usually amidship.
Molded Beam. The maximum transverse dimension of a ship to the outside edge of the hull structural members excluding the shell plate. Usually measured amidships at the design water line to the inside of the ship hull plating on each side.
Extreme Beam. The width of a ship including the hull plating and any permanently installed underwater or abovewater projecting or overhanging gear, such as sonar domes or lifeboats.
Water-line Beam. The maximum molded beam at the design water line.

Bearing
The angular direction or orientation of an object with respect to an observer. Bearings may be compass or relative depending on the reference line whether from north or with respect to the ship longitudinal direction.

Bend
A channel turn that is designed as a continuous curve with a given radius; usually provided for large channel changes (or turn angles) in direction.

Berth
A vessel position at a dock or wharf for loading or unloading cargo and designed to provide safe mooring. More generally, a place where a vessel is moored at a wharf or lies at anchor. Generally, the space allocated to a vessel when secured at a pier or float, either moored or at anchor.

Bilge
The corners of a ship cross section, usually rounded, where the side of the hull meets the ship bottom. A bilge keel or fin is often fitted to the ship hull at the "turn of the bilge" to reduce rolling.

Blockage
The degree to which a ship area takes up a channel cross-sectional area; the hydrodynamic effects of the flow around the ship from the channel banks and boundaries.

Block Coefficient (C_B)
The nondimensional ratio of the displacement volume (underwater volume) of the molded form of a ship to the volume of a rectangular block with the main ship dimensions of the effective length, beam, and draft. The molded beam and draft to the specified water line (which is usually the design water line) and the length between perpendiculars are used to calculate the block coefficient. A measure of ship "fullness" or "fineness."

Boat
A generic term to refer to any of several watercraft of relatively small size; a small vessel, usually less than 50 ft in length. May be propelled by sails, oars, or some kind of motor engine.

Body Plan
A ship drawing that is part of the ship lines drawings showing two half end views of a ship, a bow view as seen from ahead and a stern view as seen from astern. The body plan also shows the form of the ship at the various cross sections.

Bollard Pull
The pull or push of a vessel, such as a tug or towboat, exerted at zero speed ahead. Generally, equal to the vessel propeller thrust and used as a means of rating tug capability.

Bow Wave
The wave set up by the bow of a vessel while moving through the water.

Bow
The forward part of a ship or vessel. Generally, the forward 10 percent of the length of the ship hull where most of the hull curvature (flare) is located.

Breakwater
A structure made of riprap, stones, or concrete blocks built to reduce wave effects and create a harbor or improve navigation conditions at a harbor entrance channel.

Bridge
The control room of a vessel; also called a wheelhouse or pilothouse. An overhead structure over water to carry pedestrians, vehicles, or railroad traffic.

Bring About
To reverse direction of a vessel. The maneuver executed in a turning basin prior to or after docking.

Broaching
An involuntary and dangerous change in vessel heading produced by a severe following or quartering sea. A sudden and uncontrolled turning of a ship so that the hull is broadside to the waves. Sometimes leads to capsizing without strong corrective action.

Bulkhead Line
A demarcation line defined in a harbor to denote the extent to which banks may be filled and bulkheads built for the purpose of port development. Piers may extend beyond the bulkhead lines but must be open in construction, such as on pilings.

Buoy
Floating marker moored to the bottom in a specific place used as an aid to navigation marking the edge of channels or indicating wrecks, rocks, or other navigation hazards.

Can
A flat-topped cylindrical buoy painted green used to mark the port or left side of a channel.

Canal
An excavated watercourse, usually artificially cut through land area, without any existing channel, designed for navigation. Canal edges or borders usually extend above the water surface with visible banks and important ship and bank interaction effects.

Captain
A title bestowed on the person in charge of a vessel while underway. The master of a ship.

Cast Off
To loosen and unfasten mooring lines from a vessel to a dock preparatory to departure from a berth in a port or harbor. The start of an outbound ship transit from a port to sea.

Center of Gravity (CG)
The point center at which the total weight of a ship, including the hull structure, acts. The total weight is considered as concentrated in the longitudinal, vertical, and horizontal axis at the CG. The origin of the coordinate axis used to describe list, trim, and dynamic ship motions from waves and in maneuvering.
Longitudinal Center of Gravity. Distance measured from midships to the center of gravity (MG).
Vertical Center of Gravity. Distance measured from the keel to the center of gravity (KG).
Transverse Center of Gravity. Distance measured from the ship center line to the center of gravity (TG).

Channel
The deeper, navigable portion of a waterway, usually marked and designated on the appropriate navigation charts with known widths and depths. Part of a watercourse used as a fairway for the passage of shipping. May be formed totally or in part through excavation, such as dredging.

Channel Depth
The vertical distance from the water surface to the bottom of a channel; normally referred to some datum, such as mean lower low water (mllw) in a tidal channel.

Channel Limit
The location of the authorized channel as designated on project design documents and depicted on hydrographic survey sheets. Often provided as a channel width on navigation charts.

Charts
Maps of water areas provided to mariners and intended for navigation. Charts usually provide land and underwater depth data as well as location of aids to navigation. Other useful navigation information, such as shore contours, hazards, and landmarks are also provided.

Conn
To oversee the steering of a vessel by watching her course and directing the helmsman. To be in charge of the navigation and control of a ship; a pilot directing a ship into harbor.

Controllability
A subjective term used to describe the apparent adequacy of response to ship control by the mariner; the inherent quality of a ship to stay on track.

Controlling depth
Actual (as measured) minimum depth of a navigable waterway or channel at its shallowest point. The least depth of water available for navigation in a channel. This depth controls the draft of loaded ships that may safely enter a harbor or port.

Coupling
The influence of one mode of motion on another; coupling between pitch and heave.

Course
The intended direction in which a vessel is to be steered. A straight leg of a vessel’s route from one point to another in a voyage.

Coursekeeping
(a) The mariner’s primary task of providing steering control to maintain a given ship course or track between navigation channel turns or way points.
(b) The quality of a ship to maintain a course and stability to return to that track after an outside force or impulse.

Course Made Good
The direction of a line connecting two points describing the start and end of a desired ship track. The course covered by a vessel with respect to the bottom; the course sailed with an allowance for the effects of current and wind (leeway).

Crabbing
Vessel sideways drifting due to wind or other effects. To cause a ship to head into a crosswind or crosscurrent by the appropriate use of rudder to counteract drift. The projected ship width is greater than the ship beam and is a function of the drift angle. To drift sideways from current or wind; to make leeway.

Crosscurrent
The magnitude of the tidal or river current component perpendicular to the channel center line or intended ship track.

Current
A generic term referring to the horizontal movement of water caused by various forces, as river currents or tidal currents. Currents may be described by magnitude and direction, the latter being presented as the angle toward which the current flows. The direction of a current is called its set, and the speed is referred to as its drift. A fair current is favorable with respect to the ship sailing direction; a ship in a contrary or adverse current is said to be “stemming the tide.” Currents across a ship’s bow are called crosscurrents and have a major effect on ship piloting and navigation, especially in harbors when ship speeds are normally reduced.
Tidal Current. The reversing horizontal movement of water associated with the rise and fall of the tide caused by the astronomical tide-producing forces.
Ebb Current. The tidal current away from shore and toward the sea; usually downstream in a tidal stream and associated with a decrease in tide height.
Flood Current. The tidal current toward shore or up a tidal stream; usually associated with an increase in tide height.
Strength. The peak speed of current in either direction, as strength of ebb.
Slack. The period of time during the tide when current is at or nearly zero and not discernable in direction.

Cutoff Turn
A method of providing increased ship maneuvering room around a channel turn by dredging the inside corner of the apex of a turn. Thus the channel width is increased locally by adding a triangular area in the turn.

Datum
The plane or level to which soundings, elevations, tide heights, and channel depths are referenced. Usually, some low-water datum is used, such as mean lower low water (mllw).

Deadweight Tonnage (dwt)
The rated carrying capacity of ships in tons. The capacity will vary with actual ship draft. The total weight of cargo, stores, crew, fuel, fresh water, etc., which a ship can carry. The difference between the loaded and light displacement tonnages. Usually given in metric tons today, but also rated in long tons for older vessels.

Deck
A platform in a ship consisting of plating covering beams corresponding to the floor of a building. The main or freeboard deck is the uppermost continuous deck with the capability of sealing off all hatches and openings against the sea.

Deep-Draft Channel
Navigation channels (usually excavated, as by dredging) provided for the movement of self-propelled vessels with drafts of more than about 5 m (15 ft). Includes channels for seagoing and Great Lake ships and other vessels usually designed for international trade and commerce.

Depth
(a) The vertical dimension in a transverse plane from the bottom of the ship hull to the top of the main or freeboard deck measured at the ship midlength. Not to be confused with the ship draft, which is smaller. The depth is equal to the freeboard plus the draft.
(b) The vertical distance from the channel bottom to the still water surface, usually based on a specified water datum. See also *Molded Depth*.

Design Vessel
A hypothetical or real ship with dimensions of the largest vessels that a navigation project is designed to accommodate.

Dimensions
The main measurements used to describe the ship geometry consisting of the length, beam, depth, freeboard, and draft. Usually given as molded dimensions, which refer to the outside of the hull frame structure, but inside the ship plating.

Directional Stability
The relative tendency for a ship to stay on, return to, or to deviate from its original track after an outside disturbance. A stable ship will tend to return to or stay on track after the disturbance; deviations from the original track will tend to increase after the disturbance if the ship is unstable. Usually, directional stability is specified with the rudder fixed at amidships (0 deg).

Displacement
The mass of the salt water at standard conditions displaced by the floating ship. The displacement will vary with the ship loading condition, i.e., the draft. When expressed in long tons, the displacement is equal to the total weight of the ship.
Light Displacement. The mass of the ship itself, including the hull, machinery, equipment, liquids in the machinery, permanent ballast, but without any cargo or fuel and other expendables, and with the ship ready for loading and service.
Loaded Displacement. The displacement of a ship when floating freely, usually at her greatest allowable (design) draft. Equal to the mass of water displaced and to the sum of the light displacement and the deadweight.
Displacement Volume. The volume of the equivalent saltwater displacement mass. Can be calculated by multiplying the displacement in tons by the unit volume of salt water.

Dock
A general term referring to various structures along a port waterfront to accommodate ships and their cargo; wharves, piers, terminals, etc. The water space between adjacent piers or wharves in which vessels are berthed and cargo is loaded or unloaded.

Dolphin
A cluster of piles driven into the bottom.

Draft
The submerged depth of a ship below the water line measured vertically to the lowest part of the hull. Generally, the minimum depth of water in which a ship will float.
Molded Draft. The draft of a ship measured to the molded hull form, which is to the inside edge of the hull plating. This is the draft specified in ship design and normally listed in tables of ship particulars.
Keel Draft. The draft measured to the extreme bottom of the ship keel and normally used as the reference for the ship displacement calculations and the reference marks painted on the ship.
Summer Load Draft. Standard ship draft when in fully loaded condition compatible with the summer navigation season load line freeboard allowance for normal oceangoing, registered cargo-carrying ship assignment in seawater. The summer load draft is marked on ships (called the Plimsoll lines) horizontally through the center of a ring with the registering authority designated on the marking.
Design Draft. Ship draft used to design the ship; distance from the design load waterline (LWL) to the bottom of the keel. The maximum draft to which the ship can be safely loaded.
Partially Loaded Draft. A ship draft less than the maximum allowable, either design or summer load draft; partially loaded ship.
Ballasted Draft. The average ship draft without any cargo load. The minimum ship draft, which is usually obtained by filling the ship ballast tanks, required for adequate maneuverability and to submerge the ship propeller and rudder.
Forward Draft. The ship draft at the forward perpendicular; the draft at the ship bow.
After Draft. The ship draft at the after perpendicular; the draft at the ship stern.
Mean Draft. The average of the forward and after draft of a ship.
Scantling Draft. The maximum allowable draft at which a ship complies with the classification society requirements for the ship's frame and hull structural strength. Usually used when the scantling draft is different from the maximum design draft corresponding to the classification society's load line convention, which assigns the minimum freeboard and maximum permissible draft.

Drift Angle
The angular offset of the resultant vessel track from the desired target track caused by drift. The angular difference between the ship heading and the direction of ship motion about the center of gravity.

Drift
Deviation of a ship from an intended course from wind or currents. The sideways motion of a vessel from its track as it makes its transit through a waterway. Side drift (drift angle) is the difference between the intended track or leading line and the longitudinal ship axis. The speed of a tidal or other water current.

Effective Lane Width
The total maneuvering lane width requirement for a ship because of a combination of the ship track width and the cross-channel projection of the ship due to yaw.

Entrance
That portion of the ship length forward of the parallel middle body. The forward part of a ship from the bow to the end of the curved section.

Entrance Channel
The main access channel into a bay, harbor, or port.

Even Keel
The condition of a ship in an upright position with her keel floating parallel to the water surface without any trim.

Excursion
Total movement at any particular location of a ship in the vertical or horizontal direction.
Submergence. The vertical motion of a part of an oscillating ship below the still water surface due to dynamic wave effects.
Bow Submergence. Total vertical movement as a result of the combined motions of pitch and heave at the ship bow.
Stern Submergence. Total vertical movement because of the combined motions of pitch and heave at the ship stern.
Bilge (or Side) Submergence. Total vertical movement as a result of the combined motions of heave and roll at the port or starboard ship side, amidships.
Horizontal Drift. The horizontal motion of a part of an oscillating ship about an intended course from yaw and sway due to dynamic wave effects.

Fairway
A navigable pathway in an open and unobstructed waterway, such as a bay, lake, sound, or strait, usually leading into a harbor from the open sea. Includes waters convenient for navigation outside a buoyed channel, ordinarily used by vessel traffic, and so designated by appropriate authority.

Fore
The forward portion of a ship; at or adjacent to the bow.

Forebody
The portion of the ship hull forward of amidships.

Forward Perpendicular (FP)
The vertical line perpendicular to the ship keel line through the intersection of the ship design water line and the fore side of the bow (stem).

Freeboard
The vertical distance from the design water line to the surface of the main or freeboard deck at the side of the ship, amidships.

Freeboard Deck
Normally, the main or uppermost complete deck exposed to weather and sea conditions makes a main entry which has permanent hatch covers for watertight seals.

Harbor
A fully or partially enclosed body of water offering safe anchorage or reasonable shelter to vessels against adverse environmental conditions; a protected water area that may be natural, artificial, or a combination.

Heading
The horizontal direction in which a ship points or heads, usually given in degrees of azimuth.

Heave
Oscillatory vertical linear component of ship motion (up and down) about the center of gravity caused by changes in buoyant forces, normally a result of wave effects.

Heel
A transverse tilt, usually temporary, of a vessel pushed from the vertical by the wind or shifting of weight to one side; noncontinuous inclination or leaning to one side of a ship about a longitudinal axis as a result of wind forces, high-speed ship turning effects, or other nonpermanent effects.

Height of Eye
The height above the design waterline to the line of sight from the ship bridge.

Hull
The structural body and skin of a vessel, not including the superstructure, between the deck and the keel.

Hull Speed
The speed of the ship hull through the water, as contrasted to the speed of the propeller.

Hydrography
The configuration and measurement to describe the relief and depth of the underwater surface of a water body.

Ice Boom
A mechanical device (usually floating) designed to restrict the movement of ice away from navigation channels at critical waterway sites.

Jetty
A structural barrier built out from a seashore designed to confine and increase tidal currents and scour the entrance channel. Also used to protect a harbor entrance channel from wave effects and to decrease shoaling from littoral material.

Keel
The principal fore-and-aft structural member of a ship frame, located along the centerline of the hull bottom.

Landmark
A conspicuous object, natural or artificial, located near a harbor, which aids pilots in navigation. Not a part of the formal, specially designated aid-to-navigation system in a waterway.

Leeway
The leeward (away from the wind) motion of a vessel caused mainly by the wind. The off-course lateral movement of a ship through the water when underway as a result of wind and current. The resultant deviation from a vessel's true course is expressed as the angular difference between the course steered and the course made good (through the water).

Length
Generally, the longitudinal distance along a ship hull center line from the bow to the stern.
Length Overall (LOA). The extreme length of a ship hull measured from the foremost point of the stem to the aftermost part of the stern; the length from the tip of the bulbous bow to the stern overhang.
Length Between Perpendiculars (LBP). The ship length between the forward perpendicular (FP) and the after perpendicular (AP). The generally accepted characteristic ship length defined and used by naval architects for hydrodynamic analysis and design.
Length on Design Waterline (L_{WL}). The horizontal ship length between the extreme design or fully loaded water line positions at the bow and stern of the ship hull.
Length on the Waterline (LWL). The ship length used in design calculations, normally the same as the LBP.

Lighterage
The unloading of oil from a large tanker by means of smaller tankers or barges that can be accommodated in a nearby oil terminal or harbor. Lightering operations may be conducted at sea in coastal areas near an oil port or in protected waters. Sometimes used to permit the large tanker to proceed in a light-loaded condition to a terminal with limited channel depth. Sometimes used for other cargoes/ships in harbors with limited depths.

List
The inclination of a vessel at rest, usually caused by imbalance of weight. A continuous condition in which a ship is not floating in an upright position with respect to the water surface, i.e., longitudinal vertical center plane not perpendicular to the water surface. List is a static situation due to asymmetrical loading conditions and is correctable by moving cargo or changing ballast.

Maneuverability
The quality of a ship used to describe the ability to change course or to move off track while underway by the application of steering and engine controllers.

Maneuvering
That branch of naval architecture used to describe vessel response; relates the ease of changes in direction and speed with rudder and engine control parameters.

Maneuvering Lane
Portion of channel width within which a ship may deviate from a mean line while transiting through the channel and maintain safe channel bank clearances or safe distance from an approaching vessel. An allowance used in setting channel design widths. The maneuvering lane is equal to or some multiple of the swept path envelope width of ship tracks from a simulator study or field data, if available.

Model Tests
The testing of small-scale models in a towing tank or model basin to determine ship powering requirements, maneuvering capability, and seakeeping performance to help design full-scale ships.

Molded Depth
The ship depth to the outside of the structural hull frame from the molded keel to the molded deck. Also, the depth from the inside of the hull plate at the keel and molded deck plating.

Molded Form
The three-dimensional lines used by naval architects to describe the geometry of a ship hull to the outside edge of the frame or structural members. The molded lines extend to the inside edge of the ship hull plating for steel ships; the plating is typically less than 1 in. The ship beam, depth, and draft are referred to as the molded dimensions or sizes. The outside edge of the hull plating is referred to as the displacement lines or form. Ship dimensions may refer to molded or displacement beam, depth, draft, and freeboard, the difference being related to the hull plating thickness.
Molded Beam. The maximum horizontal width of a ship from the insides of the ship plating to each side of the ship, measured at the design water line, and usually at the amidship cross section.
Molded Depth. The perpendicular distance in a transverse plane from the top of the keel to the underside of the main deck plating at the ship side, usually at the amidship cross section.
Molded Draft. The perpendicular distance in a transverse plane from the top of the keel to the design water line, at amidships.

Neap Tide
Tide height variation of decreased range and resulting smaller tidal currents occurring every 2 weeks during the lunar month.

Nun
A tapered, conical-shaped buoy painted red to serve as a marker for the starboard or right side of a channel.

Overbank Depth
The depth on each side of a channel beyond the channel limits in trench (dredged) channels.

Overhead Obstructions
Any structure built above and across a navigable waterway that could cause navigation hazards or problems. Examples are highway, railroad, or pedestrian bridges and overhead power lines, conveyors, or pipelines.

Paddlewheel Effect
The tendency for the ship propeller to develop a sideways force (propeller side force or bias). With reverse propeller and a right-handed screw, the ship will back with a tendency of the stern to go to port; this will cause the ship bow to turn to starboard.

Period of Encounter
The time interval between successive crests of a train of waves as observed from a moving ship.

Penetration
The maximum depth or submergence of a vessel when it is responding to wave motion.

Pier
A structure, usually of open construction, extending out into the water from land to serve as a berthing place for navigational vessels.

Pile
A long, heavy timber, concrete, or steel member for driving into the earth to serve as a support or protection.

Pilot
An expert shiphandler with specific qualifications and knowledge of local waters hired for ship navigation into and out of a harbor. The person directing and controlling the maneuvering of a vessel is normally locally licensed to guide vessels through a waterway.

Pitch
The oscillatory rotation (angular component of the motion) about the ship's center of gravity (alternating bow up, stern down) about the transverse (lateral) axis. Pitch is the dynamic equivalent of static trim.

Pivot Point
The point about which a ship actually turns; not the same as the ship center of gravity or midpoint. The pivot point varies as the ship is maneuvered and depends on all forces and moments acting on the ship.

Port
(a) A place in which vessels load and discharge cargoes and passengers. Facilities normally include berths, cargo handling equipment and personnel, cargo storage facilities, and land transportation connections. Often with a city, town, or industrial complex.
(b) The left side of a vessel, while facing forward; to turn to the left.

Quay
A stretch of paved bank or solid, developed dock parallel to a navigable waterway for use in loading and unloading vessels.

Rate of Turn
The circular speed (normally given in deg/sec or deg/min) of ship turning; the rate of change of course heading.

Reef
A rocky shoal at or near the surface of the water, sometimes exposed at low tide and constituting a hazard to navigation.

Restricted Water
A navigable waterway sufficiently narrow to cause hydrodynamic responses on the ship due to channel banks.

Roll
The oscillatory angular component of ship motion (transverse rotation around the ship center of gravity) leaning alternately to the port and starboard sides about the longitudinal (fore and aft) ship axis. Roll is the dynamic motion equivalent of the static ship list and usually caused by wave action.

Rudder Area
The projected area of the movable part of the rudder.

Rudder Area Ratio
The ratio of the rudder area to the gross underwater area (normally L_{BP} H draft) of the ship hull. This ratio is an important parameter in determining ship maneuverability.

Rules of the Road
Any of various codes of regulations used to govern vessel traffic in navigable waters to reduce collision and improve safety.

Running Trim
The increase in trim due to dynamic flow effects when a ship is underway. Running trim occurs in deep water, but increases significantly as a ship moves into shallow water and even higher in restricted water, such as a canal. The amount of change in at-rest and underway ship drafts at the bow and stern is a measure of the running trim. Magnitude of running trim will change with ship design and speed.

Scantling
The nominal dimensions of a ship's hull structural steel members, such as girder sizes, frames, plating, etc.

Sea
Nonperiodic, irregular, wind-generated waves produced by a local storm at the place and time of importance to a ship transit. Seas consist of waves with a large range of periods that produce a wide-band spectrum, generally with smaller energy at the higher periods.

Sea Direction
The direction of encounter of a ship moving through a train of sea waves.
Beam Sea. A condition in which a ship and waves advance toward each other at right angles.
Bow Sea. A condition in which a ship and waves advance at oblique angles to each other.
Following Sea. A condition in which a ship and waves advance in the same direction; seas coming from astern.
Head Sea. A condition in which a ship and waves advance in opposite directions; waves coming from dead ahead.
Quartering Sea. A condition in which a ship and waves advance at oblique directions; waves coming from halfway between abeam and astern.

Seakeeping
That branch of naval architecture that seeks to describe vessel response to waves by using theory and testing of ship models.

Set
The amount of deflection from a desired ship course; the direction toward which a current flows.

Shallow Water
A descriptive term to characterize navigation in waterways where the depth of water is shallow enough to cause significant ship hydrodynamic responses. Normally, at depth to draft ratios of 5 or less.

Sheer
A wide swing or turn of a vessel off course while underway. A ship in a channel sailing off the channel center line is said to take a sheer toward the opposite bank from the off-center line bank.

Ship
A self-propelled, decked vessel used in oceangoing, deep-water navigation for military purposes or waterborne commerce.

Shoal
An area of shallow water, usually near a channel or in a waterway, usually consisting of deposited material, and particularly considered a hazard to navigation.

Significant Wave
A statistical definition of waves relating to the one-third highest waves of a given, irregular wave group given by the average of their heights and periods.
Significant Wave Height. The average height of the one-third highest waves in an irregular pattern.
Significant Wave Period. The period of the one-third highest waves with an irregular pattern in a wave group.

Simulator
A facility with capabilities to apply computer-based mathematical models, ship bridge consoles, and visual graphical imagery to produce realistic ship maneuvering response for use in evaluating ship or waterway design and for training and research.

Sinkage
The vertical bodily drop of a ship when underway as a result of the generation of following waves and dynamic pressures on and near the underwater portion of the ship hull. Ship sinkage occurs in deep water but becomes larger and more important in shallow water and even higher and more critical in restricted water, such as canals. The amount of sinkage is the difference in the at-rest and underway ship drafts at midships.

Slipstream
The stream of water thrust aft by a rotating propeller.

Speed
The magnitude of the motion of a vessel, usually in a longitudinal direction, either ahead or astern.
Speed Over Ground. Vessel speed relative to the bottom or a fixed earth that includes the effects of water currents.
Speed Through the Water. Vessel speed relative to the water, after subtracting for the effects of water currents.

Squat
The total drop of a ship in motion due either to sinkage plus running trim or to water level depression; the change in the at-rest and underway ship underkeel clearances.
Shallow-Water Squat. The ship squat in a wide, unbounded, shallow-water region is the sum of sinkage and running trim at the ship bow or stern, whichever is higher. Slender ship theory in unrestricted shallow water (very wide channel) is used to calculate squat.
Canal Squat. The ship squat in a canal is the water level depression due to increased flow of the water past the moving ship. The squat can be calculated using a one-dimensional form of the Bernoulli and continuity equations taking into account the ship blockage in the canal.

Stability
The property of a vessel that tends to restore it to its original state after some disturbance.

Starboard
The right side of a ship, while facing forward; in piloting, a right turn.

Stern
The aftermost part of a ship hull.

Suction
The tendency to force a ship bodily in a transverse direction (sway force) when running close to a channel bank. Usually the ship will tend to move toward a channel bank; thus the force is called bank suction.

Surge
The longitudinal oscillatory linear motion about the center of gravity (origin of body axis) in the ship travel direction, usually due to wave effects; motion backward and forward (fore and aft direction).

Sway
The transverse oscillatory linear motion about the ship body axis; lateral or athwartship (normal to the ship heading) motion from side to side.

Swell
A long, wind-generated wave that has traveled a long distance from the storm-generation area of the ocean. Usually characterized by a long period and flat-crested wave with more regular periodicity than locally generated waves (seas). The spectrum from a swell is at higher periods than the seas and usually at a smaller range of periods (narrow-band spectra).

Swept Path
A single trace of the path of the extremities of the vessel planform as it makes its track while it transits the waterway. Account is taken of drift, drift angle, and yaw.

Swept Path Envelope
The outer boundaries of several swept paths with the most extreme deviations from target track that encompass one or more of the swept paths of the vessels that transited the waterway.

Tidal Advantage
The additional channel depth and thus ship draft that can safely be brought into a port by taking advantage of vertical tide fluctuations and the additional available water when the tide level is higher than the channel depth datum (usually mean lower low water).

Tide
The periodic rising and falling of the water that results from gravitational attraction of the moon and sun acting on the rotating earth. The tide should be distinguished from tidal current.
Range. The difference in height of water surface between consecutive high and low (or higher high and lower low) water. The mean tide range is often used to characterize harbors for navigation purposes.
Diurnal. A tide with one high water and one low water in a lunar tidal cycle.
Semidiurnal. A tide with two high and two low waters in a lunar tidal cycle.
High Tide. The maximum water elevation reached by each rising tide.
Low Tide. The minimum water elevation reached by each falling tide.
Neap Tide. Tide of decreased range and current that occurs about every 2 weeks during the lunar tidal cycle; the lowest tide.
Ebb Tide. The portion of the tide cycle during which falling tide occurs; the period between high water and the succeeding low water.
Tidal Cycle. The time of the interval between two successive transits of the moon over the local meridian, approximately 24.84 hr (24 hr and 50 min); also called the lunar day.
Spring Tide. Tide of increased range and current that occurs about every 2 weeks during the lunar tidal cycle; the highest tide.
Flood Tide. The portion of the tidal cycle between low water and the succeeding high water during a rising tide.

Tonnage
A measure of internal volumetric cargo-carrying hull capacity of a ship. Various nations and canal authorities have set up vessel measurement tonnage rules that are used to collect tolls and fees for various services. The rules are designed to have fees in proportion to the earning capability of ships, which is equal to the volumetric capacity of cargo. By international agreement, 2.8317 cu m (100 cu ft) of vessel volume is equal to one register ton. Note that this is not a weight measure and is developed using a complicated system of space allocation, deductions, and exemptions, some of which is described below.
Gross Register Tonnage. A measure of the total internal volumetric capacity of space within a ship, including superstructure, engine compartment, and other noncargo space.
Net Register Tonnage. Gross tonnage minus the volume of noncargo space, which does not earn revenue. The deductions are considered to be those spaces necessary for operating the ship. Some examples of these deductions include engine room, ballast tanks, fuel and water tanks, and crew space.

Topping Off
The practice used by shippers in taking on additional ship loads at a deeper channel port than available at the normal port. This technique is used to take advantages of favorable commodity pricing at one port and adding an incremental commodity load at some nearby deep-water port.

Total Equivalent Unit (TEU)
A measure of total carrying capacity of containerships, usually at the design draft with given loaded containers. The number of standard sized container boxes that may be on board a containership.

Tow
One or more barges or other vessels being pulled, towed alongside, or pushed ahead.

Towboat
A combination of barges lashed together in a flotilla being pushed by a high-powered vessel specially designed to operate on the shallow, inland waterways of the United States.

Track
A trace or trajectory of the path (usually the vessel center of gravity) of a vessel as it makes its transit of a waterway. A vessel's line of travel or course made good.

Transit
A passage of a vessel from point to point in a waterway.

Transverse
An athwartship direction; at right angle to the ship longitudinal axis.

Trim
The fore-and-aft attitude of the floating hull of a vessel relative to the designed, static waterline. The long-term longitudinal inclination of a ship. A long-term condition in which a ship is not floating at the designed water line or parallel to the designed waterline (uneven keel). The amount of trim may be expressed as an angle between the water line and the ship base line; more usually trim is given as the difference between the ship draft forward and the draft aft. If the draft forward is greater, the ship will "trim by the bow"; with a higher draft aft, she will "trim by the stern." Usually, trim is a result of static cargo load and ballast conditions and is controllable by cargo and ballast changes.

Tug, Tugboat
A strongly built, highly powered vessel specially designed to pull or push other vessels while maneuvering at low speeds.

Turning Basin
An open area along or (more usually) at the end of a waterway or navigation channel to allow vessels to bring about to change direction of ship transit.

Turning Circle
The circle a vessel describes when turning with rudder hard over. One of the definitive maneuvers that describe the maneuvering performance of ships.

Underkeel Clearance
The space or distance between the keel of a (usually) loaded ship and the channel bottom in a static or stillwater condition. The allowable margin of safe water for which ship passages are deemed adequate by local port authorities and pilots. The difference between the loaded ship draft and the lowest safe channel depth.

Underway
A vessel, making progress through the water, in motion, en route, not at anchor or at a berth.

Up
In ship maneuvering, usually, toward the direction in which currents are coming from or setting. Normally, an upriver or upstream direction, as in upbound. Also, sometimes referred to as positioning the ship "high."

Veer
The act of changing direction of a vessel, usually suddenly; to swerve off course or to take a sheer, as from a current.

Vessel
A general term referring to all types of self-propelled watercraft including ships, towboats, barges, tugs, yachts, and small boats.

Visibility
The extreme distance at which an object can be seen by the naked eye, usually given in nautical miles.

Wake
The disturbance made in the water from a moving vessel; the waves and eddies resulting from the passage of the hull of a ship.

Wash
The water pushed astern by the propeller with the ship engine at thrust ahead; the propeller slipstream, jet, or propeller race so induced. The increased local velocity caused by the propeller past a ship rudder that provides rudder effectiveness in turning the ship.

Water
The quality of a water body referring to the quantity or depth of water adequate for navigation; as for example, navigable water or U.S. waters.
Shallow Water. A body of water in which the depth boundary is close enough to a ship to affect the resistance, speed, maneuvering, or other performance characteristic as compared to the performance in unlimited depth (ocean) water.
Restricted Water. A body of water in which the width boundary is close enough to a ship to affect the performance characteristics compared to open, unlimited ship performance. Principally applies to the proximity of horizontal water boundaries, as in ships sailing in canals or channels.

Waterline
The intersection line of the water surface with the loaded ship hull surface, usually in still water, but could be at design speed ahead with the normal ship motion induced waves.

Waterway
A navigable body of water connecting two or more geographical points in which vessels travel, including connecting basins, canals, and berthing areas. May be natural, man-made, or a combination of both.

Wave
A disturbance or undulation of the surface of the sea that usually moves across the water surface.
Amplitude. The maximum value of the fluctuating water surface from the mean value; for a harmonic wave, the amplitude is one-half the wave height.
Height. The vertical distance between a wave crest and the preceding trough; twice the amplitude of a harmonic wave.
Period. The time required for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.
Length. The horizontal distance between adjacent wave crests on two successive waves in the direction of advance.
Direction. The direction, usually the azimuth, from which a wave approaches.
Spectrum. Usually a graph showing the distribution of wave energy as a function of wave period or frequency.
Steepness Ratio. The ratio of wave height to length.

Wharf
A waterside structure, usually parallel to the waterway bank, at which a vessel may be berthed alongside from which cargo or passengers can be loaded or discharged. A pier or dock built on the shore of a harbor, river, or canal.

Wheel
A circular, spoked apparatus used to steer a ship. Also, the ship or vessel propeller.

Wind
Natural movement of air in a horizontal direction over and above the surface of the earth. The wind's direction is indicated as from a given bearing; a south wind blows from a southerly direction. The magnitude of the wind is its speed given in knots or mph, sometimes as a mean speed with gusting up to another higher speed.

Relative Wind
The apparent wind is the wind direction and force as observed from a vessel in motion. With respect to the speed and direction of a ship sailing, the relative wind is referred to as:
Head Wind. A wind blowing from the ship bow; a wind from ahead.
Beam Wind. A wind blowing across the ship beam and perpendicular to the keel.
Following Wind. A wind blowing from astern of the ship; a fair wind.

Windage
The vessel surface above the waterline exposed to the wind, which causes wind effects.

Yaw
A temporary swing off course by a vessel, usually because of waves, but may be caused by poor steering, currents, or wind. The horizontal angular deviation of a vessel's longitudinal axis from the desired line of track. The angular, oscillatory motion (rotation) about the ship vertical axis; to alternately swing to and fro off course, usually by wave action.