ASCE MANUALS AND REPORTS ON ENGINEERING PRACTICE NO. 107

Ship Channel Design and Operation

ASCE

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(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

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PREFACE

This manual was completed by ASCE's Task Committee for updating Manual 80, *Ship Channel Design*, 1993. Task Committee members were: Bruce L. McCartney, Chairman and Editor; Dr. Laurie L. Ebner, Portland District, Corps of Engineers; Dr. Lyndell Z. Hales, Waterways Experiment Station, Corps of Engineers; and Eric E. Nelson, Seattle District, Corps of Engineers.

Chapter 3, "Ship Characteristics" was authored by Ogden Beeman, Maritime Consultant. Eric Christensen, Commander, U.S. Coast Guard, authored Chapter 20, "Coast Guard Activities that Support Navigation." All other chapters and appendices were assembled by Bruce L. McCartney.

Additional contributions were made by the following: Dr. Cyril Galvin, Coastal Engineer; Andrew M. Tuthill, Cold Regions Research and Engineering Laboratory, Corps of Engineers; R. Anne Sudar, Institute for Water Resources, Corps of Engineers; and Charles C. Calhoun, Jr., President COPRI, 2003–2004.

Waterways Committee Review was performed by the following: Dr. Anatoly B. Hochstein, Director, National Ports and Waterways Institute; Dr. B. K. Lee, Consulting Engineer; and E. Clark McNair, Jr., Consulting Engineer.

Peer review was performed by the following: Dr. James R. Houston, Director, Engineering Research Directorate, Corps of Engineers; Doug Thiessen, Chief Harbor Engineer for Port of Long Beach, California; Dr. William H. McAnally, Research Professor, Mississippi State University; and Dr. Kees d'Angremond, Professor Emeritus, Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering.

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Chapter 1
INTRODUCTION

1.1 PURPOSE

This manual provides an overview of the design process and operation of deep-draft navigation projects. Information was obtained from many sources with significant contributions from recent U.S. Army Corps of Engineers Manuals, publications of the Permanent International Association of Navigation Congresses (PIANC) and the following web sites:

U.S. Army Corps of Engineers	COE, Digital Visual Library www.images.usace.army.mil
U.S. Coast Guard	U.S. Coast Guard Digital www.equi.uscg.mil
National Oceanic and Atmospheric Association	NOAA Photo Library www.photolib.noaa.gov

It should be noted that web site addresses can be temporary and may disappear in the long term as agencies reformat navigation information.

English measurement units are used for the U.S. navigation system and design guidance, metric is used for guidance reported by PIANC (1 m = 3.3 ft).

Ship Channel Design and Operation (ASCE Manuals and Reports on Engineering Practice No. 107) was prepared by a task committee of the Waterways Committee, which is part of the Coasts, Oceans, Ports, and Rivers Institute.

This manual provides an overview of the design process and operation of deep-draft navigation projects. The reliability of ship channels is not only of immense importance to commerical navigation but is also vital to national defense interests for rapid deployment of Navy, Army, and Coast Guard vessels.

The manual covers channel design practice, dredging and disposal, construction practices, operation activites, environmental considerations, and contributions of the United States Coast Guard and National Oceanic and

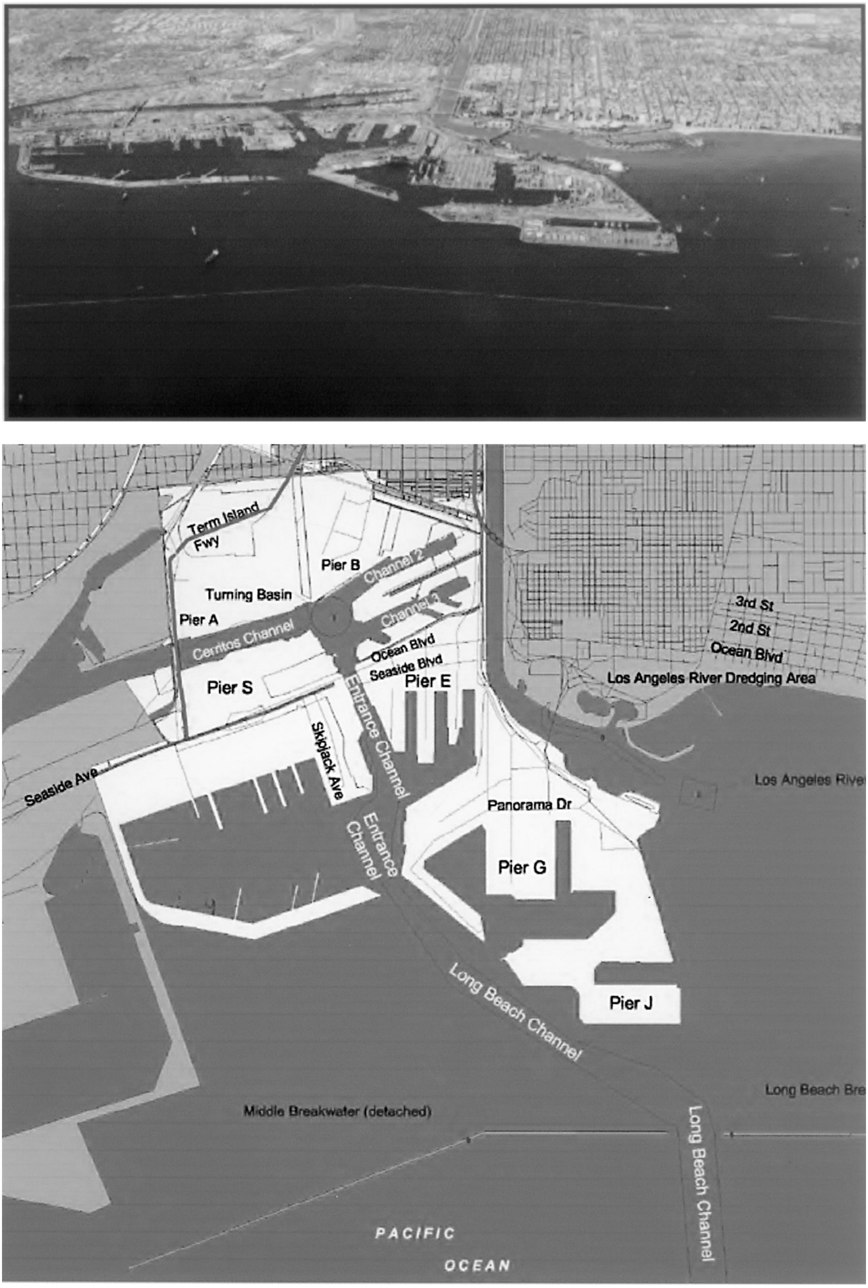

FIGURE 1-1. Long Beach Harbor (spl.usace.army.mil).

Atmospheric Administration (NOAA) to navigation. Channel design practice includes both the United States experience, primarily by the United States Army Corps of Engineers and methods used in other parts of the world as reported by the Permanent International Association of Navigation Congresses (PIANC).

This manual is intended as a design guide for practicing engineers, a reference for government agencies involved with the design and operation of deep draft navigation systems, and a text book for classes or short courses related to navigation engineering.

1.2 BACKGROUND

The reliability of ship channels is not only of immense importance to commercial navigation but is also vital to our national defense interests for rapid deployment of our Navy vessels.

Ship channels are the connecting link between the ocean shipping lanes and coastal or inland deep-water ports. These channels can be very short when the port is immediately behind coastal breakwater, such as in the Port of Long Beach (Figure 1-1).

The ship channel also could wind its way up a major river, like the 106-mi-long Columbia River channel that serves the Port of Portland, Oregon (Figures 1-2 and 1-3).

The 965-ft Evergreen Class container ship (4,200 TEU Capacity) is an example of a commercial vessel that uses ship channels (Figure 1-4).

FIGURE 1-2. Columbia River Ship Channel (COE, Digital Visual Library).

FIGURE 1-3. Ports of Portland, Oregon, and Vancouver, Washington (Port of Portland/Spencer Gross Photography).

1.3 NATIONAL DEFENSE

A major component of the U.S. national defense system is the Navy war ships. The U.S. Army also has a considerable fleet of vessels. These ships need a home port in a protected harbor. Ship channels provide the vital link between the home port and the vessel operation in the open ocean. Therefore, a safe and reliable navigable channel is crucial to the rapid deployment of the Navy and Army fleets. Figure 1-5 shows one of the aircraft carriers in the Chesapeake Bay ship channel.

The investment in these military ships is considerable. For example, the eight Nimitz-Class aircraft carriers cost about $4.5 billion each. The 27 Ticonderoga Class cruisers cost about $1 billion each.

1.4 ECONOMIC VALUE TO THE NATION

Despite the growth in high-tech communication and high-speed transportation, the nation's ports and waterways remain the crucial backbone

FIGURE 1-4. Evergreen Class Ship in Columbia River Channel (Port of Portland/Ackroyd Photography).

FIGURE 1-5. USS George Washington *at Hampton, Virginia (Navy Newstand www.news.navy.mil).*

of our economy. Nearly 25 billion tons of cargo are shipped to, from, or through 40 states each year.

- More than 95% of imported and exported goods to and from overseas move by ship, including nine million barrels of oil per day.
- The U.S. marine transportation industry supports nearly $1 trillion in commerce and 13 million jobs.
- The unit cost to transport commodities over inland waterways is two to three times lower than that of other forms of transportation. The ability to ship goods safely and reliably via inland waterways translates into about $7 billion annually in transportation savings for American businesses.
- More than 67% of all consumer goods purchased by Americans pass through U.S. harbors.

An example of regional economic values is the Port of Houston, Texas. This port moved a total of 148 million tons of cargo in 1996 and is responsible for some 200,000 jobs. In 1996, 5,400 ships and 50,000 barges moved on the channel.

According to the U.S. Department of Transportation, the U.S. international traffic is expected to double by 2020.

1.5 PROJECT RESPONSIBILITIES

The deep-draft navigation system in the United States includes most major coastal ports, some river systems, such as the Mississippi to Baton Rouge and Columbia to Portland, and the Great Lakes. The major entities in design and operation of this system include the following:

- U.S. Army Corps of Engineers—channel design, construction, and maintenance.
- U.S. Coast Guard—safety issues, aids to navigation, accident assessments, search and rescue, and vessel traffic control at some projects.
- NOAA—charts, global positioning systems (GPS), and weather forecasts.
- Ports Authorities—design, operation, and maintenance of port facilities.
- Users—shipowners and captains who are responsible for safe ship operations.

1.6 SCOPE

This manual focuses on ship channels 20 ft and deeper. Design of the inland navigation system, primarily 9-ft-deep channels for barge traffic, is presented in ASCE Manuals and Reports No. 94, *Inland Navigation: Locks, Dams, and Channels* (1998). Small boat navigation (recreation and fishing boats) is covered in ASCE Manuals and Reports No. 50, *Planning and Design Guidelines for Small Craft Harbors* (1994).

These three manuals present the latest information on design and operation of the U.S. navigation system. The ultimate goal of these and future publications on the navigation system is to provide a body of technical literature for development of a "Navigation Engineering" specialty in the Civil Engineering profession.

The major subjects covered in this manual include the following:

- Design philosophy
- Vessel characteristics
- Hydraulic and weather conditions
- Channel dimensions
- Environmental sustainability
- Dredging and disposal
- Model studies
- Coast Guard activities
- NOAA activities
- Construction
- Operations and maintenance
- Lessons learned
- Case histories

The subject of port and harbor safety, for example, potential terrorist attacks, is an ongoing effort and is beyond the scope of this manual.

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Chapter 2

PROJECT DESIGN

2.1 DESIGN PHILOSOPHY

The design of a navigation project requires an understanding of the problem, the assembly and evaluation of all pertinent facts, and the development of a rational plan. The design engineer is responsible for developing the design rationale and sufficient alternatives so that the economically optimum plan is evident and the recommended plan is substantiated. To accomplish this goal, the design must recognize the needs and practices of the user.

In developing or improving deep-draft waterways, safety, efficiency, reliability, and cost must be considered. Before optimizing the project with respect to cost, the designer must first consider safety and efficiency. The safety of the project will depend on the size and maneuverability of the vessels that will use the waterway, the size and type of channel, the aids to navigation, the effects of currents and wind, and the experience and judgment of pilots. Because evaluating the human factor (i.e., experience and judgment) is difficult, potentially hazardous conditions should be eliminated insofar as practicable. Therefore, the optimum design of a specific waterway requires an evaluation of the physical environment, currents, and weather conditions, as well as the judgment of safety factors that depend on pilot response (ASCE, 1993).

A recent report, *Breakwaters and Closure Dams* (d'Augremond, 2001), which explores design philosophy and design process, further develops this subject. Although this book focuses on breakwaters and closure dams, the same philosophy and process can be applied to ship channels. Following are some excerpts from d'Augremond's report (pages 23, 24, and 25):

> When designs of specific structures are studied, one must realize that for any structure the design process follows certain procedures and routines. It is important that such procedures and routines are standardized in the design organization, especially when large numbers

of people are participating in the design. It is essential that each individual speaks the same language, uses the same terminology, and understands what is expected in each phase of the design process. To familiarize its students with a particular design philosophy, the Faculty of Civil Engineering and Geosciences attempts to use the same systematic lines through the curriculum. In following this philosophy, it is essential that the subject of the design is something that is required in practice, in this case a harbor or a closure dam. The objective of the design process is to find a concept that meets the requirement(s) and that can be realized, not only in terms of technical feasibility, but also in terms of cost-benefit ratio and social and legal acceptance. This implies that the solution of the design process must combine the following elements:

Functionality
Technology (what is feasible)
Environmental (what is allowed or accepted)
Cost and benefit
Paper work (drawing board)
Matter (actual construction)

During the design process, one can also recognize certain phases that in some countries are related to the general conditions of contract between employer and consultant. Therefore the phases may vary from country to country. The contractual contents of each phase are subject to modifications in the same way. A logical set of phases include:

Initiative
Formulation of the ultimate goals of the design object as part of the system.

Feasibility
Review of the system with respect to technical, economic, social, and environmental consequences and feasibility. Requirements are formulated on the component level.

Preliminary Design
Giving shape to the system on broad lines, including determination of the exact functionality of the components and definition of requirements at the element level.

Final Design
Composition of a set of drawings and specifications for the system in which the final shape of the components is fixed and the functionality of the elements is determined.

Detailed Design
Composition of a set of drawings and specifications in which the final shape of the elements is fixed.

2.2 TYPICAL PROJECT ELEMENTS

Figure 2-1 shows an example of a generic harbor that defines many of the typical project elements discussed below.

1. *Entrance channel.* A navigable channel connecting the ocean or lake to an enclosed body of water, such as a bay, estuary, river, or mouth of a navigable stream.
2. *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.
3. *Interior channel.* The access channel system inside a body of water that connects the entrance channel (inlet or bar) to a port or harbor with appropriate ship facilities. Interior channels usually are located to provide some protection from waves and weather, and are present in bays, estuaries, or rivers.
4. *Turning basin.* An area that provides for the turning of a ship (bow to stern). Turning basins usually are located at or near the upper end of the interior channel and possibly at one or more intermediate points along long channels.
5. *Anchorage area.* An area where ships can lie at anchor to wait for favorable conditions for a bar crossing or to wait for berthing areas to become available. These anchorage areas are usually in wave-protected areas. However, they can be offshore, such as the anchorage areas off the mouth of the Mississippi River.
6. *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 PRELIMINARY DESIGN CHECKLIST

The following checklist should be used during preliminary project design:

1. Review appropriate literature.
2. Consult with local port authority, pilot associations, and harbor terminal users.
3. Collect and analyze pertinent physical and environmental data.
4. Review appropriate local pilot or captain ship maneuvering strategy and evaluate existing project navigation conditions.

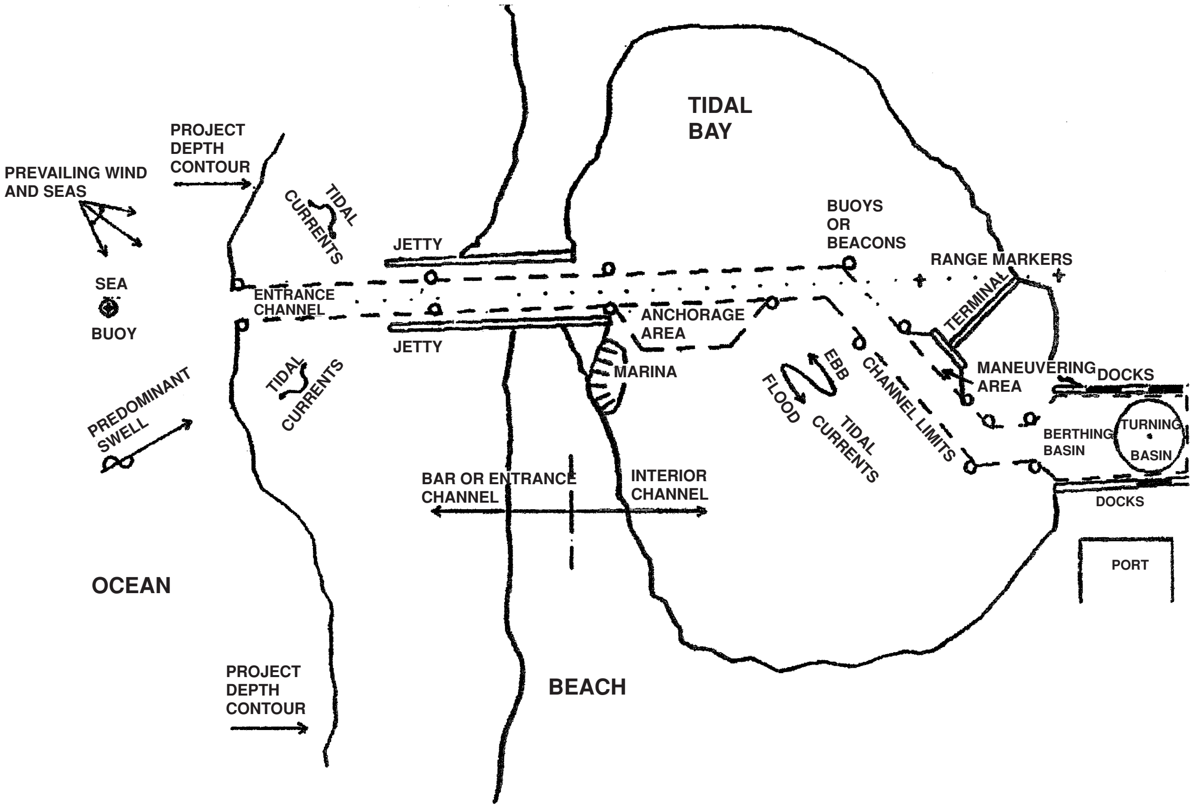

FIGURE 2-1. Generic Harbor with Typical Project Elements (EM1110-2-1613, 2002 Draft).

5. Estimate volume and type of ship traffic and largest ships to be accommodated.
6. Estimate volume and type of commodity that will be moved.
7. Estimate amount, type, and frequency of hazardous cargo (e.g., liquefied natural gas [LNG], ammunition, oil, radioactive material) movement, and evaluate special requirements.
8. Select and list the required project design operational conditions.
9. Select channel layout and alternative dimensions to be considered and determine advantages and disadvantages with annual costs.
10. Assess any adverse environmental and other impacts.
11. Define environmental mitigation needs and enhancement opportunities, especially beneficial uses for dredged material.
12. Review accident records for existing ship channels that are to be enlarged.
13. Security issues.

Economic analysis and cost/benefit studies are not discussed in this manual.

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. Economic considerations of the project will require information on commodities that will be moved by the ship traffic. The designer will use the information on traffic type to select the design ship—usually the largest major commodity mover expected to most frequently use the project improvements. The amount of ship traffic and the length of the access channel will determine the mode of navigation traffic to be provided, whether one- or two-way. Consideration also should be given to providing one-way traffic for large ships and two-way traffic for smaller vessels, and to providing channel segments with passing lanes. The designer should consider a stepped channel with different depths, with the deeper portion intended for loaded ships and the shallower for empty ships. The project layout should be prepared using various channel alignments and dimensions, each alternative evaluated on the basis of economic efficiency involving commodity tonnage to be moved, ship transit time, safety, environmental and social impact, and construction and maintenance costs.

The channel design should permit safe passage of the design vessel, at the helm of a competent pilot or captain, under most weather conditions. The probability of unsafe conditions for a design vessel that might use the channel only a few times a year could have some effect on channel design. Extreme weather or flow conditions should be analyzed for their effects on the design vessel and smaller commercial vessels, and the frequency of unsafe periods should be indicated. Weather conditions exceeding those that produce unsafe conditions at sea should be considered but should not dictate design. For example, hurricane winds and waves would not normally be selected as the design conditions for a navigation channel, as a ship at sea would not normally enter a channel under adverse weather conditions.

An example of evaluating the safety of channel and port configurations has been developed by Delft University (Groenveld, 2003). This method involves a vessel traffic-flow simulation model (SHIPRISK) to estimate the number of encounters (i.e., potential accidents) during a given period under different weather conditions and changing traffic patterns. (See Chapter 15 for further discussion.)

2.5 U.S. COAST GUARD

The local Coast Guard office should be consulted during the preliminary and final design processes. Coast Guard recommendations should be considered for navigation channel and ship safety, ship maneuverability, navigation traffic management, navigation operational restrictions, stable and unstable shoal locations, and optimum placement of aids to navigation.

The Coast Guard and Port Authorities are primarily responsible for harbor safety. Because of the present possibility of terrorist attacks, port safety will be an evolving effort.

2.6 BASELINE STUDIES

The design of a navigation project requires an analysis and evaluation of baseline information, which includes the following:

1. *Design vessel and other deep-draft vessels using waterway*
   a. Dimensions (length, beam, draft)
   b. Maneuverability and speed
   c. Number and frequency of use (congestion), including recreational traffic
   d. Type of cargo handled
2. *Other traffic using waterway*
   a. Types of smaller vessels and congestion
   b. Cross traffic
3. *Weather*
   a. Wind (velocity, direction, and duration)
   b. Waves (height, period, direction, and duration)

c. Visibility (rain, smog, fog, and snow, including duration and frequency of impairment)
d. Ice (frequency, duration, and thickness)
e. Abnormal water levels (high or low)

4. *Characteristics of channel*
    a. Currents, tidal and river (velocity, direction, and duration)
    b. Sediment sizes and area distribution, movement, and serious scour and shoal areas
    c. Type of bed and bank (soft or hard)
    d. Alignment and configuration
    e. Freshwater inflow
    f. Tides
    g. Salinity
    h. Dredged material disposal areas
    i. Temperature
    j. Water quality
    k. Biological population (type, density, distribution, and migration)
    l. Obstructions (e.g., sunken vessels and abandoned structures)
    m. Existing bridge and power line crossings (location, type, and clearances)
    n. Channel constrictions
    o. Submerged cables and pipelines
    p. Significant cultural sites (e.g., sites of archeological interest)

2.7 TYPICAL ENGINEERING STUDIES

Following are examples of topics that require detailed coverage in normal navigation project design. More information on some of these topics is presented later in this manual.

1. Design ship
2. Water level
3. Currents
4. Waves
5. Sedimentation
6. Channel depth
7. Channel width
8. Channel alignment
9. Dredging and disposal
10. Turning basins
11. Entrance channel
12. Jetties and breakwaters
13. Environmental impacts

14. Accident record
15. Pilot interviews
16. Aids to navigation
17. Model testing
    a. Hydraulic/tidal
    b. Sedimentation
    c. Salinity
    d. Water quality
    e. Ice
18. Ship-simulation study
19. Construction
20. Operation and maintenance plan

2.8 CARGO TYPES

Cargo is commonly classified as one of the following:

1. Bulk—loose, flowable material that can be loaded or unloaded by pipeline, conveyor, or grab (clamshell). These include dry products, such as grain, coal, ore, and chemicals, and wet products, such as petroleum products, chemicals, and water.
2. Container (also called Lift-on/Lift-off, or Lo/Lo)—material contained in closed boxes. These usually include perishable (e.g., bananas) or higher-value goods (e.g., electronics) that need protection from damage and pilferage.
3. Breakbulk—material loaded and unloaded piecewise by lifting and lowering. These materials often are palletized, and include metal sheets, rolls, and bars; lumber; and food products.
4. Roll-on/Roll-off (Ro/Ro)—vehicles or wheeled containers that can be rolled on and off via a ramp. These include cars/trucks, agricultural/military vehicles, and loaded truck trailers.
5. Walk-on/Walk-off (Wo/Wo)—human or animal passengers.
6. Lighterage—the process of transferring cargo from a large ship to a smaller ship. This operation is used when the harbor channel depths are less than the draft of the loaded ship.

Chapter 3
SHIP CHARACTERISTICS

3.1 INTRODUCTION

3.1.1 Purpose

The design navigation features for channels and harbors generally begin with selection of the ship types to be accommodated. For single-purpose channels or port facilities, this is accomplished by selecting the ship type to be served as the basis for design. For multiuser channels, it is necessary to look at an array of ships. The selection of the "design ship" often is complicated by the need to look ahead and forecast the future ship types that are expected to use the channels and facilities. Because marine terminals and facilities generally have design lives of 25 years and more, this aspect of the design problem is challenging, to say the least.

The purpose of this chapter is to describe standard ship types and the characteristics of the present world fleet, and to discuss issues affecting the characteristics of future fleet for design purposes. It is not intended to forecast future ship sizes for channel design purposes. That task falls to the designer.

3.1.2 Methodology and Sources

Methodology starts with the identification of commonly accepted ship types and categories. Note that new technologies and trades give rise to new types of ships, for example, container and auto carriers and liquefied natural gas (LNG) carriers. Thus, the designer must not only forecast the size of the ships but also must, at least, consider the new types of ships that may use the channel or harbor.

Many sources were used in the writing of this chapter. The Corps of Engineers Water Resources Center (WRC) compiles information on ship types and characteristics. The WRC's primary purpose is to supply data that can be used in economic studies of channel and harbor projects. Clarkson Research Studies (London) publishes registers of bulk carrier and container and other ships in the world fleet, with detailed descriptions of ship characteristics. Lloyds Registry (London) is the most complete source of ship data, compiled in three large volumes. *Containerisation International* and *International Bulk Shipping,* as well as other maritime publications, such as the *NY Journal of Commerce,* are good sources of news on new orders and ship characteristics. Some shipbuilders post ship characteristics on the Web or in their marketing material and are, thus, a source of information on special ship types, such as LNG carriers. The compilation of tables on ship dimension are from the author's substantial file of ship types, which are based on a number of years of maritime consulting in the United States and abroad.

Because of the variety of information available and used, specific references are not called out for each entry. In addition to the sources listed earlier, *Janes Merchant Ships, Ocean Ships* by David Hornsby, and data from the Port of Portland, Oregon, also were used as sources. Where characteristics are common to many ships in the fleet, these are presented based on data generally available through public sources. Where dimensions are for a specific ship, the ship name is given. The selection of such ships was purely arbitrary and used only to demonstrate the dimensions of a ship in the size range shown.

The information in this chapter is intended to provide the designer with an overview both of ship types and their important dimensions for channel design. For work on a specific design project, in-depth research beyond the scope of this chapter should be pursued. This may include checking the references previously mentioned and talking with shipowners, operators, and builders.

3.1.3 Presentation

The chapter is divided into sections on several common types of ocean carriers. Included are sections on dry bulk carriers, container carriers, liquid bulk carriers, and other ships, specifically auto carriers and cruise ships. Each section includes a brief description of the purpose served by the ship type, with some mention of its typical cargo, as well as further descriptions of subtypes of ships within general categories, if applicable. Finally, tables are used to summarize the primary characteristics that are needed for, or will assist in, channel or harbor design.

3.2 DRY BULK SHIPS

3.2.1 Description and Purpose

The dry bulk ship is the most common ship in the world fleet. The most important characteristic of this ship type is its versatility. It can be used to haul mineral ores, grain, and other commodities in bulk. It also can be used to carry forest products, including logs, chips, and packaged lumber, as well as finished steel products. It can be adapted to carry break-bulk commodities, that is, general cargo including commodities packaged and shipped in bags, boxes, or loose stowed without packaging. This type of ship also can be used to carry containers, often in conjunction with other types of general or bulk cargo. This mixed-cargo versatility is usually a capability of smaller ships. Larger, dry-bulk cargo ships tend to have a single commodity capability.

3.2.2 Ship Types

The versatility of this ship type comes from its capability to carry many types and forms of cargo. Therefore, in its basic form, the ship generally is not modified for specific commodities. Important terminology used in the discussion of this ship type includes the following:

1. Geared versus Gearless. A geared ship has cargo-handling gear, which typically is a number of cranes positioned to access each hold of the ship. These cranes can range from a simple mast and boom to sophisticated straight-line cranes for handling containers and other unitized cargo. The cranes may be equipped with hooks, slings, or buckets, depending on the type of cargo to be handled.
2. Handy Size. Refers to the numerous dry bulk carriers in the world fleet, generally weighing between 10,000 and 40,000 dead weight tons (DWT). Ships smaller than 10,000 DWT are likely to be coasters or small bulk carriers in regional or cabotage trades, and are not covered in this chapter.
3. Handymax Size. Describes a carrier with a beam less than Panamax limits but larger than the typical handy sized carrier. Typical carrying capacities range from 40,000 to 50,000 DWT. This ship type is widely used in trades with draft restrictions or when economic load sizes are less than suitable for a Panamax carrier. In general, it is the largest capacity ship that can transit the Panama Canal at or near design draft.
4. Panamax. This defines a ship with the maximum beam that can transit the Panama Canal. The Canal locks are 110 ft wide; typically a ship has 2 ft of clearance on either side, resulting in a typical beam of 106 ft. It should be noted that the term applies only to beam. Most Panamax ships in the world fleet have a design draft greater than that of the Panama Canal and will transit the canal at less than maximum load or draft. The canal locks are 1,000 ft long, and typical draft restrictions are in the range of 39 ft.
5. Cape Size. Refers to certain trades that do not use the Panama Canal. But, where shipping economics call for large loads, the Cape Size ship

is used. "Cape" generally means the ship sails around the Cape Horn in South America rather than transiting the Panama Canal. Iron ore and coal are typical commodities carried by this size ship. There is little incentive to build ships slightly larger than the largest Panamax–for example, over approximately 80,000 DWT. Therefore, many Cape Size bulk carriers start in the range of 120,000 DWT and can run up to 300,000 DWT.

6. Suezmax. This describes a ship that can transit the Suez Canal fully loaded. This is a ship with a draft of approximately 53 ft and a carrying capacity in the range of 150,000 DWT.
7. Lakers. This is a special class of ship designed for use on the Great Lakes and is unique to that trade. They are not covered in this chapter.

For channel design purposes, the important characteristics of these ships are draft, beam, and length overall (LOA). The draft is important for channel depth and calculations of under keel clearances. The beam is important for channel width and considerations of bank clearance and in ships passing in two way traffic. LOA is important for channel turns and provision of turning basins for ships in constrained channels or harbors.

Draft and future draft is an important consideration for pier and wharf design. Beam is an important consideration for cranes and other cargo

TABLE 3-1. Dry Bulk Ships.

		Dimensions in Feet			
Ship Types	DWT	LOA	Beam	Draft	Notes
Handy Size Typicals	15,000	470	70	27	
	25,000	550	80	32	
	35,000	600	90	35	
Handymax Typical	45,000	630	100	38	
Panamax Typical	60,000	715	106	42	
Lionsgate Bulker	69,100	738	106	44	
Siboeva	83,000	810	106	48	1
Cape Size Typicals					
Soma Maru	91,000	787	141	42	2
Victoria Spirit	103,000	799	138	41	2
Grafton	122,000	873	133	51	
Karoo	161,000	919	148	58	
SGC Capital	180,000	951	151	60	
SGC Express	211,000	1024	164	60	

Notes: 1. Practical size limit for Panamax.
2. Wide-beam ships, shallow draft.

or commodity-handling equipment. Length must be considered in berth length and provision of mooring dolphins or devices located on or off the wharf or pier structure.

Table 3-1 is a general guide to the important characteristics of various bulk carriers.

3.3 CONTAINER SHIPS

3.3.1 Description and Purpose

Container ships are the dominant carrier of dry cargo in world waterborne trade. Containerization was introduced in the 1960s and since then essentially has replaced dry bulk and break bulk ships for carriage on international routes. The purpose of this section is to describe typical container ships and their characteristics that affect channel design.

Container ships are described by their carrying capacity in 20-ft equivalent units (TEUs). A TEU measures 8 ft (width) × 8.5 ft (height) × 20 ft (length) and is the standard measurement unit. Other common container lengths are 40 ft long and 45 ft long, both with 8 ft width and 8.5 ft lengths. Ship types include:

1. Feeders versus mainline carriers. In some regions, including Southeast Asia and the Mediterranean, many small ports serve coastal and short sea routes by use of feeder ships connecting the port to a larger regional port, where containers are transshipped to mainline carriers. The word "feeder" implies the service more than the size of ship, although feeder ships generally are under 1,200 TEU capacity but can be in the 3,000 TEU range. These feeder vessels often are ships that have been retired from service on longer routes.
2. Geared versus gearless. Large container ships are gearless and are dependent on shoreside cranes for loading and unloading containers. Feeders and ships on short haul or regional routes often are geared so they have the flexibility of calling at ports without shoreside cranes.
3. Panamax. A Panamax ship has a beam that is approximately the maximum width for the Panama Canal, that is, 110 ft or 106 ft beam with clearance. Post Panamax are ships with beams greater than 106 ft. Ships sometimes are described by how many containers they can accommodate in a row, which usually is a multiple of 8 ft plus some allowance for the structure of the ship. A Panamax ship with beam of 106 ft can accommodate 13 rows (13 ft × 8 ft = 104 ft). Note that the number of containers in a row also governs the design of shoreside cranes.

TABLE 3-2. Container Ships.

		Dimensions in Feet			
Ship Type or Name	Capy TEU	LOA	Beam(1)	Draft(2)	DWT-mt
Typical Line Haul Ships					
Typical Panamax					
Akashi Bridge	3500	907	106	39.4	47425
Evergreen R Class	4229	965	106	41.3	49000
Typical Post Panamax					
President Kennedy	4340	903	129	41.8	54665
Hyundai Baron	4469	903	122	43.7	61152
Ever Ultra	5364	936	131	41.7	63388
OOCL Shenzen	8063	1063	140	47.5	99518

Notes: 1. Over 106′ is Post Panamax.
2. Salt water. Add 1′ for fresh water.

3.3.2 Future Ship Sizes

At the time of writing (2003), the largest container ships on the order books range just over 8,000 TEU capacity. There is disagreement in the industry about future ship sizes. Ships much larger than 8,000 TEU will require twin propulsion systems, offsetting some other economies of scale. These large ships raise design issues for channel dimensions as well as port crane sizes. In addition, there are market factors involved because of the amount of cargo required to sustain the ship. On major trade routes, the larger ships are deployed in "strings," which refers to the number of ships required by the carrier to provide weekly service.

One school of thought suggests that the 4,000 TEU carrier, which is the approximate maximum capacity within Panamax beam constraints, will dominate the "all water" trades between Asia and the United States East Coast (USEC). This, of course, would likely change with the expansion of the Panama Canal, (which is being studied but has not yet been confirmed).

This would suggest that ships in the range of 5,500 TEU would be the larger of the ships on the Asia–United States West Coast (USWC) trade. The 8,000 TEU ships are expected to be employed on the Asia–Europe, via Suez Canal routes.

Table 3-2 shows the characteristics of typical container ships.

3.4 LIQUID BULK SHIPS

3.4.1 Description and Purpose

The largest of the liquid bulk carriers transport crude oil from various origins to refineries. Many of these carriers are too large for U.S. ports and call at offshore sites, where refineries are located; at U.S. ports with natural depths suitable for the ships, such as Puget Sound in Washington; or at offshore single point mooring systems. The most interesting ships from the design standpoint are product carriers delivering product from refineries and the fleet of U.S. flag carriers transporting crude from Alaska to the U.S. West Coast.

Product carriers transport refined products from refineries to markets. There also is a significant use of oceangoing barges in this trade. Product carriers tend to be in the range of 40,000 DWT and can be accommodated in channels designed for larger container and dry bulk ships. Conversely, crude carriers often exceed deep-draft channel dimensions, which leads to use of offshore piers or single-point mooring transfer systems.

Because of increased demand for energy, there is interest in the import of liquefied natural gas (LNG) to U.S. ports. These carriers are large and the characteristics of length, beam, draft, and exposed surface to wind are all of interest in channel design.

Crude oil carriers have several categories. Smaller tankers are called product tankers, and newer ships are double-hulled in accordance with current practice and regulations. The Suezmax carrier is the largest that can transit the Suez Canal loaded. The draft constraint is around 53 ft, which results in ships of around 150,000 DWT. Larger crude oil carriers transit the Suez Canal in ballast on return trips to the Middle East. Carriers in the range of 300,000 DWT are called Very Large Crude Carriers (VLCC); the largest ships are Ultra Large Crude Carriers (ULCC), which range in sizes up to and exceeding 500,000 DWT. Of increasing interest are LNG carriers, which carry natural gas under pressure. They are usually rated in cubic meters of capacity.

Table 3-3 shows characteristics of typical ships in these trades.

TABLE 3-3. Liquid Bulk Ships.

		Dimensions in Feet			
Ship Type or Name	DWT	LOA	Beam	Draft	Comment
Torm Alice	41,000	600	106	38	Product Tanker
Neptune Auriga	102,000	790	138	48	Crude Tanker
Samuel Ginn	157,000	902	164	56	Suezmax
Tarim	300,000	1076	187	72	VLCC
Batillus	554,000	1358	206	94	ULCC
Samsung 138	68,200	914	140	37	LNG Carrier
Samsung 200	n/a	1020	158	41	LNG Carrier

3.5 NAVY SHIPS

Another important user of ship channels is the U.S. Navy, with Naval ships coming in many sizes. Following is a list of surface ships in the U.S. Navy active fleet:

Aircraft carriers
Ammunition ships
Amphibious assault
Amphibious command
Amphibious transport dock
Command ships
Cruisers
Destroyers
Dock landing ships
Fast combat support ships
Frigates
Landing craft, air cushioned
Landing craft, mechanized
Mark U special operations craft
Minehunter, coastal
Mine countermeasures
Patrol coastal
Rescue and salvage
Submarine tender

The largest of these ships is the Nimitz Class aircraft carrier, which is also the largest warship in the world. This carrier class has the following dimensions:

Length	1,092 ft
Deck Width	252 ft
Beam	132 ft
Displacement	approximately 97,000 tons full load

The Navy currently has eight of these ships in active service.

Another of the larger Navy ships is the Ticonderoga Class cruiser (27 ships in active service). This cruiser has the following dimensions:

Length	567 ft
Beam	55 ft
Displacement	9,600 tons

Additional information on Navy vessels is available at http://www.navy.gov.

3.6 OTHER SHIPS

3.6.1 Description and Purpose

Of the many other types of ships in the world fleet, there are two types, in addition to those covered earlier, that are likely to have widespread influence on channel design: auto carriers and cruise ships. These two ship types are covered together because they have some common characteristics.

Auto carriers are special-purpose ships designed for the worldwide trade in automobiles and light trucks. They were developed in the late 1960s when the number of cars imported to the United States increased sharply. Auto carriers are essentially floating parking lots with deck after deck of auto parking places. They usually are drive-on/drive-off ships equipped with side and stem ramps that facilitate loading and unloading. The unique characteristic of these ships is their high sides (which protect cargo from the weather) and shallow draft (because of the amount of air carried).

The ships often are described in terms of the number of units they can carry; the larger ships carry a range of 6,000 units. Because of the importance of the Panama Canal in this trade, nearly all large auto carriers are limited to the Panamax beam. The loaded drafts are in the range of 30 to 34 ft so they can be accommodated in most deep-draft channels in the United States. The ships' high sides also result in a very large exposure to wind. These ships, therefore, have to be considered in channel width design where their large exposure to wind and shallow draft may result in difficulty maintaining a sailing track.

Cruise ships are simply one class of passenger ship. Other passenger ships include ferries and day trip boats, which are not discussed here because they are unlikely to govern deep-draft channel design. Cruise ships are of increasing importance in channel and harbor design because of the size of the fleet and the tendency of ports to seek cruise ship service.

The most important feature of large cruise ships is their length and beam, particularly for the Post Panamax fleet. For many years, the large

TABLE 3-4. Auto Ships.

		Dimensions in Feet			
Ship Type or Name	Capy Units	LOA	Beam(1)	Draft	DWT
Delphinius Leader	5,000	656	106	33	21,514
Fidelio	5,574	623	106	29	15,861
Tanabata	5,856	622	106	33	20,082
Aida	6,118	653	106	31	29,213
Grand Pioneer	6,500	655	106	32	19,120

Note: 1. Ships tend to be Panamax beam.

TABLE 3-5. Cruise Ships.

	Dimensions in Feet			
Ship Type or Name	LOA	Beam(1)	Draft	GT(2)
The World	644	96	22	43,200
Disney Magic	965	106	26	83,300
Carnival Spirit	960	106	26	85,900
Norwegian Star	965	106	26	91,700
Carnival Victory	892	117	27	101,300
Grand Princess	950	132	28	109,000
Voyager of the Seas	1,020	155	29	137,300
Queen Mary II	1,132	135	33	150,000

Notes: 1. Panamax beam is 106 ft or less.
2. Ships are measured in gross tons.

ships in the fleet had Panamax beams. This has changed in recent years with the addition of one-ocean ships or Cape Class, which require long voyages to redeploy the ship. As is the case with auto carriers, the large exposed surface of the ship along with the shallow draft raises concerns about course-keeping ability. Furthermore, the wide beams of the Post Panamax fleet can provide governing dimensions for channel width.

Large cruise ships today carry upward of 3,000 passengers; this is comparable to the Titanic, which was put into service in 1911. However, today's ships are longer and wider. The Titanic was 882 ft long, with 92-ft beam, and 35-ft draft.

Tables 3-4 and 3-5 show the dimensions of some typical carriers in the world fleet of auto ships and cruise ships, respectively.

3.7 SUMMARY

This chapter described the dimensions of certain ships and ship types affecting channel design. These ships are typical of much of the world's fleet. However, the designer should use these ship types and characteristics as the starting point for further research when performing deep-draft channel design.

3.8 SOURCE

This chapter was authored by Ogden Beeman, Maritime Consultant, Portland, Oregon. The U.S. Navy ships information was obtained from the www.navy.gov web site.

Chapter 4

FACTORS INFLUENCING CHANNEL DESIGN

4.1 WATER LEVELS

Information on maximum and minimum water levels and frequencies, durations, and amplitudes of water-level fluctuations is needed for design of a navigation project. Water levels can be affected by storm surges, seiches, river discharges, seasonal lake-level changes, and ocean tides. Data on high water levels are used to determine wave penetration and height of jetties, training structures, and overhead obstructions. Data on low water levels are used to determine available and needed depths for various-size vessels.

4.2 TIDE PREDICTIONS

The National Ocean Service (NOS) predicts tide height and tide ranges. Figure 4-1 shows spring tide ranges for the continental United States. Published tide predictions are sufficient for many channel designs; however, prototype observations often are required. Water-level datum generally is selected to conform to the chart datum on applicable NOS navigation charts for tide-affected waterways. Mean lower low water or mean low water is normally the tidal datum plane.

4.3 WIND, WAVES, AND CURRENTS

Estimates of wind, waves, and currents are needed to determine their effects on vessel motions and controllability, to estimate the rates of sediment erosion and deposition, to determine the extent and characteristics of salinity intrusion, and to define flushing characteristics. Historical wind data is usually available from the National Climatic Data Center. Information should be coordinated with the U.S. Coast Guard for any particular problems affected by local topography. Studies should include seasonal

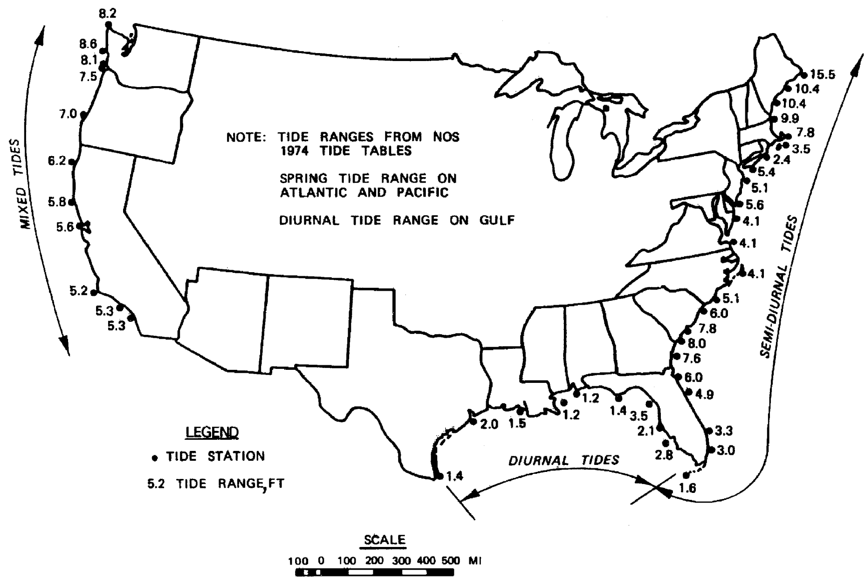

FIGURE 4-1. Ocean Tide Ranges.

variations, which can be significant. Currents generally are caused by tides, tributary streams, or river discharge. Tide predictions and river flow data will be required to determine magnitude and alignment of currents and periods affected. Tide current predictions by NOS also are available. Wave heights and periods can be estimated from (1) wind records, (2) prototype observations, or (3) regional wave records. River discharge data is published by the U.S. Geological Survey (USGS).

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. The height of waves generated in the harbor or bay area is usually low, thus, such waves 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. 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. Container ships with containers on deck
5. Ferry boats
6. LNG and liquefied petroleum gas (LPG) ships

4.4 DESIGN VESSEL

The projected vessel fleet over the economic life of the project is required for channel design and economic studies. Channel dimensions should be selected to safely and efficiently accommodate the volume and type of traffic anticipated. The design vessel is selected from the vessel fleet and normally will be one of the larger vessels expected to use the channel. The maximum-size and least-maneuverable vessels in the fleet must be able to make a safe transit, but the following special conditions may exist:

1. Suitable wind, wave, and current conditions and visibility limitations
2. Use of high tide for additional water depth
3. One-way traffic with bridge-to-bridge communications between other vessels
4. Speed restrictions to reduce squat, ship-generated wave heights, and shore damage

4.5 SEDIMENTATION

The aspects of sedimentation that must be considered for deep-draft navigation projects are: (1) characteristics of the native soils through which the project passes; (2) characteristics of sediments introduced into the upper reaches of the project by riverine flows; (3) characteristics of sediments introduced into the lower reaches of the project by littoral processes and salinity intrusion; and (4) hydrodynamic and water chemistry conditions in the project region.

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 need for entrance sand-bypass. Shoaling rates are needed for river expansions caused by port facilities and basins.

4.6 ACCIDENT RECORDS

Marine accident records are available from the U.S. Coast Guard. 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 also may be valuable in determining navigation problems. The National Transportation Safety Board (NTSB) 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.

At present, marine risk can be addressed by model studies that calculate the risk of vessels "meeting," given a pattern of movement to and from terminals. The models can be calibrated and validated with historic accident figures and then be used to assess additional risk by changes in port design or traffic density. See Section 15.5 for additional discussion of a vessel traffic flow model.

4.7 ENVIRONMENTAL SUSTAINABILITY

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 compared with the natural ecosystem cross-sectional area when the channel improvement is small. 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.

4.8 LOCAL COORDINATION

4.8.1 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 as well as the feasibility and safety of proposed channel design alternatives.

4.8.2 U.S. Coast Guard

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

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Chapter 5
ESTUARY HYDRAULICS

5.1 DEFINITION

An estuary is an area of interaction between salt and fresh water. It is most commonly defined as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard, 1963). The majority of U.S. deep-water ports are located in this mixture of salt and fresh water. An understanding of the hydraulic process in this dynamic environment is essential to the development of a functional deep-draft navigation project.

5.2 PURPOSE OF ESTUARY CLASSIFICATION

There are many types of estuaries, and design problems may vary greatly with the type of estuary. Correct classification alerts the designers to potential environmental and maintenance-dredging problems. To more fully understand what an estuary is, a classification system must be established. Pritchard's definition refers to a positive estuary (Pritchard, 1952a), an estuary in which freshwater input (river flow and precipitation) exceeds losses as a result of evaporation. Thus, the surface salinities in a positive estuary are lower than in the open ocean. When freshwater input is less than freshwater losses because of evaporation, a negative estuary results, such as the Laguna Madre in Texas. Most estuaries are positive; however, a negative situation can occur, resulting in different circulation patterns caused by hypersaline conditions.

5.3 CLASSIFICATION OPTIONS

Estuaries also are classified by topography and salinity structure. Ratio parameters of flow, stratification, and stratification-circulation can be used to identify the salinity structure class.

5.3.1 Topographic Classification

Pritchard (1952b) suggested a topographic classification of three groups: coastal plain estuaries, fjords, and bar-built estuaries.

1. *Coastal Plain Estuaries.* Coastal plain estuaries, or drowned river valleys, were formed as the melting waters from the last ice age flooded existing river valleys. River flow is normally small compared to tidal prism (the volume of water between high and low tides) and sedimentation has not kept pace with inundation. The resulting estuary maintained the topography of the former river valley, but is relatively shallow (rarely deeper than 100 ft). There are extensive mud flats with a sinuous, deeper central channel. Coastal plain estuaries generally can be found in temperate latitudes. Examples include the Chesapeake Bay estuary system in the United States and the Thames and Mersey systems in England.
2. *Fjords.* Fjords, estuaries that have been formed by glacial erosion, generally occur at higher latitudes, are relatively long and deep, and possess a shallow sill at the fjord mouth and intersections. These shallow sills can restrict the free exchange of ocean and estuary waters, in some cases producing a small tidal prism. Examples of fjords include Alberni Inlet (British Columbia, Canada), Sogne Fjord (Norway), and Milford Sound (New Zealand).
3. *Bar-built Structures.* Bar-built estuaries are formed by the same processes as the drowned river valleys. However, in bar-built estuaries, sedimentation has kept pace with inundation, resulting in a characteristic bar forming at the mouth. Associated with depositional areas, bar-built estuaries are shallow, with extensive lagoons and waterways inside the mouth. Entrance velocities can be quite high but quickly diminish as the estuary widens. This type of high-volume sediment-estuary is most often found in tropical or active coastal deposition areas. Examples of bar-built estuaries include the Roanoke River (United States) and the Vellar Estuary (India).
4. *Other.* A fourth group of estuaries includes estuaries formed by volcanic eruptions, faulting, landslides, or other processes.

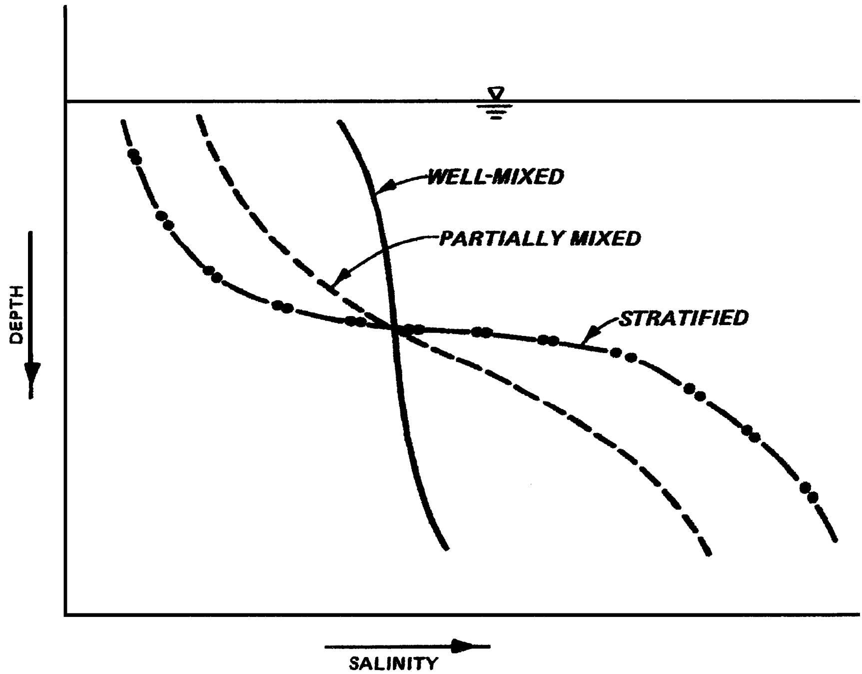

FIGURE 5-1. Vertical Salinity Structure: Classification Depends on Salinity Difference Between Surface and Bottom Values (EM1110-2-1607, 1991).

5.3.2 Classification by Salinity Structures

Most estuary systems are coastal plain estuaries with individually unique salinity and flow characteristics. These estuaries can be classified using stratification and salinity distribution as the governing criteria. The major classifications are highly stratified, partially mixed, and well-mixed (homogeneous) (Figure 5-l).

Classification depends on salinity difference between surface and bottom values.

1. *Highly Stratified.* A highly stratified, salt wedge type estuary is one in which the outgoing lighter fresh water overrides a dense incoming salt layer. The dense salt wedge will advance along the bottom until the freshwater flow forces can no longer be overcome. At this point, the tip of the salt wedge will be blunt during rising tide and tapered during falling tide. Mixing occurs at the saltwater/freshwater interface by entrainment, a process caused by shear forces between the two moving layers. As small amounts of dense water

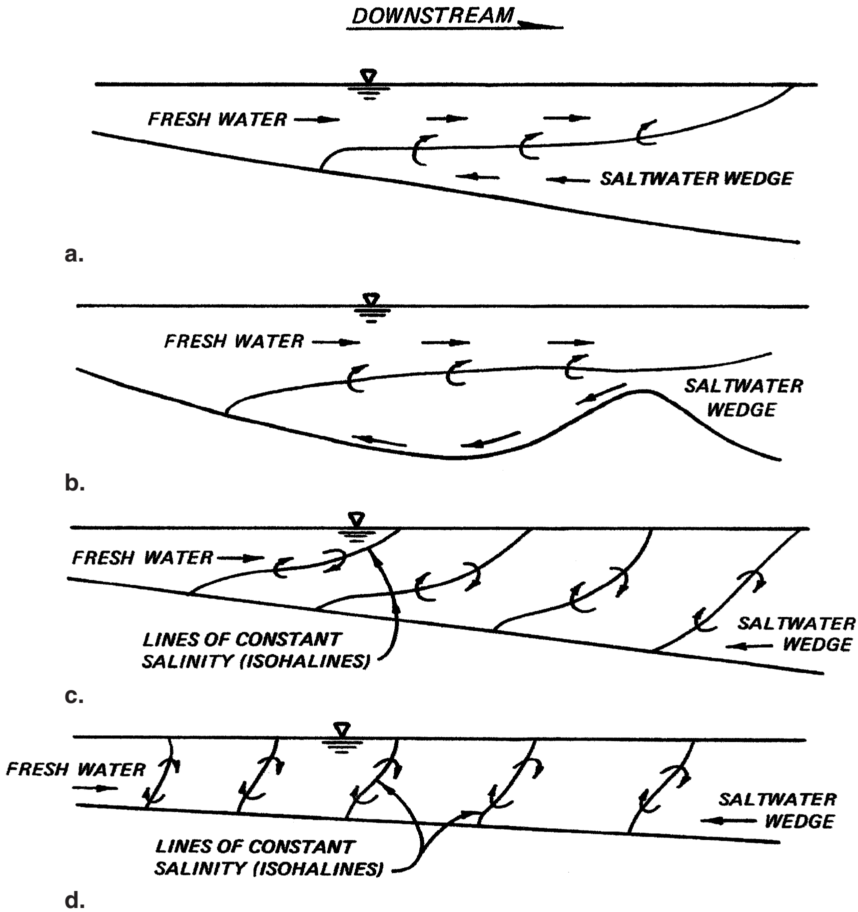

FIGURE 5-2. Estuary Classification by Salinity Structure: a, Highly Stratified Salt Wedge Estuary; b, Highly Stratified Fjord Estuary; c, Partially Mixed Estuary; d, Well-Mixed (Homogeneous) Estuary (EM1110-2-1607, 1991).

are mixed in the upper layers, more fluid enters the estuary near the bottom to compensate for the loss; more fluid leaves the estuary in the upper layers to attain equilibrium of forces (Figure 5-2a). In these river-dominated, poorly mixed estuaries, such as Southwest Pass on the lower Mississippi River, upstream flow occurs in the salt wedge regardless of tidal phase, with downstream flow on the surface. In the shallower South Pass; also on the Mississippi River, upstream flow occurs in the wedge during flood tide simultaneously with surface downstream flow, whereas during ebb tide flow at all depths is in the seaward direction. Examples include the lower Mississippi River (United States) and Vellar Estuary (India). Another form of a highly stratified estuary is the fjord type system. Similar to the salt wedge type, in a fjord, the lower, almost isohaline layer is very deep. The freshwater surface layer is almost homogeneous, and only during low-flow periods does the maximum salinity gradient ever reach the surface. Circulation over the sill may be very different from the rest of the fjord estuary because of large tidal velocities and weaker stratification at the sill. The inflow over the sill is usually a mixture of coastal and outflow water. As the water passes the sill and the tidal action decreases, the denser water settles, frequently forming a layered structure, which is the result of successive saltwater intrusions (Figure 5-2b). If water renewal is infrequent, anoxic conditions can develop on the bottom. Silver Bay (Alaska, United States) and Alberni Inlet (British Columbia, Canada) are examples.

2. *Partially Mixed.* A partially mixed estuary is one in which salinity stratification is reduced but not eliminated by turbulent mixing of higher salinity water near the bottom with lower salinity near the surface. These turbulent eddies mix salt water upward and fresh water downward with a net upward flow of saline water. As the salinity of the surface water increases, the outgoing surface flow correspondingly increases to maintain river flow, in addition to the additional upward-mixed saline water. This causes a compensating, incoming flow along the bottom. This well-defined, two-layer flow is typical of partially mixed estuaries. The salinity structure is very different from a highly stratified estuary because of the efficient mixing of salt and fresh water. The surface salinity increases steadily down the estuary with undiluted fresh water, now occurring only near the head of the estuary. A longitudinal salinity gradient along the bottom also exists (Figure 5-2c).

   In a partially mixed estuary, river flow is low compared to tidal prism. Examples include the James River (United States) and Mersey and Southampton Water estuaries (England).

3. *Well-Mixed or Homogeneous.* In estuaries in which tidal flow is much larger than river flow and bottom friction is large enough to mix the entire water column, a vertically homogeneous (well-mixed) estuary results (Figure 5-2d). If the estuary is wide, Coriolis force may form a horizontal flow separation; and in the northern hemisphere, the seaward flow would occur on the right side (looking downstream), whereas the compensating landward flow would be on the left. This vertically homogeneous, laterally nonhomogeneous condition can be found in the lower reaches of the Delaware and Raritan estuaries in the United States. A vertically and laterally homogeneous (sectionally homogeneous) condition occurs in narrow estuaries in which salinity increases evenly toward the mouth.

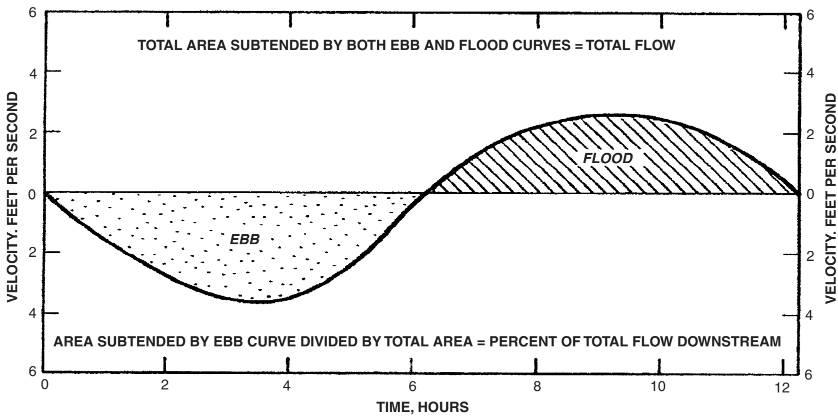

FIGURE 5-3. Definition Sketch: Flow Predominance (EM1110-2-1607, 1991).

5.4 FLOW PREDOMINANCE

The concept of flow predominance is useful in understanding the effects of density-induced currents on velocities. In a conventional 12-hr plot of velocity versus time, velocity values will be positive (flood flow into the estuary) and negative (ebb flow out of the estuary) (Figure 5-3). To determine flow predominance, the area under the ebb portion of the curve (all negative values) is divided by the total area under the curve (ebb portion plus flood portion). The result, ebb predominance, is the percentage of the total flow per tidal cycle that is moving in the ebb direction at a given velocity sampling depth. In a highly stratified estuary, the freshwater surface flow will always be ebb dominant, whereas the bottom salt wedge layer will be strongly flood dominant. Near the entrance of a well-mixed estuary, the bottom flow will be slightly flood dominant, whereas the surface will be strongly ebb dominant. Further upstream, the flow will be ebb dominant throughout the entire depth. In a partially mixed estuary, the bottom flow will be mainly flood dominant within the salinity wedge, and the surface flow predominantly in the ebb direction. Examples of flow predominance in Savannah Harbor, Charleston Harbor, and the Hudson River are presented in Ippen, 1966.

5.5 NULL POINT

Along with the concept of flow predominance, it should be noted that the net flow may be balanced at a certain point (i.e., no net flow occurs in either direction). This point is called the null point.

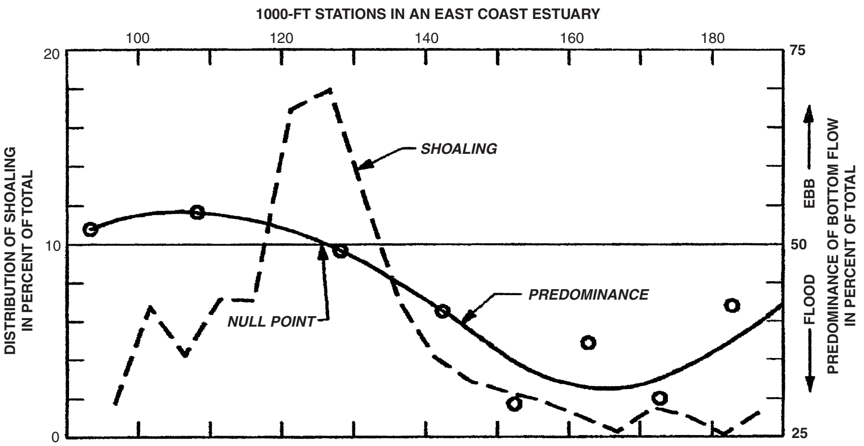

FIGURE 5-4. Relationship of Shoaling and Predominance of Bottom Flow (EM1110-2-1607, 1991).

5.6 SALINITY EFFECTS ON SHOALING

Saltwater intrusion is important to estuary sedimentation because saline water enhances flocculation of suspended clay particles, and density currents tend to move sediments upstream along the bottom. Thus, sediments entering the estuary may become trapped instead of moving out to sea. Frequently, shoaling occurs between the high-water and low-water positions of the upstream limit of salinity intrusion. The region most likely to experience heavy shoaling is the reach that brackets the 50% value (or null point) of the bottom flow predominance (Figure 5-4).

5.7 SUMMARY OF ESTUARY CLASSIFICATION

The classification of estuaries uses variables of topography, river flow, and tidal action as factors influencing saltwater and freshwater mixing. Ultimately, the salinity characteristics of an estuary determine the unique features of the system. No two estuaries are alike, but one can hope to find general principles rather than unique details to use when studying and comparing similar systems.

5.8 TIDE-GENERATING FORCES

To understand the effect of tides on an estuarine system, a brief comment should be made on the tide-generating forces and rhythms.

1. Newton's laws of gravitation state that the force of attraction between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between their centers. In our sun-moon-earth system, the sun is the largest body, but because its distance is so great from the earth, its influence on tides is only 46% of the moon's influence.
2. All forces in the sun-moon-earth system are in equilibrium; however, individual particles on the earth's surface are not. In this system of varying distances and rotation rhythms (i.e., the earth rotates around the sun once every 24 hrs, and the moon rotates around the earth once every 24 hrs, 50 min), these tide-generating forces are never constant. These forces act on land, water, and air. However, the land mass is not as elastic as liquids, and air, although elastic, has such a low density that the effects of the tidal forces, although measurable, are small. The media most free to respond in an observable manner are the earth's water masses, the oceans. Tide-generating forces are the residual forces between attraction (earth/moon and earth/sun) and centrifugal force (the rotation of two bodies about a common axis).

5.9 TIDE TERMS

Several basic terms are used to describe tides. High water is the water-surface level at its highest extent during one cycle. The term is also used to denote the time at which highest water-surface level occurs.

Similarly, low water refers to the lowest water level. Two unequal high waters and two unequal low waters occurring in one day are distinguished by referring to them as higher high water, lower high water, lower low water, and higher low water. A tidal current that flows landward is termed a flood current, whereas one that flows seaward is called an ebb current.

5.10 TYPES OF TIDES

The basic tide is the cyclic rise and fall of the water surface as the result of the tide-generating forces. There are three types of tides—diurnal, semidiurnal, and mixed—which are a result of tide-generating forces and location on earth.

1. *Diurnal.* A diurnal tide is one high and one low water level in a lunar day (24.84 hrs). Diurnal tides occur in the Gulf of Mexico (at most locations); in some parts of the Pacific Ocean, for example, the Philippines; and in certain places in Alaska.

2. *Semidiurnal.* Semidiurnal tides produce a tidal cycle (high and low water) in one-half the lunar day (12.42 hrs) or two nearly equal tidal cycles in one lunar day. Semidiurnal tides occur along the East Coast of the United States.
3. *Mixed.* Mixed tides are a combination of diurnal and semidiurnal characteristics and are found on the West Coast of the United States. There is a marked inequality in the heights of the succeeding tides, especially low waters, and there also is an inequality in time. Usually, two high and two low waters occur each day. Typically, there is a high tide, then a low tide, followed by a scanty high tide and a moderate low tide.

5.11 SPRING AND NEAP TIDES

Because of the unequal rotational rhythms of the members of the sun-moon-earth system, their forces are periodically in and out of phase. Every 14.3 days (twice a month), the earth, moon, and sun are aligned in phase. At this time, the gravitational forces reinforce each other to form higher than average tides called "spring tides." The moon and sun are at right angles to the earth also twice a month, and these forces are subtracted from each other to form lower than normal tides, called "neap tides."

5.12 INFLUENCE OF MOON AND SUN

Another factor that influences tide is the declination of the moon and sun—the angular distance north or south of the equator. The relationship of the earth's axis to the plane of its orbit around the sun results in an apparent yearly north-south movement of the sun. The plane of the moon's orbit is tilted also, and the apparent north-south migration across the equator occurs every 27.33 days. This monthly migration results in observable tidal changes. During this month, spring tides (new and full moon) happen to occur when the moon is crossing the equator. Neap tides occur at the quarter moon, and apogee (moon furthest from the earth) and perigee (moon closest to the earth) effects are noted. The spring tide occurring at perigee is larger because of the increase in tidal forces. The tides at New York are semidiurnal with a strong spring and neap influence. Tides at Port Adelaide, Australia, go from mixed to semidiurnal when the moon is over the equator, whereas tides at Seattle, Washington, are mixed at all times. Tides at Los Angeles, California, and Honolulu, Hawaii, are diurnal during neap tide when the moon is south of the equator, semidiurnal during spring tide, and mixed at other times of the month. Tides at Pakhoi, China, are strongly diurnal except when the moon is over the equator.

5.13 TIDE PREDICTION TABLES

Tide predictions were published by NOAA until the mid-1990s. NOAA tide information and predictions currently are available at http://www.co-ops.nos.noaa.gov/tide or nongovernment commercial publishers.

5.14 NONASTRONOMICAL FORCES

Nonastronomical forces also can produce waves. A tsunami, or seismic sea wave, is a very long wave that originates in a disturbance in the sea floor. The wave train generated from such an event (earthquake, mud slide, volcanic explosion) contains huge amounts of energy and moves at high speeds. When it reaches shallow water and the shoreline, it can be extremely destructive. Other nonastronomical waves are produced by boat wakes, explosions, landslides, and any force that can disturb the surface of the water.

5.15 WAVEFORMS

The tide may enter the estuary as a progressive wave manifested by the forward movement of the waveform. Some estuaries experience tides that are standing waves against the coast. The current velocity and water-surface elevations in this waveform are in phase. As the wave progresses up the estuary, the waveform changes shape, the face becomes steeper, and the rear slope becomes more gradual. Areas of constriction increase the wave amplitude, and boundary friction is a means of energy dissipation. At some point in time, as the wave reaches the end of the estuary, it may be reflected. The interaction of the forward-advancing progressive wave and the returning reflected wave may produce a standing wave. In a standing or stationary wave, the current velocity and water-surface elevation are out of phase by 90°. Most estuaries are intermediate, displaying characteristics somewhere between progressive and standing wave features.

5.16 WINDS AND WIND-GENERATED WAVES

Meteorological factors such as changes in barometric pressure and the uneven heating and cooling of the earth produce pressure differences that result in winds. Winds blowing across the surface of bodies of water transmit energy to the water, and waves are formed. The size of these wind-generated waves depends on the wind velocity, the length of time the wind is blowing, and the extent of open water over which it blows (fetch). Water depth is also a factor in limiting growth of waves.

5.17 SETUP, SETDOWN, AND STORM SURGE

In addition to the creation of wind waves, wind also can cause a condition known as "setup" or "setdown." Wind stress on the water surface can result in a pushing or piling up of water in the downwind direction and a lowering of the water surface in the upwind direction. When the wind blows landward, water will set up against the land. This setup, superimposed on the normal tidal elevation, causes apparent higher than normal tides. This frequently produces flooding during storms. A seaward wind will push water toward the sea and away from land, causing a lower than normal water level. When the wind stops, the setup or setdown water surface will return to normal levels. In enclosed waters, this return may occur as successive oscillations that are diminished by friction.

During a storm, there may be a substantial rise in sea level along the coast, called a "storm tide" or surge caused by wind setup, wave setup, and air pressure drop. The difference in pressure between an atmospheric low-pressure area and the surrounding high-pressure area causes the sea surface to "hump." The wind-generated storm waves superimposed on the normal tides and storm surge can have disastrous effects on shore structures and lead to flooding of coastal and inland areas.

5.18 SEICHE

If the surface of an enclosed body of water, such as a harbor or bay, is disturbed, long waves may be generated that will rhythmically slosh back and forth as they reflect off the opposite ends of the basin. These waves, called seiches, will travel back and forth until the energy is lost to frictional forces. The period of a seiche is dependent on the size and depth of the basin. If an arriving wave train has a period similar to the natural frequency of a harbor, each arriving wave will increase the intensity of the seiche, producing rougher waters inside the harbor than on the surrounding sea.

5.19 FRESHWATER SOURCES

So far, we have discussed the topographic classification of estuaries, astronomical tide-generating factors, and meteorological and seismic wave-generating factors. The final critical forcing function of an estuary is the amount of fresh water delivered to the system. This fresh water can flow from the drainage basin of the river, ground water, discharge from dams and reservoirs, and rain falling on the water surface. The U.S. Geological Survey (USGS) Water Resources Division, in cooperation with state and local governments, collects and disseminates hydrologic data of stream discharge or stage, reservoir and lake storage, groundwater levels, and the quality of surface and ground water. All data is stored in the USGS National Water Storage and Retrieval System (WATSTORE) and is available on request from the USGS regional office or the USGS in Reston, Virginia.

5.20 EPISODIC EVENTS

Episodic events that produce extreme quantities of water in a drainage basin can have a significant effect on the freshwater/salinity balance of an estuary. The seaward displacement of the salinity zone by sediment-laden fresh water will result in drastically different salinity and shoaling patterns.

5.21 CHANGES IN SEA LEVEL

Sea level rise or the apparent rise in the ocean surface when compared to a stable landmark is a very general description for a more complicated event. The actual rise in the ocean is not one that is readily noticeable, especially when historic records indicate an average value of 0 to +1 centimeters per year. The geologic record indicates that shifts in climate and the associated changes in sea level are attributed to the global freeze and thaw cycles. These trends have been most noted in the Pleistocene Epoch, or ice age, when the ocean level was much lower because much of the available water was frozen in the glaciers. Other events and factors can affect the rate of change:

1. *The Greenhouse Effect.* Overall global warming (postulated by the greenhouse effect) will cause thermal expansion of the seas and melting of snow and ice at increased rates and, thus, increase ocean levels. The greenhouse effect is not a part of the cyclic warming or cooling periods of natural weather patterns but is related to man-influenced changes in the atmosphere and ozone layer. Future low, medium, and high rates of sea level rise are estimated by the National Research Council.
2. *Subsidence.* Along coasts that consist of deposited materials, subsidence may occur, due in part to consolidation of recent sediments. Subsidence also may occur as a result of man's activities, such as withdrawal of oil, natural gas, and water, or by the additional weight of structures or land reclamation.

3. *Tectonic Activity.* Events such as earthquakes and earth crust movements may raise or lower coastal areas somewhat and, as a result, negate or magnify the rising sea level.
4. *Geomorphology of the Area.* Some coastlines are defined as sinking (such as the U.S. East Coast), whereas some are considered to be rising (U.S. West Coast). Few, if any, reliable measurements are available.

5.22 APPARENT SEA LEVEL RISE

Because of certain factors, including those that were previously mentioned, use of the term "apparent sea level rise" would be more accurate because of the possibility that the particular area in question may actually be subsiding. Additional reading on this topic can be found in books on oceanography, geology, and geomorphology.

5.23 SEA LEVEL RISE IMPACT ON NAVIGATIONAL CHANNELS

Although historic estimates of sea level rise could impact shoreside facilities over the long term, it would have a negligible effect on a navigational channel which has a 50 year design life. A rise in the sea level datum would result only in less dredging to maintain authorized channel depth.

5.24 SOURCE

The information for this chapter came from EM 1110-2-1607, Tidal Hydraulics, March 15, 1991.

Chapter 6
CHANNEL DEPTH

6.1 CHANNEL DEPTH DESIGN METHODS

The depth of the project design channel should be adequate to safely accommodate ships with the deepest drafts expected to use the waterway. Normally, 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 by an economic analysis of the expected project benefits compared with project costs.

The two most commonly used methods for channel depth selection are the Permanent International Association of Navigation Congresses (PIANC) guidance report and the U.S. Army Corps of Engineers engineering manuals.

The design details of these two methods are very similar. Site-specific wind, wave, and ship motion are evaluated with the use of vessel simulators or other mathematical or physical models.

The PIANC method, used to estimate channel depth for concept design, is presented in PIANC (1997), page 20. This supplement states the following:

Depth is estimated from:

- at-rest draught (draft) of the design ship;
- tide height throughout transit of the channel;
- squat;
- wave-induced motions;
- a margin depending on type of bottom;
- water density and its effect on draught (draft).

The values for draught (draft), which include water density effects, squat, wave-induced motions, and margin, are additive. After the depth/draught (draft) ratio has been calculated, it should be checked to ensure that it is not less than a safe minimum. A minimum of 1.10 should be allowed in sheltered waters, 1.3 in waves up to 1.0 m in height, and 1.5 in higher unfavorable waves.

The Froude Depth Number, F_{nh}, must be less than 0.7.

The hydrodynamic resistance to motion of a ship in shallow water is governed by the Froude Depth Number, F_{nh}, which is, broadly, a nondimensional ratio between speed and depth. It is defined as

$$F_{nh} = V/(gh)^{1/2}$$

where

- V = the speed through the water in feet/second
- h = the undisturbed water depth in feet
- g = the acceleration due to gravity (about 32.2 ft/sec^2)

When F_{nh} approaches or equals unity, the resistance to motion reaches very high values, which most displacement ships have insufficient power to overcome. In fact, such ships are unlikely to be able to exceed F_{nh} values of 0.6 or 0.7 (the former for tankers, the latter for container ships), which results in an effective speed barrier.

These depth/draft ratios can be applied to channels worldwide. However, local conditions may indicate that deviations are justified. Detailed Design, which would follow Concept Design, would address the particular features of a given site.

The following steps would be used for the (PIANC) channel depth determination during concept design (first rough estimate).

Step 1. Estimate - Ship draft
- Tide height through transit of the channel
- Squat
- Wave-induced motion
- A margin of safety
- Water density and its effect on draft.

Step 2. Select the appropriate safe minimum depth/draft ratios:

Wave conditions	*Minimum depth/draft ratio*
Sheltered waters	1.1
Waves up to 1 m	1.3
Higher waves with unfavorable periods and directions	1.5

Step 3. Compare estimated channel depth for a site-specific project (step 1) with safe minimum depth (step 2). The concept design channel depth will be the larger (deeper channel) depth of these two values.

The Army Corps of Engineers method for both preliminary and final design evaluates each component of channel depth determination for each project using site-specific information of wind, wave, and design shop characteristics. These components include:

Sinking because of fresh water
Ship motion from waves
Ship squat when under way
Safety clearance
Advance maintenance
Dredging tolerance

These components are shown in Figure 6-1.

Further discussion of the components of the Army Corps of Engineers method follow.

6.2 DESIGN SHIP LOADED DRAFT

This component also would include an estimate of trim. Trim is defined as the difference in draft from bow to stern and controlled by loading. Ship operators generally prefer to trim a ship to an even keel, but this is often a complex and expensive operation and in rare instances could induce some undesirable stresses in the hull structure. A vessel down by the bow loses some of its maneuverability and therefore is often loaded to keep the stern lower than the bow. Information on trim is becoming of increased importance in channel design as vessels become larger. For instance, a 1000-ft-long ship trimmed 1% (less than 1°) by the stern would have a draft at the stern about 5 ft greater than that at midship. Information on trimming can be obtained through observations of actual operations and through consultations with port shipping officials.

6.3 EFFECTS OF FRESH WATER

When passing from sea water to fresh water, the vessel draft increases because of the decrease in the density of the water. When passing from sea water with a specific gravity of 1.026 (64 lb/cu ft) into fresh water with a specific gravity of 0.999 (62.4 lb/cu ft), a vessel's displacement will increase approximately 3%. Therefore, a vessel with a saltwater draft of 35 ft will have a draft of 36 ft in fresh water, and intermediate drafts in brackish waters.

6.4 SHIP MOTION FROM WAVES

Waves and swells affect vertical ship motion by three components, pitch, roll, and heave, as shown in Figure 6-2. The deepest excursion of the vessel

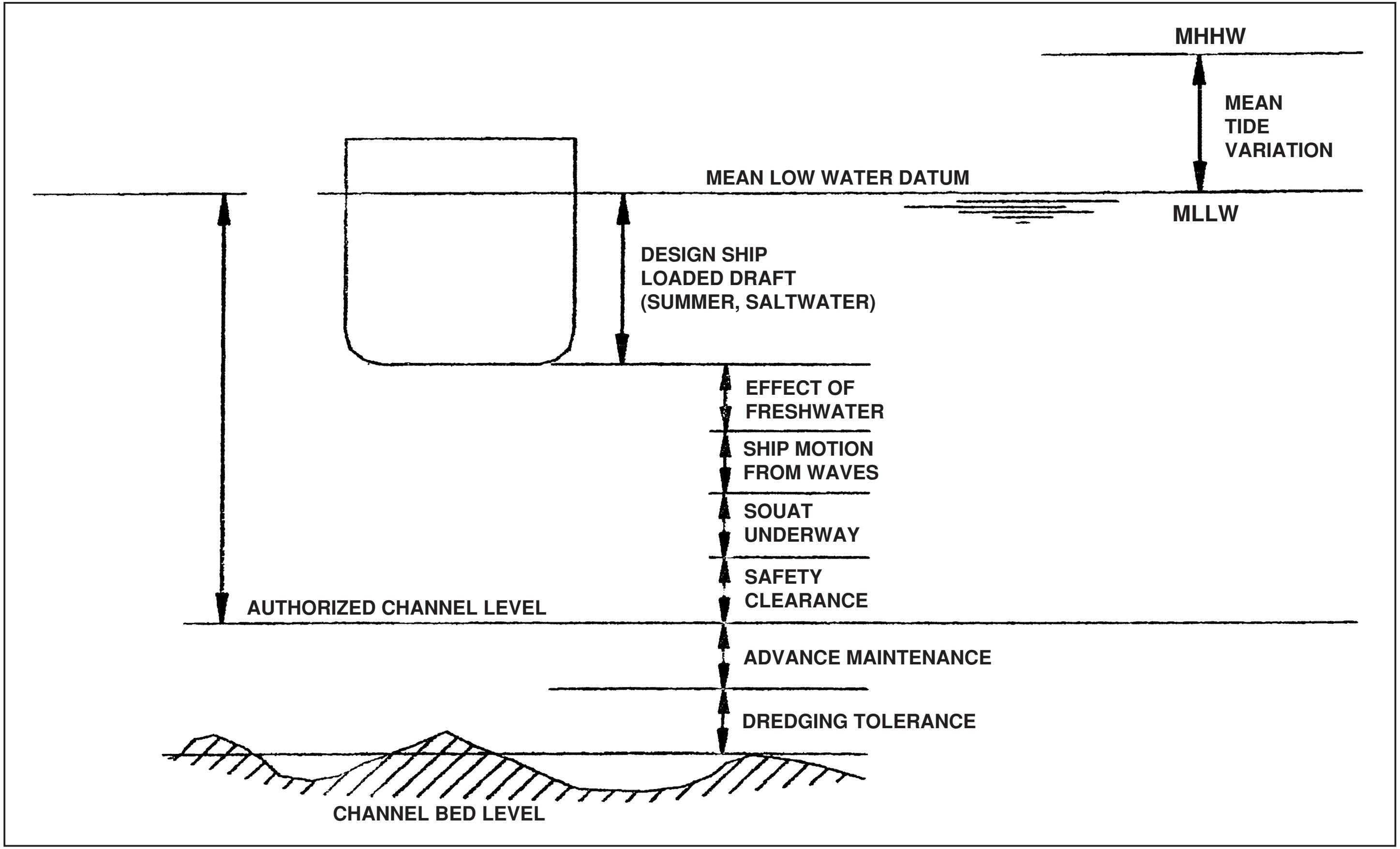

FIGURE 6-1. Channel Depth Allowances.

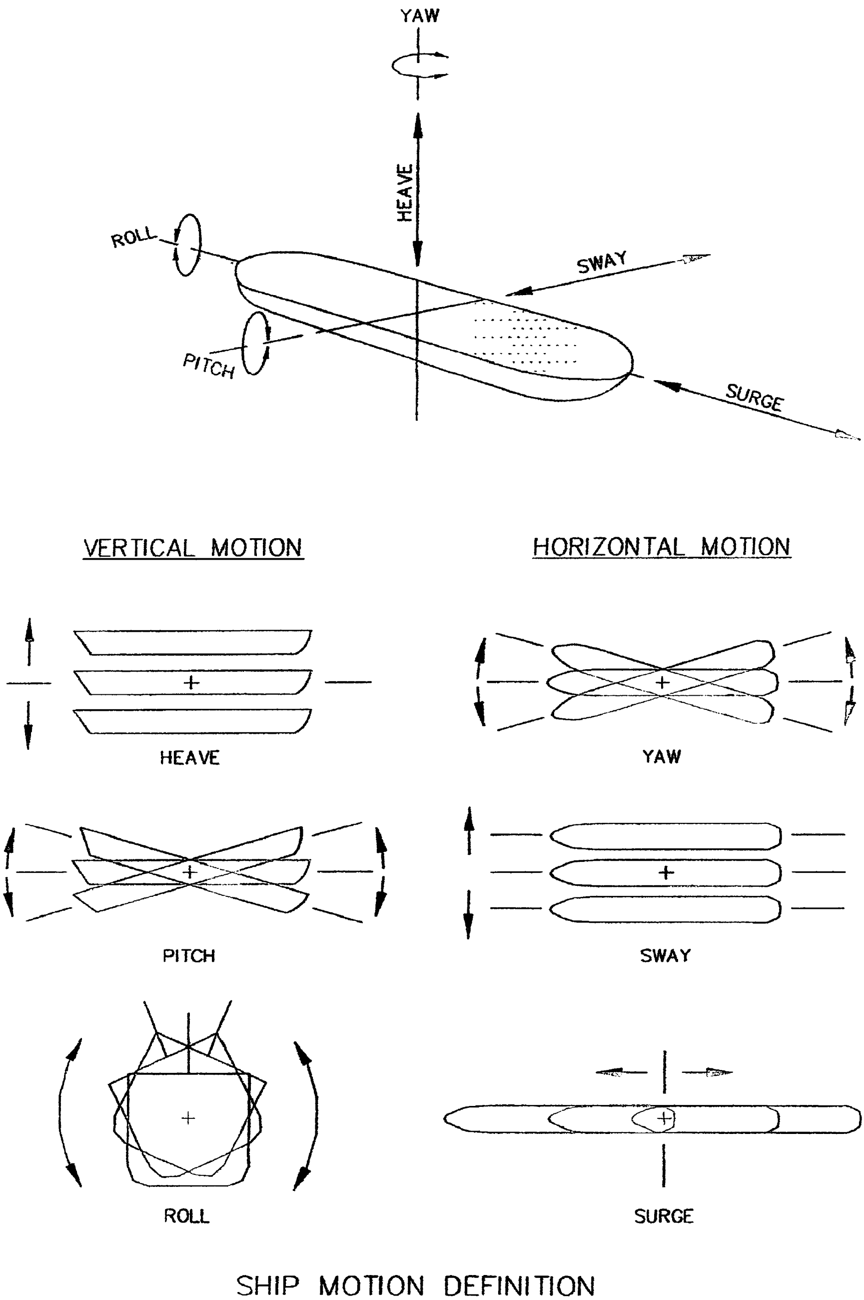

FIGURE 6-2. Ship Wave Motion Definitions.

bottom below the water surface, which is caused by waves, must be considered in the design of channel depth. In open-sea conditions, a pitch angle of 2.5° in a 1000-ft-long ship would increase draft forward about 22 ft. Prototype observations of ship motion in the Columbia River entrance indicated downward pitch motions in excess of 25 ft. The maximum vertical excursion, however, did not take place with the deepest draft ship but with a small ship. It appears this ship was affected by the relationship of the ship length to wave length during the time of crossing. Some pilots and ship captains consider the Columbia River bar one of the most severe channel entrances in the world; thus, this example should be considered an extreme example. At times, the bar pilots judge the wind, wave, and current conditions too dangerous to navigate, and ships must wait for more favorable conditions (Wang and Noble, 1982). A 5° angle of roll for a ship having a beam of 100 ft would increase amid-ship draft about 4.2 ft. This is not an unusual roll at entrances or in some semiprotected waters, caused by waves, wind, and turn angle.

6.5 SQUAT UNDERWAY

A ship in motion will cause a lowering of the water surface because of the increase in velocity past the ship, causing the hull to be lowered with respect to the bottom. Although this phenomenon also affects the ship's trim (usually by lowering the stern slightly more than the bow), the effect is minor and normally is neglected. The amount of lowering referred to as "squat" depends on several factors including the vessel speed, characteristics of the channel and vessel, and interaction with other vessels. Squat is generally in the 1- to 3-ft range and increased in confined channels. A model developed by Huval (1993) can calculate squat for canal, trench, and fairway channels as shown in Figure 6-3. Prototype measurements on the Columbia River channel indicated squat in the range of 3-ft for a 600-ft container ship traveling 16 knots in an unconstrained channel (Beeman, 1985; PIANC Bulletin No. 51).

6.6 SAFETY CLEARANCE

In the interest of safety, a clearance of at least 2 ft should be provided between the bottom of a vessel in motion and the channel bottom to avoid damage to the ship's propellers from sunken timbers and debris, to reduce displacement of bottom material, and to avoid the fouling of pump and condensers by bottom material. When the bottom of the channel is hard—consisting of rock, consolidated sand, or clay—the clearance should be increased to at least 3 ft. Actually, the minimum depth should be considered on a project-by-project basis, and should take into account the many local

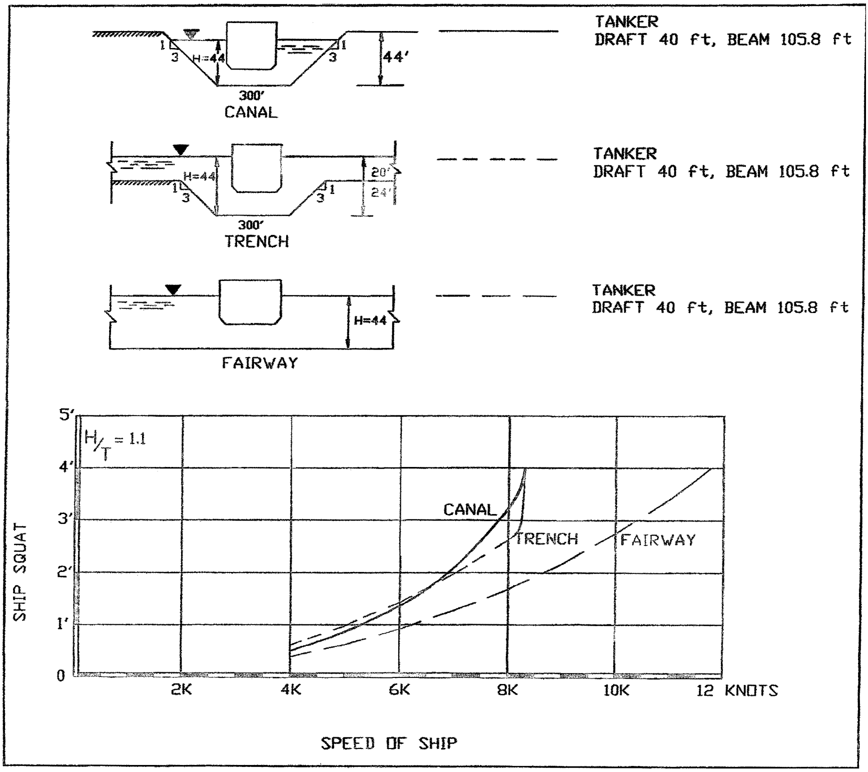

FIGURE 6-3. Example of Squat Calculations (EM 110-2-1613, 2002 Draft).

variables, such as channel configuration and traffic mix, in addition to type of bottom.

6.7 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 channel depth reliability and economy of less frequent dredging. Deeper channels will tend to be more efficient sediment traps and could shoal faster. However, a deeper channel might tend to localize shoaling and could reduce the reach of channel to be dredged and cost of maintenance dredging. Estimates on several depth increments of advance maintenance and their effect on shoaling rates are needed to determine the optimum depth. Conditions will vary with each project, and the design depth and overdredging that might be applicable should be based on an evaluation of conditions at each project.

6.8 DREDGING TOLERANCE

In addition to the advance maintenance dredging, an additional 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 a fluctuating water surface. This additional dredging is referred to as dredging tolerance.

6.9 NAUTICAL DEPTH

The concept of nautical depth applies to ship channels with a channel bottom that consists of a liquid layer of silt or mud and no easily definable bottom. Larger ships can easily transit several meters deep of this semi-liquid layer. However, pilots and ship captains are less than enthusiastic in this channel transit because depth records show negative keel clearance, and all astern bells ring. Following is a discussion of fluid mud channel bottoms from PIANC, 1997, page 43.

> Many navigational channels have bottoms which are covered with fluid mud suspensions, characterized by low density (1050–1300 kg/m^3) and weak shear strength. For several reasons, bottom and depth are not clearly defined in such conditions.
>
> Traditional survey techniques, such as lead lines and echo-sounders, are not adequate for depth determination in muddy areas. Measurements with echo-sounders making use of acoustic signals of different frequency may result in different values for depth, as high frequency signals reflect on the water-mud interface, while low frequency waves penetrate into the sediment deposit and yield a larger water depth value.
>
> For channels with a solid bottom, a minimum underkeel clearance (UKC) is selected in order to avoid contact between the moving ship and the bottom. In muddy areas, the question arises whether this minimum, referred to as the water-mud interface, cannot be reduced. Although the upper part of the mud layer has a somewhat higher density than water, its rheologic properties are comparable to those of water, so that a ship's hull suffers no damage when it penetrates this interface.
>
> Even navigation with an underkeel clearance which is negative, referred to as the interface, can be considered, which implies that the ship's keel is permanently in contact with the mud. On the other hand, safety of navigation requires that the pilot must always be able to compensate for the effects of mud on ship behavior by means of its own control systems or external assistance (e.g., tugs).

An acceptable compromise between the safety of navigation and the cost of channel maintenance can only be reached by introduction of non-conventional definitions and survey methods, and requires additional knowledge about the navigational response of ships in muddy areas. (PIANC, 1997)

6.10 SOURCE

Most of this information was extracted from EM 1110 -2-1613, Hydraulic Design of Deep-Draft Navigation Projects, April 8, 1983, and PIANC-IAPH Working Group 11-30 Report, "Approach Channels, a Guide for Design," June 1997.

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Chapter 7
CHANNEL ALIGNMENT

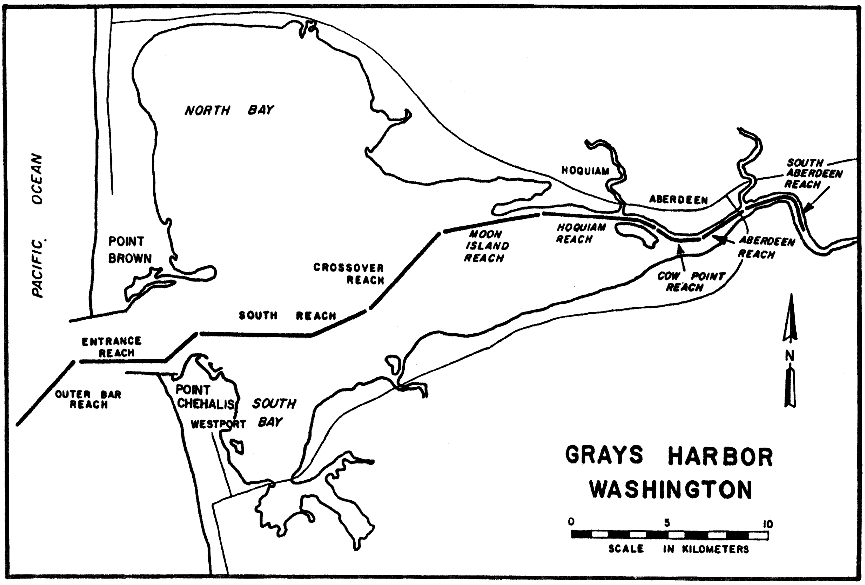
7.1 GENERAL

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. Note, however, that there often are separate flood and ebb channels that may not be continuous. Although bends in the alignment should be minimized as much as possible, straight reaches with small curves may be needed to follow the natural deep water channels in the estuary. Straight reaches between bends should be at least five times the length of the longest vessel. Where gradual bends are not practical, cutoffs should be considered. Structures such as groins, revetments, and wave absorbers might be required to maintain acceptable channel alignment, channel dimensions, and wave conditions. Channel alignment that cuts across sandbars or mud bars shou1d be avoided unless training structures to control the movement and deposition of sediment are provided.

7.2 VARIABLE ALIGNMENT

The strength of the hydraulic forces in the estuary will usually dictate channel alignment. Estuaries with high tide ranges and, therefore, strong ebb currents or large river discharges, normally will have navigation channels with changing alignments. An example is Grays Harbor, Washington, which has high tides and a large tide prism, as shown in Figure 7-1.

These systems may have channels that migrate, such as Grays Harbor, where the channel has migrated to a position adjacent to the South Jetty (Figure 7-2). Normally, the ship channel alignment is adjusted over time to follow the natural channel migration.



Notes:
Mean tide range 9.00 feet
Maximum tide range 17.5 feet
ship channel 26 miles long

FIGURE 7-1. Variable Alignment Ship Channels (Adapted from ASCE Manual No 80).

7.3 STRAIGHT ALIGNMENT

Straight ship channels are possible when the hydraulic dynamics of the system are small. Projects in the Gulf of Mexico or South Atlantic coast have small tide ranges and, therefore, small tide prisms. The Gulf Coast not only has low tide ranges (1 to 3 ft) but also has a tide cycle that is diurnal (i.e., one high and one low tide in a lunar day [24.84 hours]). The East Coast has semidiurnal tides, which produce two nearly equal tide cycles in a lunar day. West Coat tides are mixed with two unequal tide cycles a day. Therefore, channel tidal velocities are determined by the size of the tide prism and the number of tide cycles a day. Many of the Great Lakes ship channels have straight alignment because of the absence of tidal effects and because river discharges often are small. Figure 7-3 shows an example of a straight ship-channel project in Mobile, Alabama.

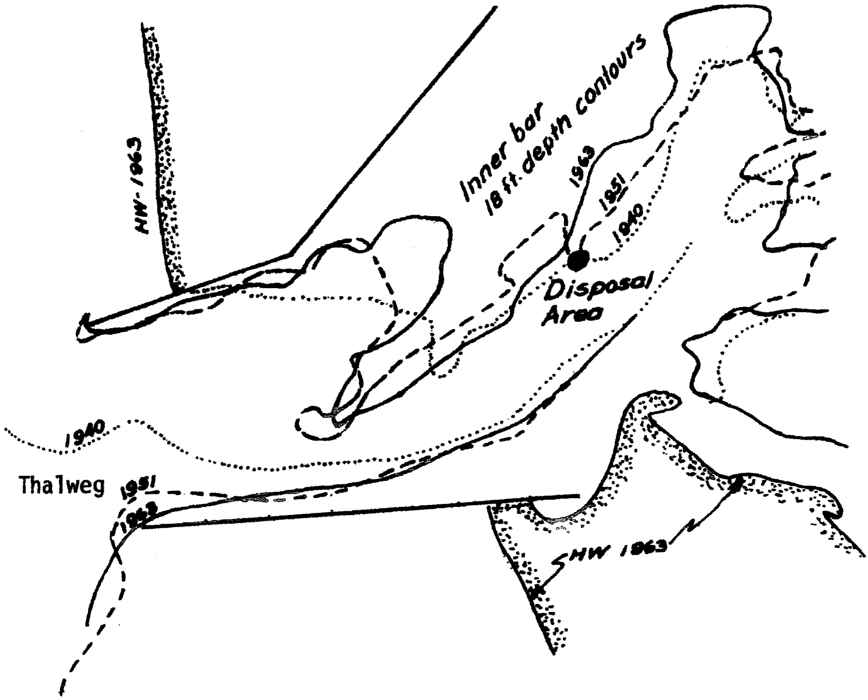


FIGURE 7-2. Grays Harbor Channel Migration (Committee on Tidal Hydraulics, Corps of Engineers, 1995).

7.4 PIANC METHOD

The concept design guidance given in PIANC (1997) page 14 follows.

"Channel alignment should be assessed with regard to:

- the shortest channel length;
- conditions/basins, and so on, at either end of the channel;
- the need to avoid obstacles or areas of accretion, which are difficult or expensive to remove or require excessive (and, hence, costly) maintenance dredging;
- prevailing winds, currents, and waves;
- avoiding bends close to port entrances;
- the edge of the channel should be such that ships passing along it do not cause disturbance or damage.

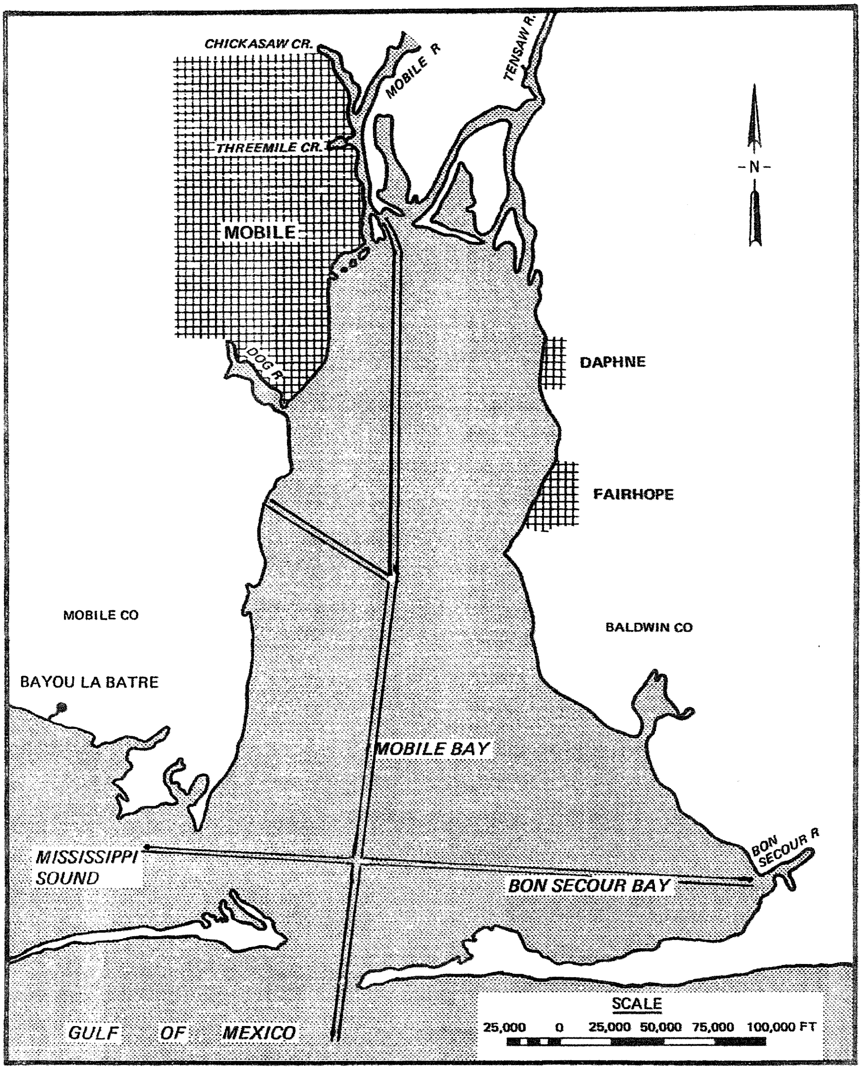


FIGURE 7-3. Straight Ship Channel (From Lieutenant (jg) B. McCartney).

Straight channel legs are preferable to curved ones. The designer should strive for an alignment consisting of a series of straight legs connected by smooth bends, and not abrupt angles. Individual legs may have different widths and depths and should be navigated at different speeds.

It is preferable to have the prevailing currents aligned with the channel to minimize cross currents and to avoid large gradients in cross current along the channel. This also applies to wind and waves, although these may come from any direction. Usually, the prevailing wind and wave direction are considered in design, with a judgment on whether possible downtimes as a result of strong winds or high waves from other directions are acceptable.

Finally, it is advisable (and important in the case of channels navigated by ships carrying dangerous goods) that the channel be aligned to prevent the ship heading directly at the quay or jetty during its approach. Any channel whose direction is perpendicular to the berthing face should be aligned to one side of the quay or jetty, so that a ship must turn (or be swung) to arrive at the berth. This minimizes the risk of ships demolishing the jetty or quay in the event of losing all control on the approach."

The use of vessel simulators to finalize channel alignment is recommended for the detailed design phase.

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Chapter 8
CHANNEL WIDTHS

8.1 GENERAL

Channel widths should be designed to provide for the safe and efficient movement of vessels that are expected to use the channel. The minimum channel width will depend on the size and maneuverability of the vessels, channel shape and alignment, traffic congestion, wind, waves, currents, visibility, quality and spacing of navigation aids, and whether one-way or two-way traffic is required. Width of the channel is measured at the bottom of the slope at the design depth. In accordance with Section 5 of the Rivers and Harbors Act approved on March 4, 1915, ". . . . the channel dimensions specified shall be understood to admit of such increases at entrances, bends, sidings and turning places as may be necessary to allow free movement of boats." Channel widths have to provide for the width of the maneuvering lane, clearances between vessels when passing, and bank clearances, particularly in restricted channels. Additional clearances will be required in channel entrances and in channel bends. The elements of channel width analysis are shown in Figure 8-1.

The bank clearance width, maneuvering lane width, and ship clearance width are expressed as multiples of the ship beam, as shown in Tables 8-1 through 8-7. For example, in Table 8-1, the maneuvering lane width for a vessel with good controllability in a straight channel would be 160% of the beam, or 1.6B. If the design vessel has a beam (B) of 100 ft, then the maneuvering lane width would be 160 ft (1.6B).

8.2 MANEUVERING LANE

The maneuvering lane is that portion of the channel width within which the vessel might deviate from a straight line without encroaching on the safe bank clearance or entering a zone that would cause danger to passing ships.

TABLE 8-1. Minimum Channel Width Values (EM 1110-2-1613, 83).

Minimum Channel Width in Percent of Beam (Ship Beam Multipliers)				
	Vessel Controllability			
Location	Very Good	Good	Poor	Channels with Yawing Forces
Maneuvering lane, straight channel	160(1.6B)	180(1.8B)	200(2.0B)	*Judgment
Bend, 26-degree turn	325(3.25B)	370(3.7B)	415(4.15B)	*Judgment
Bend, 40-degree turn	385(3.85B)	440(4.4B)	490(4.9B)	*Judgment
Ship clearance	80(0.8B)	80(0.8B)	80(0.8B)	100 but not less than 100 feet
Bank clearance	60(0.6B)	60 plus (0.6+B)	60 plus (0.6+B)	150(1.5B)

*Judgment will have to be based on local conditions at each project.

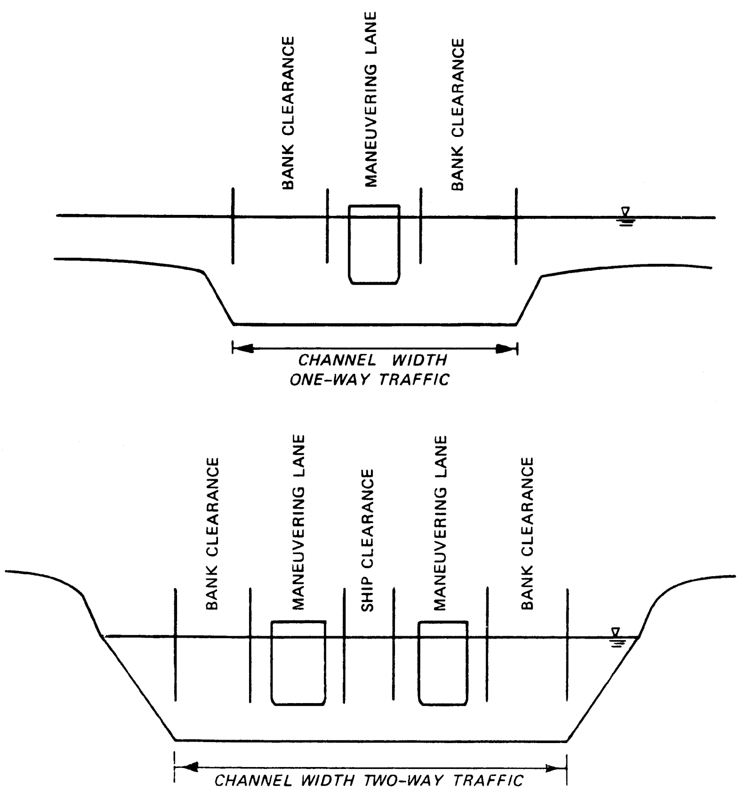

FIGURE 8-1. Channel Width Elements (ASCE Manual No. 80).

8.3 SHIP CLEARANCE

To avoid interference and danger of collision, a clearance lane is needed between maneuvering lanes for channels designed for two-way traffic.

8.4 BANK CLEARANCE

Bank clearance is the horizontal distance between the adjacent maneuvering lane edge and the bottom of the channel side slopes.

8.5 CHANNEL TYPES

Two-way traffic channels allow free movement of vessels. Figure 8-2 shows an example of a two-way traffic channel.

One-way traffic channel segments are used where excavation of a larger channel would be very expensive or traffic volume is low. Figure 8-3 shows a one-way traffic channel.

The Suez Canal is an example of a one-way channel. The 121-mi-long canal has long one-way segments with several passing bays. When it opened, the canal had a 72-ft bottom width, 190-ft surface width, and 26-ft

FIGURE 8-2. Two Lakers Passing in the St. Clair River, Michigan (COE, Digital Visual Library).

FIGURE 8-3. 1,000-Foot Laker in the Rock-Cut Portion of the St. Mary's River, Michigan (COE–Digital Visual Library).

depth. The current canal dimensions are 197-ft bottom width and 58-ft depth with several passing segments. The long-term plan is to continue deepening the canal to an eventual depth of 92 ft.

8.6 PRELIMINARY DESIGN GUIDELINES FOR STRAIGHT SEGMENTS

Several guidelines have been developed to select the appropriate channel width elements. These guidelines are applicable for preliminary design (i.e., concept design). Final design should rely on vessel simulation studies and other computer programs for appropriate channel-width selection.

Both preliminary and final designs normally assume that the vessel (or vessels) are guided by a competent pilot or captain and that the vessel is in good operational condition (i.e., it has had no vessel breakdowns). However, simulations can be used to evaluate blackout (breakdown) scenarios to investigate how serious the consequences could be.

The U.S. Army Corps of Engineers used the values presented in Table 8-1 for preliminary design and final design from the 1960s until the development of computer simulation models in the 1980s.

These values were first presented in Report No. 3 of the Committee on Tidal Hydraulics, U.S. Army Corps of Engineers, May 1965, "Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena."These values were again presented in EM 1110-2-1613, Hydraulic Design of Deep-Draft Navigation Projects, April 8, 1983.

Some recent work by the Corps (2nd Ed of EM 1112-1613, 2002, Draft awaiting publication) using information generated from ship simulation studies suggested the minimum channel widths presented in Table 8-2.

The canal- and trench-type channels are shown in Figure 8-4.

TABLE 8-2. Minimum Channel Width Values with No Wave Effects (EM 1110-2-1613, 2002 Draft).

	Maximum Current, Knots		
Design Ship Beam Multipliers—One-Way Traffic			
Channel Cross-Section	0.0 to 0.5	0.5 to 1.5	1.5 to 3.0
Best Aids to Navigation			
Shallow—constant cross-section	3.0	4.0	5.0
Canal—constant cross-section	2.5	3.0	3.5
Trench—constant cross-section	2.75	3.25	4.0
Average Aids to Navigation			
Shallow—variable cross-section	3.5	4.5	5.5
Canal—variable cross-section	3.0	3.5	4.0
Trench—variable cross-section	3.5	4.0	5.0
Design Ship Beam Multipliers—Two-Way Traffic			
Uniform Channel Cross Section	0.0 to 0.5	0.5 to 1.5	1.5 to 3.0
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

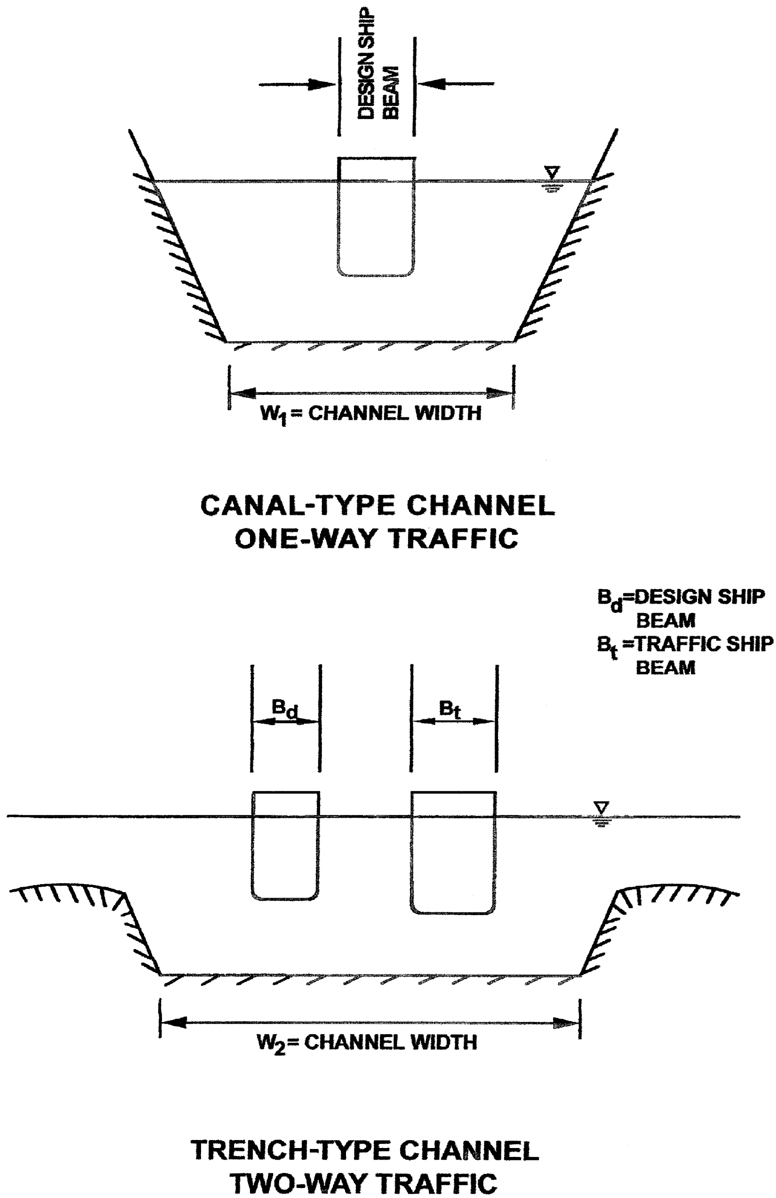

FIGURE 8-4. Canal and Trench Type Channels (EM 1110-2-1613, 2002 Draft).

TABLE 8-3. Basic Maneuvering Lane Width (PIANC, 1997, page 20).

Ship Maneuverability	Good	Moderate	Poor
Basic Maneuverability Lane Width	1.3 B	1.5 B	1.8 B

A third set of values for channel-width selection is presented in PIANC report "Approach Channels, A Guide for Design" Supplement to Bulletin No. 95, June 1997 (see Table 8-3).

These values assume a straight canal as well as favorable environmental (wind and wave) and operational conditions. Additional width allowances can be estimated by the factors presented in Table 8-4. These factors are intended to compensate for less than perfect conditions.

The passing distance (ship clearance) width element is show in Table 8-5.

Bank clearance is shown in Table 8-6.

A comparison of these three suggested preliminary design values is shown in Table 8-7. This comparison assumes very good environmental and operational conditions, moderate vessel speed, no hazardous cargo, and a water-depth-to-ship draft ratio of between 1.5 and 1.15.

This comparison shows good agreement for preliminary (concept) design use.

8.7 PRELIMINARY DESIGN GUIDELINES FOR CHANNEL BENDS

8.7.1 General

The swept path of a ship that is making a turn is wider than its swept path in a straight channel simply because of the ship's geometry. Experience has shown that controllability of a ship while it is turning is degraded compared to its maneuverability in a straight channel, thus causing a wider swept path. The width of the swept path is dependent on the following factors:

- Ship yaw angle when turning
- Length and beam of the ship
- Ship rudder angle
- Location and spacing of aids to navigation in the turn
- 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 the reduction in sight distance, the reduced effectiveness of aids to navigation, the changing channel cross-sectional area, and the greater effect from varying current and bank suction forces.

TABLE 8-4. Additional Widths for Straight Channel Sections (PIANC, 1997, page 21).

Width W_I	Vessel Speed	Outer Channel Exposed to Open Water	Inner Channel Protected Water
(a) Vessel speed (knots)			
- fast > 12		0.1 B	0.1 B
- moderate > 8–12		0.0	0.0
- slow 5–8		0.0	0.0
(b) Prevailing cross-wind (knots)			
- mild ≤ 15 (≤Beaufort 4)	all	0.0	0.0
- moderate > 15–33	fast	0.3 B	—
(>Beaufort 4–Beaufort 7)	moderate	0.4 B	0.4 B
	slow	0.5 B	0.5 B
- severe > 33–48	fast	0.6 B	—
(>Beaufort 7–Beaufort 9)	moderate	0.8 B	0.8 B
	slow	1.0 B	1.0 B
(c) Prevailing cross-current (knots)			
- negligible < 0.2	all	0.0	0.0
- low 0.2–0.5	fast	0.1 B	—
	moderate	0.2 B	0.1 B
	slow	0.3 B	0.2 B
- moderate > 0.5–1.5	fast	0.5 B	—
	moderate	0.7 B	0.5 B
	slow	1.0 B	0.8 B
- strong > 3	fast	0.7 B	—
	moderate	1.0 B	—
	slow	1.3 B	—
(d) Prevailing longitudinal current (knots)			
- low ≤ 1.5	all	0.0	0.0
- moderate > 1.5–3	fast	0.0	—
	moderate	0.1 B	0.1 B
	slow	0.2 B	0.2 B
- strong > 3	fast	0.1 B	—
	moderate	0.2 B	0.2 B
	slow	0.4 B	0.4 B

TABLE 8-4. (Continued)

Width W_I	Vessel Speed	Outer Channel Exposed to Open Water	Inner Channel Protected Water
(e) Significant wave height H_s and length λ(m)			
- $H_s \leq 1$ and $\lambda \leq L$	all	0.0	0.0
- $3 > H_s > 1$ and $\lambda = L$	fast	$\approx$ 2.0 B	
	moderate	$\approx$ 1.0 B	
	slow	$\approx$ 0.5 B	
- $H_s > 3$ and $\lambda > L$	fast	$\approx$ 3.0 B	
	moderate	$\approx$ 2.2 B	
	slow	$\approx$ 1.5 B	
(f) Aids to Navigation			
- excellent with shore traffic control		0.0	0.0
- good		0.1 B	0.1 B
- moderate with infrequent poor visibility		0.2 B	0.2 B
- moderate with frequent poor visibility		$\geq$0.5 B	$\geq$0.5 B
(g) Bottom surface			
- if depth $\geq$ 1.5T		0.0	0.0
- if depth < 1.5T then			
- smooth and soft		0.1 B	0.1 B
- smooth or sloping and hard		0.1 B	0.1 B
- rough and hard		0.2 B	0.2 B
(h) Depth of waterway			
- $\geq$1.5T		0.0	$\geq$1.5T 0.0
- 1.5T-1.25T		0.1 B	<1.5T-1.15T 0.2 B
- <1.25T		0.2 B	<1.15T 0.4 B
(i) Cargo hazard level			
- low		0.0	0.0
- medium		$\approx$ 0.5 B	$\approx$ 0.4 B
- high		$\approx$ 1.0 B	$\approx$ 0.8 B

TABLE 8-5. Additional Width for Passing Distance in Two-Way Traffic (PIANC, 1997, page 22).

Width for Passing Distance, W_p	Outer Channel Exposed to Open Water	Inner Channel Protected Water
Vessel speed (knots)		
- fast > 12	2.0 B	—
- moderate > 8–12	1.6 B	1.4 B
- slow 5–8	1.2 B	1.0 B
Encounter traffic density		
- light	0.0	0.0
- moderate	0.2 B	0.2 B
- heavy	0.5 B	0.4 B

TABLE 8-6. Additional Width for Bank Clearance (PIANC, 1997, page 22).

Width for Bank Clearance (W_{Br} or W_{Bg})	Vessel Speed	Outer Channel Exposed to Open Water	Inner Channel Protected Water
Sloping channel edges and shoals:	Fast	0.7 B	—
	Moderate	0.5 B	0.5 B
	Slow	0.3 B	0.3 B
Steep and hard embankments, structures:	Fast	1.3 B	—
	Moderate	1.0 B	1.0 B
	Slow	0.5 B	0.5 B

Note: B = Beam, L = Length, T = Draught, for Tables 8-4, 8-5, and 8-6.

TABLE 8-7. Comparison of Corps 83, Corps 02, PIANC 97 Methods.

Method	Traffic	Bank	Maneuvering Lane	Ship Clear	Maneuvering Lane	Bank	Channel Total Width
Corps	One way	0.6 B	1.6 B			0.6 B	2.8 B
1983	Two way	0.6 B	1.6 B	0.8 B	1.6 B	0.6 B	5.2 B
Corps	One way						3.0 B
2002	Two way						5.0 B
PIANC	One way	0.5 B	1.5 B			0.5 B	2.5 B
1997	Two way	0.5 B	1.5 B	1.4 B	1.5 B	0.5 B	5.4 B

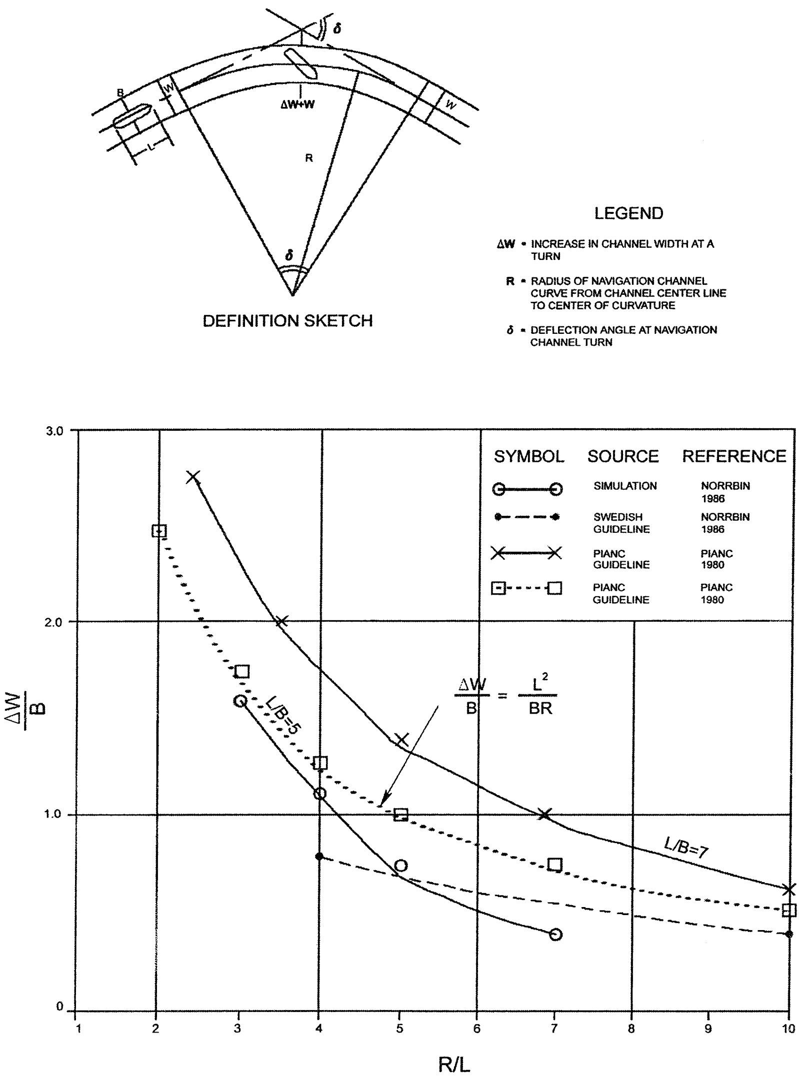

FIGURE 8-5. Channel Width Increase in Turns (EM 1110-2-1613, 2002 Draft).

8.7.2 Channel Width in Turns

Because the swept path of a ship making a turn is wider than its path in a straight channel reach, a greater channel width is required in turns and bends. The swept path of a turning ship depends mainly on the channel turn radius and the ship length. Figure 8-5 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 also may be a factor. Because pilots often use the bank effects to assist in a turn, the bank conditions also are very important to the design of the turn. However, the recommended turn design does not include bank effects. The graph shown in Figure 8-5 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 maneuver hydrodynamically around a sharper turn.

8.7.3 Turn Design

The increase in channel turn width shown in Table 8-8 can be designed in several ways. Recommendations for specific turn types varying from a straightforward (unwidened) angle to connecting circular arcs also are presented in Table 8-8 as a function of the turn deflection angle. The deflection angle in deep-draft channels is defined as the angle of the turn, not the angle between the vessel and the channel. 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. These configurations are shown on Figure 8-6. Alternatively, multiple straight lines can be used to replace the single line on the inside of the turn. In some cases, the outer point also can be cut off, because ships would not use the outer turn apex. The apex turn

TABLE 8-8. Recommended Channel Turn Configurations (EM 1110-2-1613, 2002 Draft).

Deflection Angle, Deg	Ratio of Turn Radius Ship Length	Turn Width Increase (Factor × Ship Beam)	Turn Type
0~~1~~0	0	0	Angle
10~~2~~5	3~~5~~	2.0~~1~~.0	Cutoff
25~~3~~5	5~~7~~	1.0~~0~~.7	Apex
35~~5~~0	7~~1~~0	0.7~~0~~.5	Curved
>50	>10	0.5	Circle

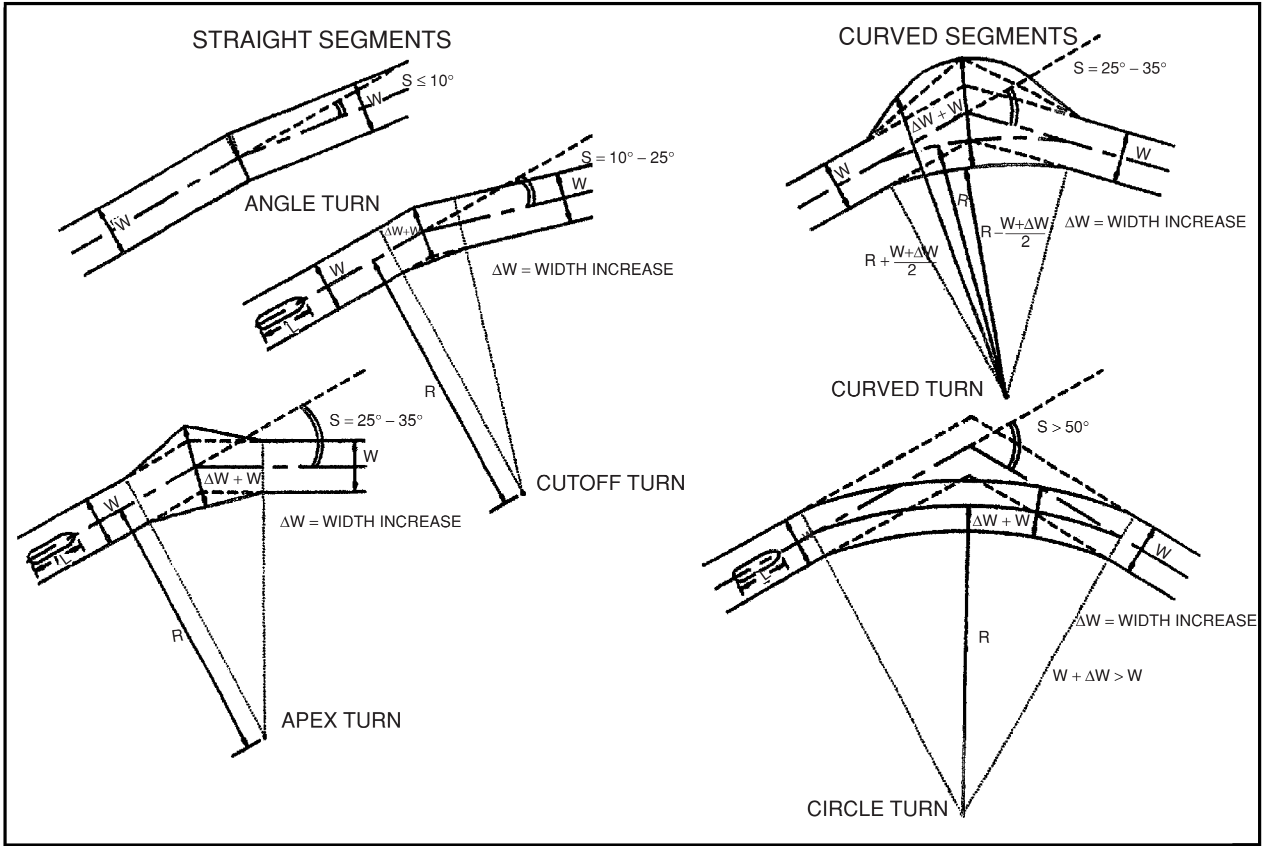

FIGURE 8-6. Recommended Channel Turn Configurations (EM 1110-2-1613, 2002 Draft).

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.

8.7.4 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. A straight segment of at least five times the design ship length 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.

8.8 CHANNEL WIDTH FINAL DESIGN

Selection of the channel widths (both straight and bend segments) should utilize site specific vessel simulator studies. An example of simulation studies for final design is the Houston ship channel enlargement project. These studies were run with the help of local ship pilots to assure accuracy and credibility.

Three scenarios were tested:

1. Existing conditions: 400 ft wide $\times$ 40 ft deep for model validation
2. Phase I: 530 ft wide $\times$ 45 ft deep channel (design ships 156 and 140 ft beams)
3. Phase II: 600 ft wide $\times$ 50 ft deep channel (design ships 173 and 140 ft beams)

Preliminary channel width guidance given in Table 8-7 for the Corps 1983 method indicates minimum channel width of 5.2B for two-way traffic with ideal conditions. This would result in the following preliminary channel design width:

Phase I Average Beam Width $\dfrac{156 + 140}{2} = 148$ ft

Preliminary Channel Width $148 \times 5.2 = 769.6$ ft

Phase II Average Beam Width $\dfrac{173 + 140}{2} = 157$ ft

Preliminary Channel Width $157 \times 5.2 = 816.4$ ft

The simulations show that the Phase I 530-ft wide and Phase II 600-ft wide channels were adequate for safe two-way vessel traffic. Therefore, considerable channel excavation was saved; however, this was only after numerous ship simulation runs using local pilots. Additional information on ship simulation studies and the Houston ship channel enlargement studies is presented in Chapter 15.

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Chapter 9
SEDIMENTATION

It is crucial to accurately predict sedimentation in a proposed navigation channel in order to determine the economics of the project (maintenance dredging cost) and reliability and duration of project depths.

9.1 NATIVE SOILS

Native soils must be considered, first, from the standpoint of channel construction. Problem soils encountered in channel construction include consolidated clays, cemented sands, or outcroppings of bedrock. These materials may require special dredging equipment, techniques, and disposal, and, thus, will 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 also must be considered from the standpoint of maintenance dredging following project construction. The presence 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. Surface sediment sampling should be conducted throughout the project area, and core borings 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.

9.2 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 or suspended load, and silts and clays carried as suspended load. When the project channel includes the zone in which 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 the velocity 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 are the reason why maintenance dredging for control is required. The finer sands and silts usually will be deposited in the lower reaches of the navigation project, but the deposition usually will 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. Deposition of clay particles depends on the hydrodynamics and water characteristics of the lower reaches of the navigation project. If the project is in an estuarine setting in which salty water from the ocean can mix with the sediment-carrying riverine waters (e.g., Savannah Harbor) a phenomenon known as flocculation occurs, whereby clay particles aggregate into larger and heavier flocs that are likely to deposit. In some instances, very heavy concentrations of flocs remain in suspension in a layer near the bottom. This is referred to as fluff or fluid mud. Before 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 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 throughout the areas of clay particle deposition.

9.3 RIVER REACHES

In cases in which 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, Louisiana, 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.

9.4 LITTORAL SEDIMENTS

Sediments are introduced into the navigation project from the littoral systems that exist in all lakes and oceans. Near shore, currents driven by waves, wind, or tides 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.

9.5 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 the collection of prototype data, such that future behavior can be extrapolated or developed into general design principles and 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. However, it is not possible to accurately predict deposition volumes. Numerical modeling of sedimentation phenomena has become a relatively well-developed technique, which 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 that involve the application of physical and numerical models may be used, as well as prototype data and analytical procedures to take advantage of the strong points of each technique.

9.6 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 also needed for river expansions caused by port facilities and turning basins.

9.7 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.

9.8 SOURCE

This information was taken from EM1110-2-1613, 2002 Draft.

Chapter 10

DREDGING AND DISPOSAL

10.1 DREDGES

Dredges used for ship-channel dredging fall into two categories: hydraulic and mechanical.

Hydraulic dredges use pumps and pipes to pull channel-bottom sediment up to the dredge, where it is held for later disposal or pumped through a pipeline to a disposal site. Self-propelled hopper dredges and cutter-head pipeline dredges are the most common hydraulic dredges.

Mechanical dredges, such as clamshell and dipper dredges, lift bottom sediment using a bucket/crane arrangement.

10.2 HOPPER DREDGES

Hopper dredges are self-propelled seagoing ships of from 180 to 550 ft long, with the hulls and lines of ocean vessels (Figure 10-1, a and b).

They are equipped with propulsion machinery, sediment containers (hoppers), dredge pumps, and other special equipment required to perform the essential function of removing material from a channel bottom or ocean bed. Hopper dredges have propulsion power that is adequate for required free-running speed and dredging against strong currents and excellent maneuverability for safe and effective work in rough, open seas. Dredged material is raised by dredge pumps through drag arms connected to drags in contact with the channel bottom and is discharged into hoppers built in the vessel. Hopper dredges are classified according to hopper capacity. Large-class dredges have hopper capacities of 6,000 cu yd or greater, medium-class hopper dredges have hopper capacities of 2,000 to 6,000 cu yd, and small-class hopper dredges have hopper capacities of from less than 2,000 to 500 cu yd. During dredging operations, hopper dredges travel at a ground speed of from 2 to 3 mph and can dredge in depths of about 10 to over 80 ft. They are equipped with twin propellers a.

b.

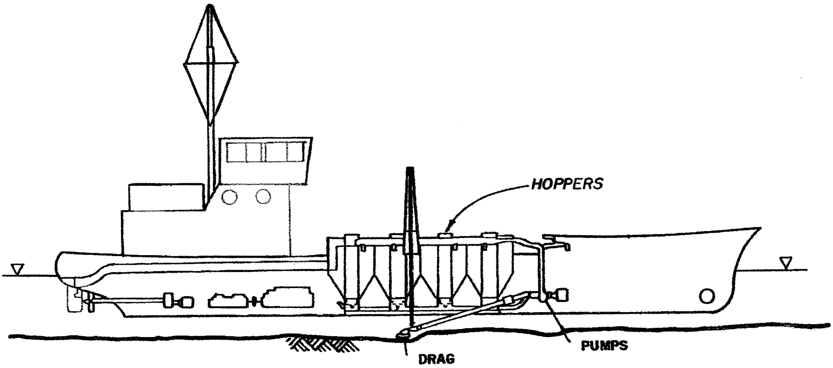

FIGURE 10-1. Self-propelled Seagoing Hopper Dredge (COE Portland District, Dredge Biddel).

and twin rudders which provide the required maneuverability. Table 10-1 gives available specifications for vessels in the Corps hopper dredge fleet at the time of writing (2004). Nongovernment hopper dredges generally are larger, with capacities of up to 32,000 cu yd.

Operation of a seagoing hopper dredge involves greater effort than that required for an ordinary ocean cargo vessel, not only because of the needs of navigation of a self-propelled vessel but also because the needs

TABLE 10-1. Characteristics of Corps of Engineers Hopper Dredges.

Name	Hopper Capacity Cu Yd	Draft Loaded	Dredging Depth Max	Vertical Clearance Required	Special Capability
Essayons	6000	27′	80′	—	Direct Pumpout
Wheeler	8400	29′ 5″	80′	—	Direct Pumpout
Yaquina	825	12′	45′	—	Direct Pumpout
Macfarland	3140	22′ 0″	55′	90′	Direct Pumpout/ Sidecasting

associated with its dredging purposes must be satisfied. Dredging is accomplished by progressive traverses over the area to be dredged. Hopper dredges are equipped with large centrifugal pumps similar to those employed by other hydraulic dredges. Suction pipes (drag arms) are hinged on each side of the vessel with the intake (drag) extending downward toward the stern of the vessel. The drag is moved along the channel bottom as the vessel moves forward at speeds up to 3 mph. The dredged material is sucked up the pipe and deposited and stored in the hoppers of the vessel. Once fully loaded, hopper dredges move to the disposal site to unload before resuming dredging. Unloading is accomplished either by opening doors in the bottoms of the hoppers and allowing the dredged material to sink to the open-water disposal site or by pumping the dredged material to upland disposal sites. Because of the limitations on open-water disposal, most hopper dredges have direct pumpout capability for disposal in upland, confined sites. Before environmental restrictions were in place, the primary objective for operating hopper dredges was to obtain the maximum economic load; that is, to remove the maximum quantity of material from the channel prism in the shortest pumping time.

An example of disposal at designated sites at sea is shown in Figure 10-2.

Hopper dredge disposal also can be at a dispersive site in or near a naturally deep portion of the ship channel. Dredged material deposited at these sites will be carried out to sea on the ebb current. Figure 10-3 shows these sites at the Grays Harbor project.

Another disposal option for a hopper dredge is the overflow method. The dredged material from the channel bottom is pumped, then allowed to overflow back into the water column. This method is effective where strong river currents transport sediment seaward, such as in the Mississippi River channel.

FIGURE 10-2. Hopper Dredge Splits Its Hull in Gulf of Mexico near Galveston, Texas (COE, Digital Visual Library).

10.3 HYDRAULIC PIPELINE DREDGE

The hydraulic pipeline cutterhead suction dredge is the most commonly used dredging vessel and is generally the most efficient and versatile (Figure 10-4). It performs the major portion of the dredging workload in the United States. Because it is equipped with a rotating cutter apparatus surrounding the intake end of the suction pipe, it can efficiently dig and pump all types of alluvial materials and compacted deposits, such as clay and hardpan. This dredge can pump dredged material long distances to upland disposal areas.

The cutterhead dredge is generally equipped with two stern spuds used to hold the dredge in working position and to advance the dredge into the cut or excavating area. During operation, the cutterhead dredge swings from side to side alternately using the port and starboard spuds as a pivot. Cables attached to anchors on each side of the dredge control lateral movement. Forward movement is achieved by lowering the starboard spud after the port swing is made and then raising the port spud. The dredge is then swung back to the starboard side of the cut centerline. The port spud is lowered and the starboard spud lifted to advance the dredge. The excavated material may be disposed of in open water or in confined

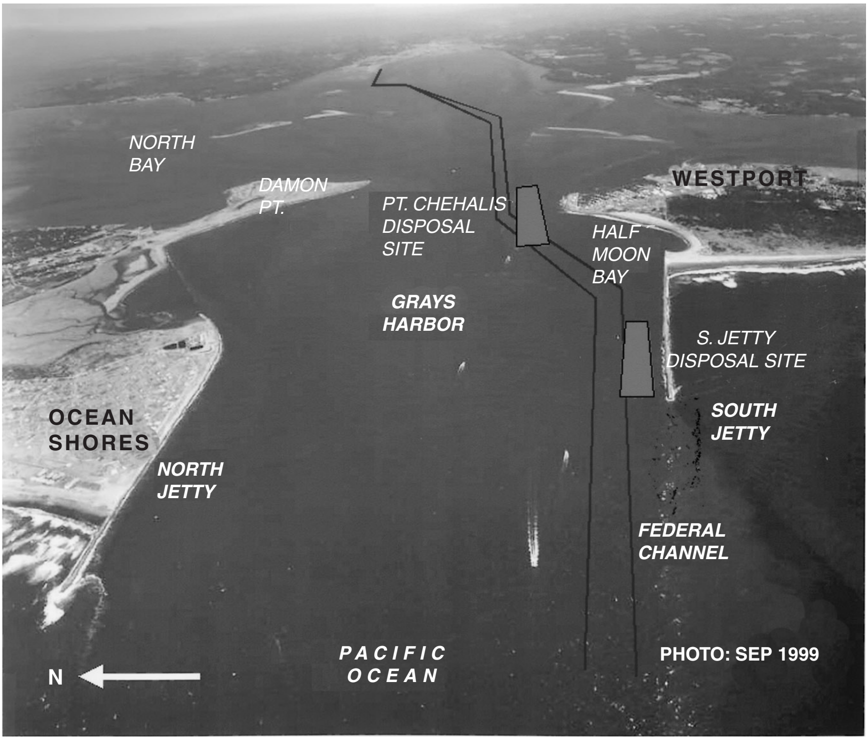

FIGURE 10-3. Dredged Material Disposal Sites, Grays Harbor, Washington (COE, Seattle District).

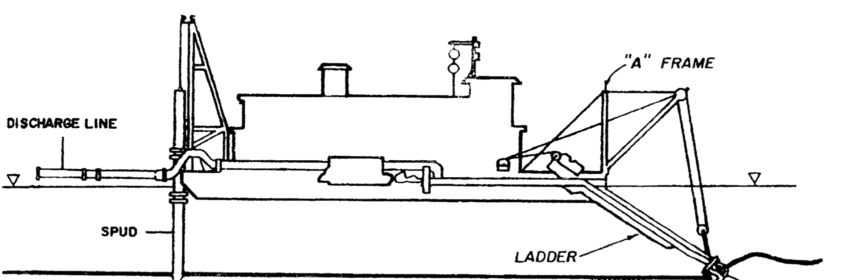

FIGURE 10-4. Hydraulic Pipeline Cutterhead Dredge Components (EM 1110-2-5025, 1983).

FIGURE 10-5. Dredging Sacramento Ship Channel (COE, Digital Visual Library).

disposal areas located upland or in the water. In open-water disposal, only a floating discharge pipeline, made up of sections of pipe mounted on pontoons and held in place by anchors, is required. Additional sections of shore pipeline are required when upland disposal is used. In addition, the excavated materials may be placed in hopper barges for disposal in open water or in confined areas that are remote from the dredging area. In cutterhead dredging, the pipeline transport distances usually range up to about 3 miles. For commercial land reclamation or fill operations, transport distances are generally longer, with pipeline lengths reaching as far as 15 miles, for which the use of multiple booster pumps is necessary. Figure 10-5 shows a hydraulic pipeline cutterhead dredge in action.

10.4 DUSTPAN AND SIDECASTING DREDGES

Dustpan and sidecasting dredges are specialized versions of the hydraulic-type dredge. They can only discharge into open water adjacent to the navigation channel. Details of these and the hopper and pipeline dredges are presented in EM 1110-2-5025, "Dredging and Dredged Material Disposal," March 25, 1983.

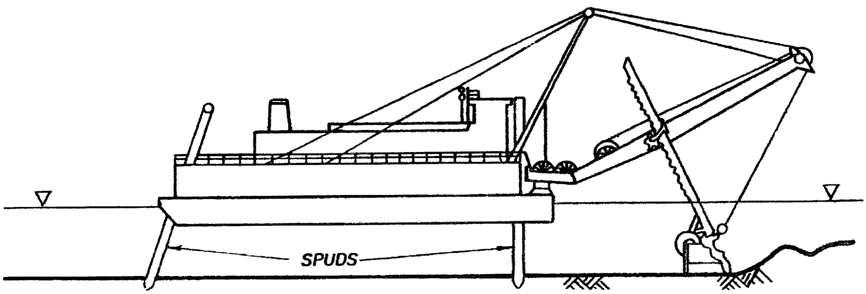

FIGURE 10-6. Dipper Dredge (EM 1110-2-5025, 1983).

10.5 MECHANICAL DREDGES

The two major types of mechanical dredges are the dipper and bucket dredges. The dipper dredge is basically a barge-mounted power shovel. It is equipped with a power-driven ladder structure and operated from a barge-type hull. A schematic drawing of the dipper dredge is shown in Figure 10-6. A bucket is firmly attached to the ladder structure and is forcibly thrust into the material to be removed. To increase digging power, the dredge barge is moored on powered spuds that transfer the weight of the forward section of the dredge to the bottom. Dipper dredges can work in depths of up to 50 ft. Although there is a great variability in production rates, dipper dredges routinely achieve 30 to 60 cycles per hour.

The best use of the dipper dredge is for excavating hard, compacted materials, rock, or other solid materials after blasting. Although it can be used to remove most bottom sediments, the violent action of this type of equipment may cause considerable sediment disturbance and resuspension during maintenance digging of fine-grained material. There will be a significant loss of the fine-grained material during the hoisting process. The dipper dredge is most effective around bridges, docks, wharves, pipelines, piers, or breakwater structures because it does not require much area to maneuver; there is little danger of damaging the structures as the dredging process can be controlled accurately. No provision is made for dredged material containment or transport, so the dipper dredge must work alongside the disposal area or be accompanied by disposal barges during the dredging operation.

The bucket type of dredge is so named because it utilizes a bucket to excavate the material to be dredged (Figure 10-7). Different types of buckets can perform various types of dredging. The types of buckets used include the clamshell, orangepeel, and dragline, and can be quickly changed to suit operational requirements. The vessel can be positioned and moved within a limited area using only anchors; however, in most cases, anchors and spuds

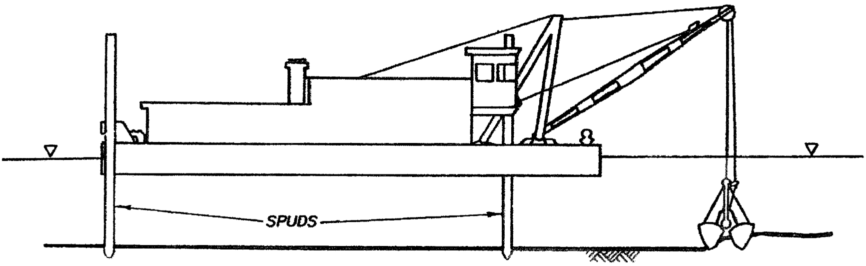

FIGURE 10-7. Bucket Dredge (EM 1110-2-5025, 1983).

are used to position and move bucket dredges. The material excavated is placed in scows or hopper barges that are towed to the disposal areas. The crane is mounted on a flat-bottomed barge, on fixed-shore installations, or on crawler mounts. Twenty to thirty cycles per hour is typical, but large variations exist in production rates because of the variability in depths and materials being excavated. The effective working depth is limited to about 100 ft. Figure 10-8 shows a clamshell dredge in New York Harbor.

FIGURE 10-8. Clamshell Dredge (COE, Digital Visual Library).

10.6 DISPOSAL

Disposal options for dredged material include in-water or diked containment. The in-water methods include the following:

- Open ocean
- In-channel at a dispersal location
- Uncontained site in the estuary
- Returned to water column by agitation or overflow method

Diked containment option can be used for contaminated dredged material and as a way to insure the sediment will not return to the channel.

The development of habitat is one of the beneficial uses of dredged material. The four general categories of habitat options are:

- marsh
- upland
- island
- aquatic

The corps of engineers manual EM 1110-2-5025, "Dredging and Dredged Material Disposal," March 25, 1983, provides detailed coverage of disposal alternatives.

10.7 SOURCE

Most of the information for this chapter was taken from EM 1110-2-5025.

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Chapter 11

JETTIES

11.1 LAYOUT

In order to reduce channel waves and control sediment movement, entrance channel alignment must be carefully oriented. 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 to the selected channel alignment. However, this alignment can be curved to establish a stable deep channel on the outside of the bend. These curved jetties act like a river training system; however, strong tidal or river currents are needed for proper performance. Converging alignments (arrowhead type) often produce an unsatisfactory layout for the following reasons:

1. They are more costly because of their greater length.
2. They allow more wave action in the channel than parallel jetties.
3. They allow channel meandering or poor alignment because they lack the channel-training ability of parallel jetties.

The channel and jetty layout considerations to be taken in to account follow:

1. Natural entrance channels in noncohesive granular material normally are unstable.
2. Parallel aligned twin jetties are generally preferred over arrowhead or single jetties when tidal currents are strong.
3. In certain situations, curved alignment should be considered if there is a significant ebb flow discharge or river discharge. This alignment takes advantage of river hydraulics to discharge and maintain navigation depths on the outside of the bend. Caution should be exercised with such a design, as the channel could undermine the jetty.
4. Straight jetty alignments required closer spacing than a curved alignment to maintain channel depths. Hydraulic model tests are generally advisable for jetty layout to optimize alignment, lengths, and stability of jetty armor.

11.2 SPACING

It is important to consider navigation difficulties that could be encountered because of wave action and poor visibility when planning spacing between jetties. The distance between the inner toes of the jetties should be at least 50% greater than the length of the design vessel and not less than 400 ft. It might not be possible to hold the original alignment following construction, because most tidal entrance channels tend to migrate to an alignment adjacent to one of the jetties. It is usually uneconomical to maintain a channel in a different location from its natural migration tendency; however, if the channel gets too close to the jetty, the structural integrity of the jetty could be threatened, and additional toe protection will be needed. Jetty spacing also should be wide enough to allow safe vessel transit for the design wind, wave, and current conditions.

11.3 LENGTH

As a general rule, jetties should be long enough to extend beyond the littoral drift zone so that sediments and breaking waves do not impact entrance channel navigation. It is also desirable to end the jetty at the bottom contour equal to the entrance channel depth. This is not always

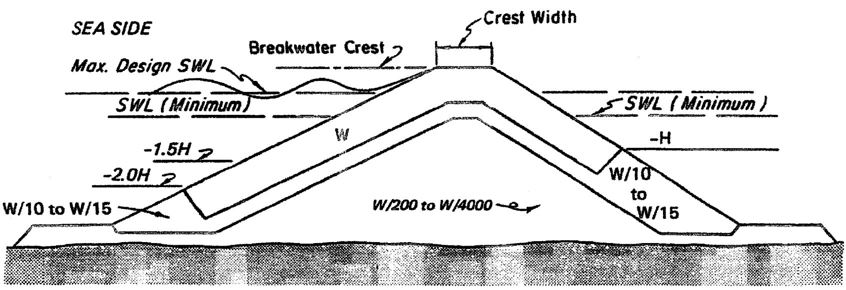
FIGURE 11-1. Coos Bay Jetties, Oregon Coast (COE, Digital Visual Library).

possible when the channel is dredged in a gentle, sloping continental, such as the Gulf of Mexico. A typical jetty configuration is shown in Figure 11-1.

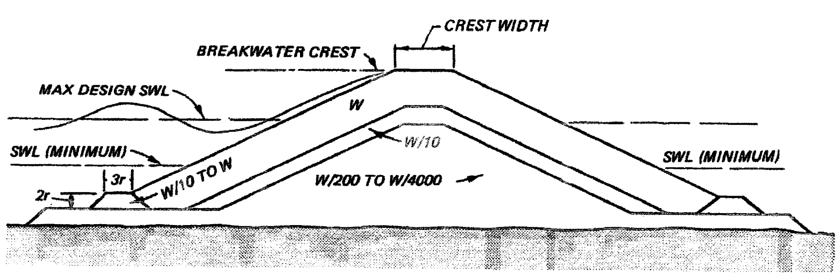
11.4 TYPES

The most common type of jetty is rubble-mound (stone). Cross-sections for this type are shown in Figure 11-2.

Rubble mound structures are usually cost-effective if a suitable rock quarry is accessible. For high wave environments, adequate armor rock might be 20 tons or more. Figure 11-3 shows the size of armor rock needed for repair work on the Oregon Coast.



a. RUBBLE-MOUND SECTION FOR SEAWARD WAVE EXPOSURE WITH ZERO-TO-MODERATE OVERTOPPING CONDITIONS



b. RUBBLE-MOUND SECTION FOR WAVE EXPOSURE FROM BOTH SIDES WITH MODERATE OVERTOPPING

ROCK SIZE	LAYER	ROCK SIZE RANGE (%)
W	PRIMARY COVER LAYER[1]	125 TO 75
W/10	TOE BERM AND FIRST UNDERLAYER[2]	130 TO 70
W/200	SECOND UNDERLAYER	150 TO 50
W/4000	CORE AND BEDDING LAYER	170 TO 30

H = WAVE HEIGHT
W = WEIGHT OF INDIVIDUAL ARMOR UNIT
r = AVERAGE THICKNESS OF ONE LAYER OF MATERIAL (n = 1)

FIGURE 11-2. Typical Rubble-Mound Cross-Sections for Nonbreaking and Breaking Waves (EM 1110-2-2904, 1986).

FIGURE 11-3. Armor Rock for Yaquina Jetty Repair Work (COE, Portland District).

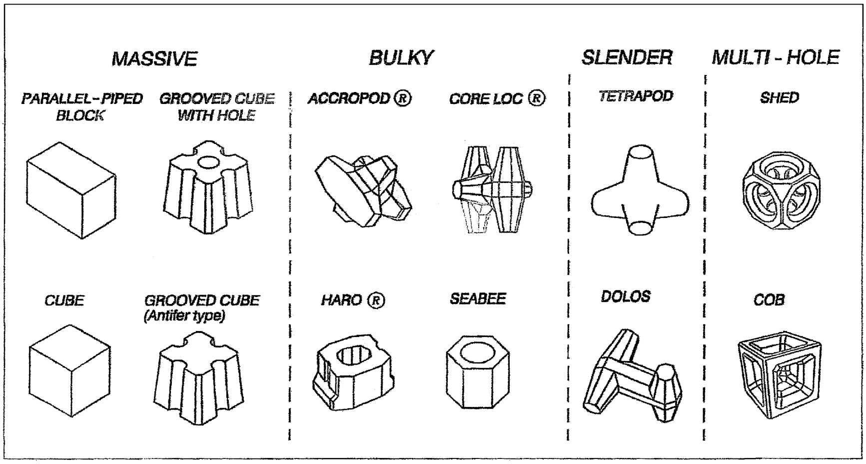


FIGURE 11-4. Examples of Concrete Armor Units (EM 1110-2-1100, Part VI, awaiting publication).

The advantages of rubble-mound jetties include its mass for absorbing wave impacts; its ability to adjust to changes in the sand foundation; and the lack of catastrophic failure, only slow degradation.

In areas where suitable armor rock is not available, precast concrete armor units can be a cost-effective solution. Examples of these types of armor units are shown in Figure 11-4.

The most common concrete unit to be used at the present time is the Dolos. Figure 11-5 shows Dolos units being cast in Tacoma, Washington, for use in a jetty repair in Hawaii. It was more cost-effective to cast these units in the mainland United States and transport them to Hawaii than to ship all the materials to Hawaii and cast them on site.

The latest addition to the concrete armor unit family is the Core Loc (see Figure 11-4). This unit combines the best elements of the Accropod and Dolos. The additional bulk of the Core Loc mitigates the breakage problems with Dolos units.

Another common type of jetty is the cellular type, shown in Figure 11-6. This type has been used in the Great Lakes and Gulf Coast where there are seasons of relatively mild or no wave action. This allows a calm season for construction. This type of jetty can be cost-effective because the cells are filled with sand or gravel.

Composite jetties with a rubble base and concrete or timber crib top have been used in the Great Lakes. Figure 11-7 shows this type of jetty at the entrance to the Port of Duluth.

FIGURE 11-5. Dolos Armor Units Cast in Tacoma, Washington (COE, North Pacific Division).

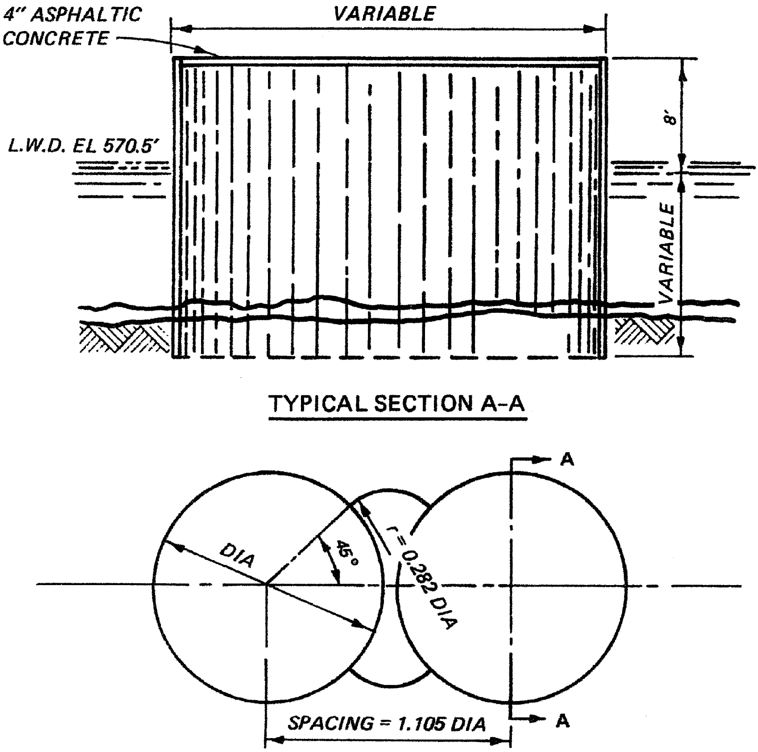


FIGURE 11-6. Cellular Jetty (EM 1110-2-2904, 1986).

FIGURE 11-7. Concrete Composite Jetty at Duluth Harbor (COE, Digital Visual Library).

11.5 SOURCE

Design details and additional information is presented in EM 1110-2-2904, *Design of Breakwaters and Jetties*, 8 August 1986 and EM 1110-2-1100, *Coastal Engineering Manual*, Part VI, Chapter 2, "Types and Functions of Coastal Structures," awaiting publication.

Chapter 12

SHIP LOCKS

Locks often are an integral part of a ship channel. Locks can (1) provide flat pools for waterways with elevation changes; (2) prevent flooding from high water on connecting rivers, storm surges, or high tides; and (3) prevent salinity intrusion. Locks are used in the following situations:

1. *To handle waterway elevation changes:* the Saint Lawrence Seaway, Weiland Canal, and locks at Sault Saint Marie, Michigan, provide navigation from the Atlantic Ocean to Lake Superior, with an elevation increase of 600 ft. The Poe Lock at Sault Saint Marie, Michigan, is shown in Figure 12-1.
2. *To prevent flooding:* the Inner Harbor Locks in New Orleans prevent high Mississippi river stages from flooding a low land area and still provide ship transit from the Gulf of Mexico into the Mississippi River navigation channel. River stages can be as high as 18 ft above the Inner Harbor Navigation Canal water level (Figure 12-2).
3. *To prevent salinity intrusion and stabilize upstream water levels:* the Hiram M. Chittenden Locks in Seattle provide a stable lake level for Lake Union and Lake Washington and a salinity barrier to the salt seawater of Puget Sound. This lock also has special provision to minimize salt water migration into the lakes during lockage (Figure 12-3). Rotterdam and Inchon, Korea, are examples of locks in tidal zones that provide a stable water level upstream from the locks.

Table 12-1 lists the ship locks presently operating in the United States.

Some planned changes to these locks include a replacement of the Davis and Sabine Locks with a single lock that has the same dimensions as the Poe Lock. Also, the Inner Harbor Lock in New Orleans is scheduled to be replaced with a 1,200-ft-long and 110-ft-wide lock at the same site. The Inner Harbor lock planned construction is unique in that lock modules will be fabricated off-site and floated in by barges. The estimated construction start date for this project is October 2006. A photo of the existing site is shown in Figure 12-2.

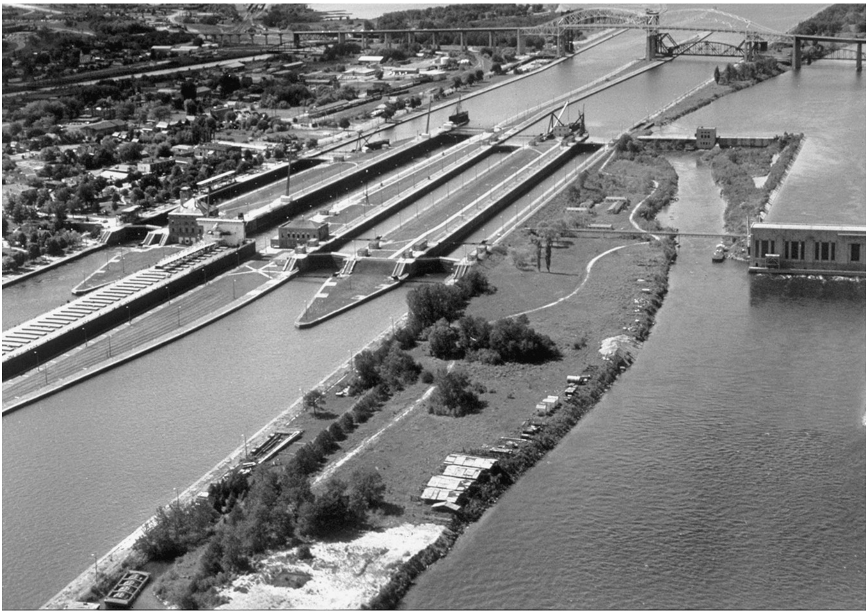


FIGURE 12-1. Soo Locks at Sault St. Marie, Michigan; Ship Departing from Poe Lock (COE, Digital Visual Library).

FIGURE 12-2. Inner Harbor Canal Lock (COE, Digital Visual Library).

TABLE 12-1. Ship Locks in the United States.

Name/ Year Opened	Waterway Location	Width in Feet	Length in Feet	Minimum Depth on Sill in Feet	Normal Lift in Feet
Hiram M. Chittenden (2 locks) 1916	Lake Washington Ship Canal Seattle	80 28	760 123	29 16	26 26
Inner Harbor Navigation Canal 1923	Gulf Intercoastal Water Way New Orleans	75	640	32	9
MacArthur 1943	Connection between Lake Huron and Lake Superior St. Marys River, Mich.	80	800	31	22
Poe 1968	Connection between Lake Huron and Lake Superior St. Marys River, Mich.	110	1200	32	22
Davis 1914	Connection between Lake Huron and Lake Superior St. Marys River, Mich.	80	1350	23	22
Sabine 1919	Connection between Lake Huron and Lake Superior St. Marys River, Mich.	80	1350	23	22

FIGURE 12-3. Hiram M. Chittenden Locks, Seattle, Washington; Large Lock for Ships, Small Lock for Pleasure Craft (COE Seattle District).

The St. Lawrence Seaway/Great Lakes is the most extensive ship channel and lock system in North America. This navigation system is 2,038 nautical miles long and extends from the Atlantic Ocean to Duluth, Minnesota. There are 14 locks at 6 different locations for a total lift of 600 ft. The 15 locks between Lake Erie and the Atlantic are 766 ft long, 80 ft wide, and 30 ft of clearance over the gate sill. The maximum size of vessels using these locks is 740 ft long, 78-ft beam, and 26-ft, 3-in draft.

TABLE 12-2. Ship Lock Comparison.

	Lock Size, Ft		Depth Over	Maximum Ship Size, Length, Ft		
Location	Length	Width	Sill, Ft	Length	Beam	Loaded Draft
St. Lawrence Seaway	766	80	30	740	78	26.25
Poe Locks at Sault St. Marie, MI	1,200	110	32			
Panama Canal	1,000	110	41	950	105.75	39.5*

*Draft in fresh water, less in the dry season

The four parallel locks at Sault St. Marie, Michigan, are of various sizes; the largest is the Poe Lock, which is 1,200 ft long, 110 ft wide, and 32 ft minimum depth over the sill.

In contrast, the Panama Canal locks are 1,000 ft long and 110 ft wide. The maximum size of ships that use this system is 950 ft long, 105.75-ft beam, and 39.5-ft draft in fresh water (smaller in the dry season). Table 12-2 compares these two systems.

Chapter 13
OTHER PROJECT FEATURES

13.1 GENERAL

This chapter covers ship channel features that are found in some but not all projects. These features include the following:

1. Turning basins
2. Anchorage areas
3. Salinity barriers
4. Diversion works
5. Bridges
6. Hurricane barriers
7. Sediment traps
8. Training dikes and revetments
9. Port berthing and maneuvering areas

13.2 TURNING BASINS

In normal operations, turning basins are used by pilots in conjunction with two or more tugs to bring a ship about. Pilots also take full advantage 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, or sometimes both), these will be used to the fullest. The ship engine and rudder, which will provide additional control, are usually manipulated. Care is 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 bridge on the ship. When the bridge is located at or near the stem of the ship, turning will be accomplished using the stern and another visible reference to control and monitor ship position.

Navigation-channel project improvements should provide for a turning basin to enable the ship to reverse direction and to 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 should be designed to provide sufficient area to allow the design ship to turn around using its bow and stern thrusters (if available), and the assistance of the local port tug. Preference in turning basin location should be given to a site with the lowest current effects, which has a major impact on the turning ship, and the size of the turning basin. Figure 13-1 shows recommended shape and size of turning basins in low and high current locations.

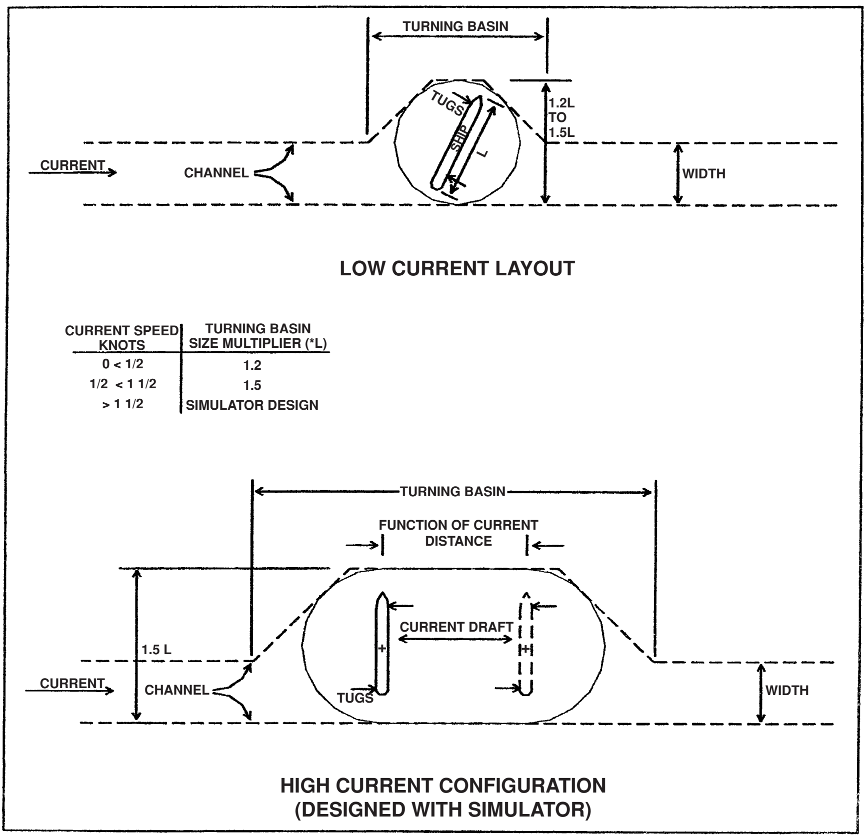


FIGURE 13-1. Turning Basin Alternative Designs (EM 1110-2-1613, 2002 Draft).

13.2.1 Size

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 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 13-1). Turning operations involving empty ships or ships with high sail areas and wind speeds of greater than 25 knots should also be designed using a ship simulator.

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 should be at least equal to the design multiple (1.2 or 1.5, depending on the current) times the ship length. The ends should make angles of 45° 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.

13.2.2 Depth

Normally, the depth of a turning basin should be equal to the channel depth leading to or adjacent to the basin proper to prevent confusion, which could cause grounding accidents. The normal dredging tolerance and advance maintenance allowance are included in the depth of the turning basin.

13.2.3 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.

13.3 ANCHORAGES

Anchorages are provided near the entrance to some ports for vessels waiting for berthing space, undergoing repairs, receiving supplies and crews, waiting for inspection, and lightering off cargo. In cases when a ship must transit a long navigation channel and encounter heavy traffic

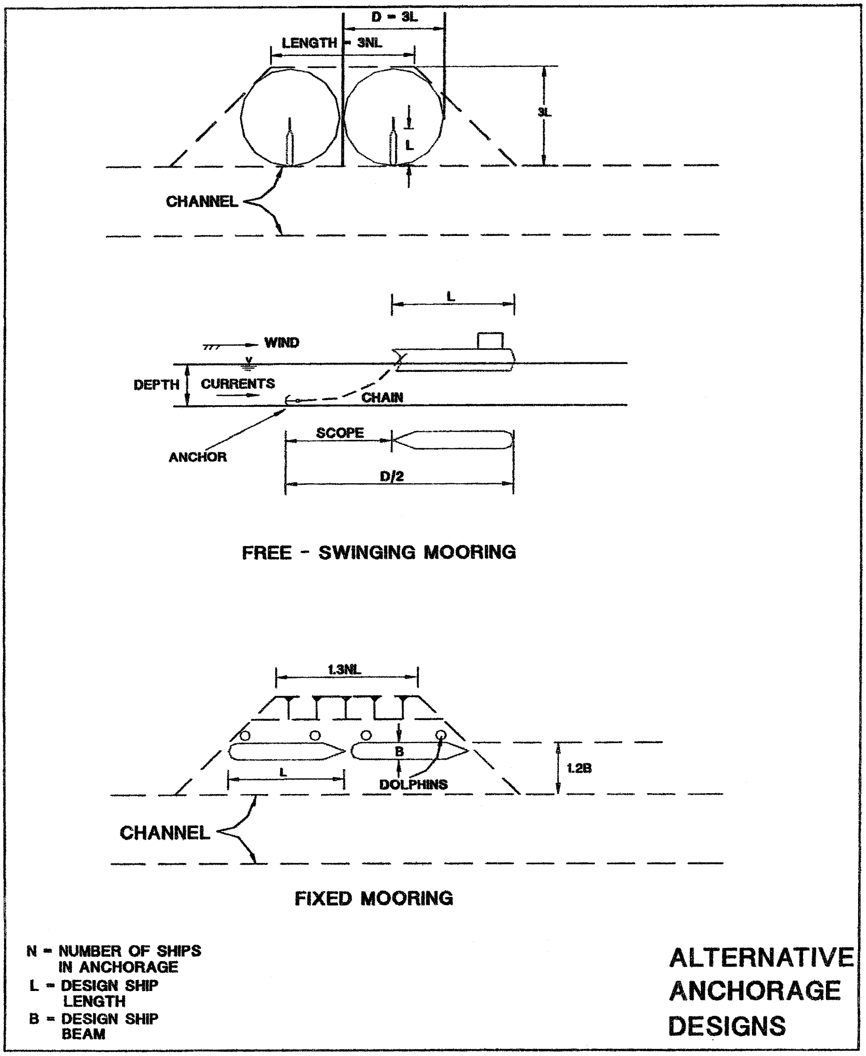


FIGURE 13-2. Alternative Anchorage Designs (EM 1110-2-1613, 2002 Draft).

to get to the port area, additional anchorage also may be provided. As shown in Figure 13-2, the 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, as some ships are not equipped with stern anchors. Free-swinging moorings require a circular area with a radius equal to the length of the ship plus the length of the anchor chain (the scope of the anchor). The U.S. Navy (1981) calculated a set of tables giving these required dimensions, from which the following approximation can be developed for average 50-ft-depth conditions and design ship lengths of 700 to 1,000 ft:

$$D/L = 3.0$$

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 90 ft of anchor drag occurs. Large free-swinging anchorages can be expensive to construct and maintain, as sedimentation frequently becomes a problem. The designer should consider the use of fixed mooring dolphins, which can substantially reduce the dredging area costs. Figure 13-2 presents two design anchorage configurations for two ships with free-swinging and fixed mooring situations.

13.4 SALINITY BARRIERS

13.4.1 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 migrating 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 with regard to lock approach conditions, which should provide adequate distance without waves, turns, and cross-currents. An additional concern is the density-driven salt water admitted into the lock chamber and then into the upper pool during the lockage of vessels for navigation. Several devices and strategies have been developed to deal with this phenomenon including 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.

13.4.2 Submerged Barriers

Barriers can be located at 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

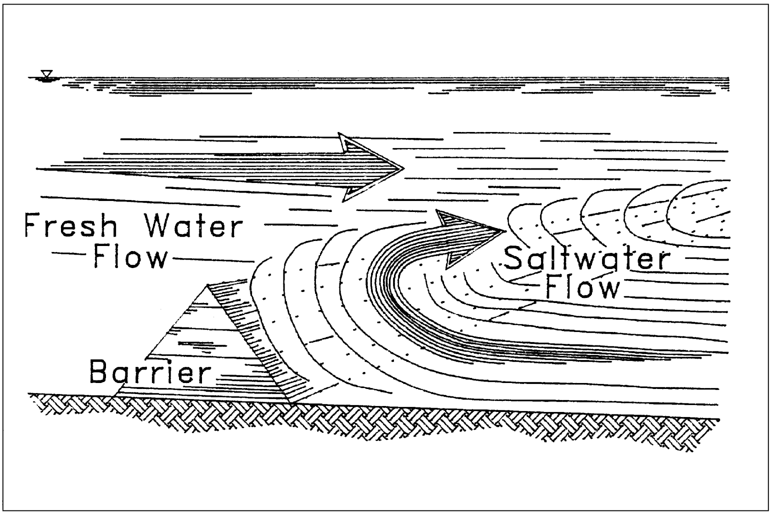


FIGURE 13-3. Saltwater Barrier (ASCE Manual No. 80).

in San Francisco Bay to reduce possible saltwater migration into the San Joaquin Delta. A temporary erodible sill was implemented in the Lower Mississippi River during the 1988 drought to help protect the freshwater supply of New Orleans. The barrier made from dredged material was successful (Figure 13-3). For maximum efficiency, the barriers should be impervious. Rubble-mound structures with an impermeable core and a curtain of impermeable fabric have been suggested and model-tested for submerged salinity barriers, but none has been built to date. The barrier must be submerged low enough to permit safe navigation in the channel; however, its crest can be higher outside the project limits. Inflatable or movable barriers can be lowered to permit passage of shipping, then raised to reduce or eliminate salinity intrusion. Air bubble screens or water jets also may be used in certain situations to minimize the effects of channel deepening on saltwater intrusion.

13.5 DIVERSION WORKS

Diversion works are constructed to separate navigation channels from upland streams and to divert upstream flows. The purpose of the diversion may 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, as well as 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 because potentially major changes in water quality and degradation of navigation conditions from crosscurrents and current increases can result.

13.6 BRIDGES

Ship-channel enlargement projects often need to accommodate wider beam ships. Consequently, bridges may need modification, replacement, or removal. The clear horizontal and vertical spacing available for navigation at overhead bridges should be sufficient to permit the safe transit of the design ship that is expected to use the navigation channel under normal operational conditions. The 1972 Waterways Safety Act placed the 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; final design will require Coast Guard approval. The following general guidance also applies to hurricane barriers, power line towers, and other structures that may obstruct navigation in a waterway.

13.6.1 Horizontal Clearance

In general, the horizontal clearance between bridge piers, including bridge fenders, should be equal to or greater than the local channel width. The location of bridge piers should be planned so that a ship will ground rather than collide with piers or obstructions when it fails to stay within the channel. Some projects with older bridges, which were built when ships were much smaller, may have very difficult navigation conditions, including having 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, shorter-than-desirable distances between bridge piers may be dependent 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. Span, alignment, and clearance of other bridges on the waterway
8. Tug assist

13.6.2 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 a bridge 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 specified water level usually corresponds to a high tide level, such as mean high tide or mean higher high tide. In rivers, some small percentage of the occurrence of water level has been used to specify the water level. A study of the variation of water surface about higher elevations should be undertaken for important waterway projects to establish vertical bridge clearance.

13.6.3 Bridge Approaches

The navigation approach to overhead bridges should preferably be straight and normal or nearly normal to the bridge alignment. Cross-current 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 a minimum of five times the design ship length.

13.6.4 Examples

The Golden Gate Bridge, shown in Figure 13-4, is an excellent example of generous vertical and horizontal clearance for ships. Figure 13-5 shows a more restricted vertical clearance in the Charleston Harbor, Charleston, South Carolina. Figure 13-6 shows a restricted horizontal clearance at Coos Bay, Oregon. The railroad bridge in the background has a center mounted swing span.

13.7 HURRICANE BARRIERS

Storm and hurricane surges historically have caused major floods and damage in Europe. In 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 following discussion presents important navigational impacts that should be considered in barrier planning and design.

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.

FIGURE 13-4. Golden Gate Bridge Provides Generous Clearance For Ships [USS Enterprise *(Navy Web, chinfo.navy.mil)].*

FIGURE 13-5. Restricted Bridge Clearance, Charleston Harbor (COE, Digital Visual Library).

FIGURE 13-6. Inbound Ship in Coos Bay Ship Channel After Passing Through Railroad Bridge (COE, Portland District).

In most cases, a navigation gap or lock 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. The design should reduce or prevent 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 to plan and design in order to optimize and balance the flood-reduction benefits of a project with the requirements of navigation.

Because current velocities through 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 appropriate numerical and physical models, as well as a ship simulator study. From these studies, an optimum arrangement and barrier location can be developed to provide for adequate surge protection and safe ship navigation conditions. Model studies also can provide assistance during project construction to reduce any adverse navigation conditions.

13.8 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. Navigation projects in both estuarine and littoral environments provide for sediment traps. The effects of the sediment trap on navigation should be considered in the design, and trap location should consider 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, which use physical and numerical models of sediment traps for estuarine areas, are outlined in EM 1110-2-1607.

13.9 TRAINING DIKES AND REVETMENTS

13.9.1 Dikes

In rivers and waterways with high sediment transport subject to shoaling, training structures frequently are 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 usually are designed to constrict flow at low-water seasons, thus increasing water currents to help flush sediment from the navigation channel. Longitudinal dikes extending along the waterway often are 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* for a more thorough discussion of this topic.

13.9.2 Revetments

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 with the use of revetments should be considered during project design. Rock riprap and articulated concrete mattress have both been used as revetments to control bank erosion. In most ship channel projects, wind waves and river or tide currents exceed the erosion power of ship waves. This is because the ship is usually moving at a moderate speed (4 to 10 knots) and the ship channel is a considerable distance from shore.

The height of waves generated by a moving vessel is dependent on the following factors:

1. Vessel speed
2. Vessel draft and hull shape
3. Water depth
4. Blockage ratio of ship to channel cross-section

The effects of waves will depend on the height of the wave generated and the distance between the ship and the smaller boats or shoreline. Figure 13-7 shows a schematic of the ship wave form.

Figure 13-8 shows a ship-generated wave in the Columbia River channel.

If ship waves will be higher than those occurring naturally from wind or ocean swell or those created by fast-moving pleasure craft, mitigation measures may be required. The two most common mitigation measures are reduced speeds and shore protection. In some cases, it may be practical to place the navigation channel at a sufficient distance from the shore so that the waves reaching the shore will not be destructive. Reducing speed could affect the efficiency of the project and have some effect on the maneuverability of the vessel. Physical model studies using the vessels expected to use the channel could provide a more accurate indication of

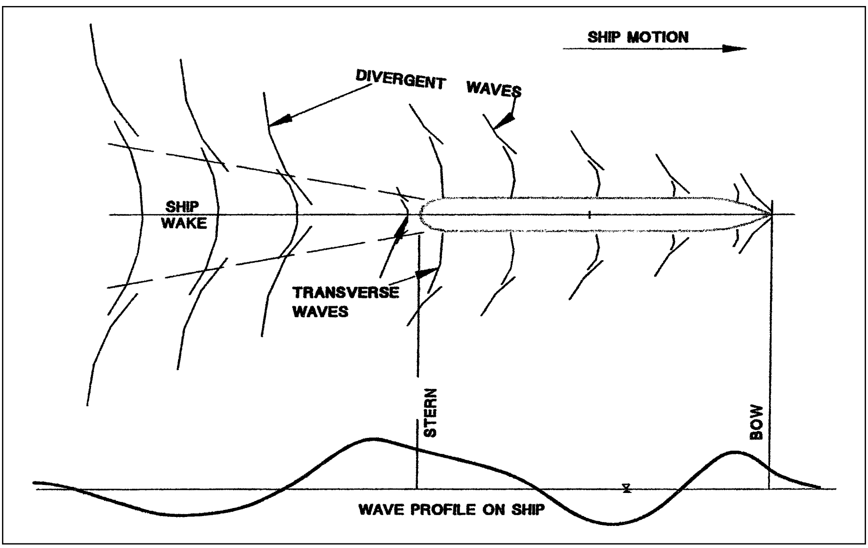


FIGURE 13-7. Schematic of Ship Wave System (EM 1110-2-1613, 2002 Draft).

FIGURE 13-8. Ship Wake in the Columbia River Channel (COE, Portland District).

the wave heights that will be developed under different conditions and the most effective means of reducing their effects. For example, a reach of the Sacramento River Deep Water Channel has experienced repetitive failure of riprap along its levees. A model study indicated that riprap failure occurred with ship speeds of 7.8 and 8.1 miph, with waterway to ship cross-sectional area ratios of 4.3 and 6.1, respectively. This indicated that riprap failure in the Sacramento channel was caused by the stern wave or bore and subsequent rapid drawdown generated by vessel speeds in excess of 6.8 miph. It was determined that the average vessel speed in the channel was 8.4 miph, which induced a stern wave with a 4 ft drawdown in one minute that could remove filter or embankment material and cause subsequent failure of the riprap. Restricting the vessel speed to a maximum of 6.8 miph reduces the stern wave and rapid drawdown and was considered more practical than enlarging the channel to a value equal to or greater than seven times the typical vessel cross-sectional area.

Another example of ship wave mitigation is the Lake Washington ship canal, Seattle, Washington. This confined canal is used by pleasure craft, commercial fishing vessels, and NOAA ships (over 300 ft long), which are based in the fresh water of Lake Union. A speed limit of 7 knots is in place to control ship wave heights. The speed limit is enforced by the Seattle Police Department.

FIGURE 13-9. Houston Ship Channel (COE, Digital Visual Library).

13.10 PORT BERTHING AND MANEUVERING AREAS

Many commercial harbors have docks parallel to the shore so the berthing area is a project element between the dock and the navigation channel. The berth width should accommodate the beam of the longest size vessel expected to be tied up at the dock. Additional width may be desirable for movement of service vessels without encroaching into the navigation channel. These service vessels could be tugs or fuel barges. Examples of shore parallel docks are the Houston ship channel (Figure 13-9) and the Port of Portland, Oregon (Figure 13-10).

The second type of dock has a configuration that is perpendicular to shore. The water space between docks is called a slip. The Seattle, Washington, waterfront is an example of this configuration (Figure 13-11).

The advantage of the shore perpendicular layout is that it can accommodate many more piers than the shore parallel. This pier configuration is often used for ferries and allows for rapid docking and undocking. Figure 13-12 shows a ferry dock orientation in Puget Sound, Washington.

The U.S. Navy uses both types of dock configurations in their many home ports around the world. Figure 13-13 shows the USS *Lexington* undocking from a shore parallel wharf in Pensacola, Florida. Design guidance for Navy slip length and width is shown in Figure 13-14.

FIGURE 13-10. Port of Portland, Oregon.

FIGURE 13-11. Seattle, Washington, Waterfront (NOAA Photo Library).

PIANC (1997) recommends the berths should be aligned within about 30° of the prevailing winds, whereas currents aligned with the berth should be no more than 3 knots and perpendicular to the berth, no more than 0.75 knots. PIANC (1997) further recommends the use of vessel simulator studies to optimize the size of berthing and maneuvering areas.

For successful docking and undocking operations, maneuvering areas may be needed, in addition to the channel width and berthing areas.

The Corps of Engineers, Waterways Experiment Station (WES) Research Ship Simulator was used to evaluate the design of Phase II of the John F. Baldwin Ship Channel, San Francisco Bay, California (TL-85-4, June 1985), to study the impact of the deepened channel on the navigability of large tankers inbound to the Long Wharf docking facility near Richmond Harbor. The present channel and maneuvering area is 35 ft deep and is inadequate for the larger tankers bringing crude oil from the Alaskan North Slope. The San Francisco District has proposed to deepen the channel to 45 ft deep. The authorized 35-ft-deep channel was simulated to verify the ship simulator setup as well as establish the base maneuvering strategies and the proposed 45-ft-deep channel was simulated to study the proposed conditions. In addition to the tankers, container ships navigating into Richmond Harbor entrance channel also were simulated to investigate the impact of channel deepening on other ships using the maneuvering area.

The proposed project will allow fully laden 87,000-dwt and partially laden 150,000-dwt tankers to unload at the Long Wharf. Present tanker

FIGURE 13-12. Ferry Boat Docks in Puget Sound, Washington (NOAA Photo Library).

FIGURE 13-13. USS Lexington *(COE, Digital Visual Library).*

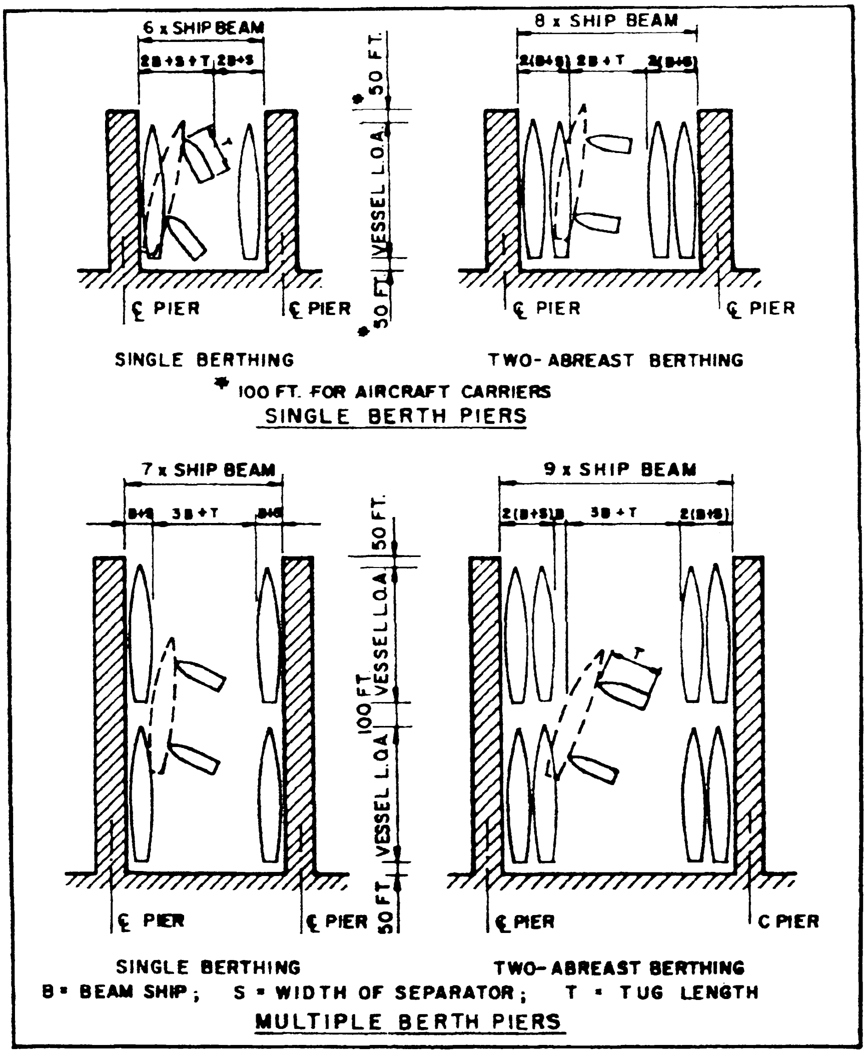


*FIGURE 13-14. Length and Width of Slips (*Piers and Wharves, *Military Handbook 1025/1, October 1987).*

operations require all but the smallest tankers to anchor in the main bay and off-load a substantial part of the cargo into shallower draft tankers that can be accommodated with the 35-ft-deep channel. The proposed channel will reduce transportation costs as well as reduce the possibility of oil spills in San Francisco Bay.

Tests for the base and proposed channel conditions were conducted using 87,000-dwt partially laden (30-ft draft) and 150,000-dwt partially laden

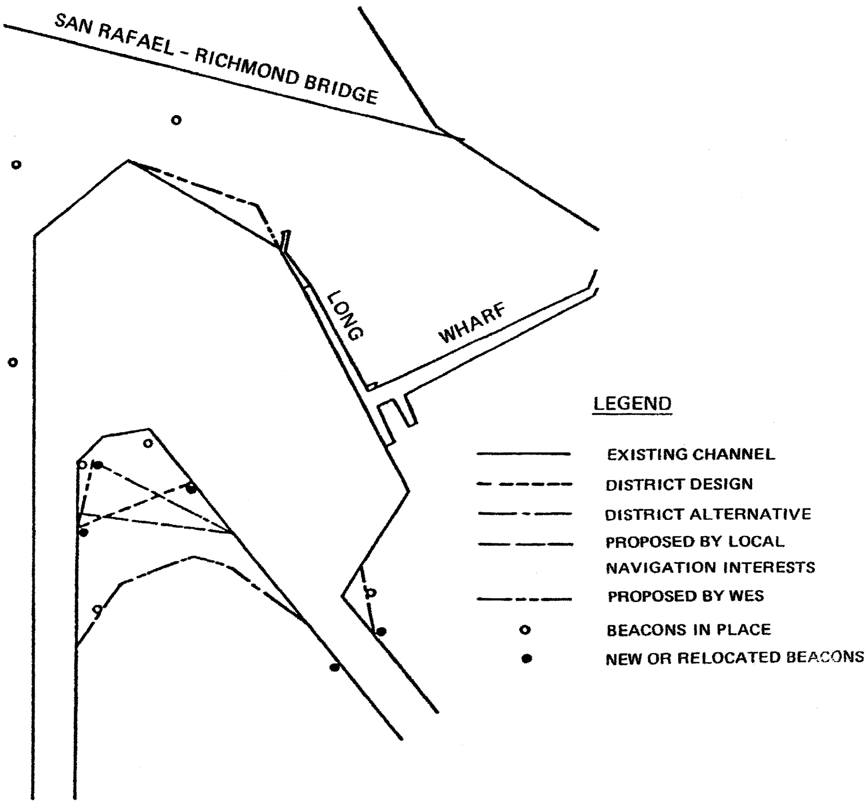


FIGURE 13-15. Alternative Designs, Maneuvering Area (TR HL-85-4).

(40-ft draft) tankers, respectively. Both flood and ebb current conditions were simulated. In addition to ship track plots, several other critical parameters were plotted and studied, such as ship speed and docking posture as it approaches the Long Wharf. The main container ship used to simulate future size ships calling at Richmond Harbor was 810 ft long and 106-ft beam loaded to a 32-ft draft. A smaller container ship with 638-ft length and 100-ft beam also was used to simulate present-day ship sizes. All simulations were run with a 20-knot wind blowing from the southwest.

Test results indicate that it is very important to reduce tanker speed in Southampton Channel for inbound transits to about 5 knots before starting the large right turn into the maneuvering area. Acceptable docking postures can be achieved for both existing and proposed channel conditions under both ebb and flood tide so as to allow safe tanker docking into the Long Wharf. The container ship tests indicate that it is reasonably safe to maneuver around the point and line up with the Richmond Harbor entrance channel on flood tide. Ebb tide conditions require very careful

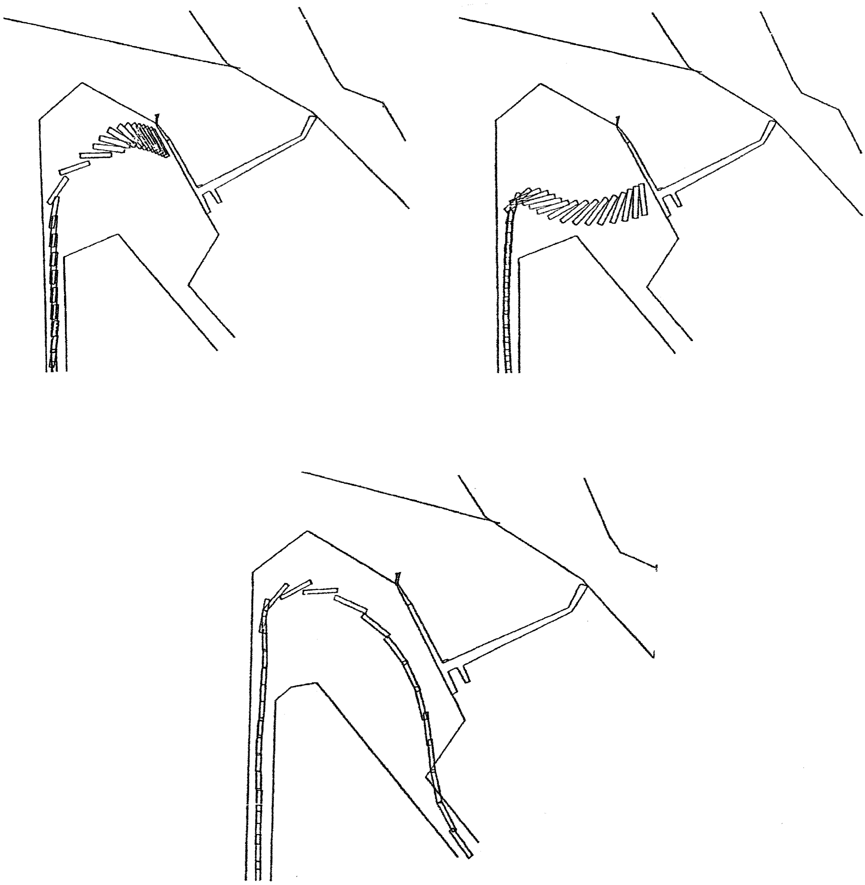


FIGURE 13-16. Typical Simulation Run for 150,000-dwt, 815-ft Long Container Ship (TR HL-85-4).

control of ship speed and position to execute a safe turn in the maneuvering area when piloting the 8l0-ft container ship. The 638-ft container ship was much easier to maneuver around the point.

Figure 13-15 shows various configurations of the maneuvering areas. Figure 13-16 shows typical simulation runs.

Chapter 14
ENVIRONMENTAL CONSIDERATIONS

14.1 GENERAL

This chapter will explore the environmental impact of ship channels in estuaries that are connected to oceans. The majority of ship channels are within this environment. Some notable exceptions include the Great Lakes and upper reaches of the Columbia River channel and the Mississippi River channel, from the Gulf to Baton Rouge, Louisiana. Ship channel construction in salt water and mixed salt- and freshwater estuaries can have environmental impacts in three main categories: (1) altered circulation, (2) dredging and disposal activities, and (3) jetty construction.

14.2 ALTERED CIRCULATION

Circulation may be altered as a result of modifications to an estuary, its tributaries, or its sea connection. Changes in circulation may result in changes in the spatial distribution of water quality constituents, in the flushing rates of contaminants, in the pattern of scour and deposition of sediments, and alteration of fish migratory and larval transport paths.

Environmental assessment of the effects of changes in circulation should initially emphasize the physical parameters such as salinity, temperature, and velocity, and their impact on plant and animal communities. Changes in vertical stratification should be considered when channel deepening is proposed. Increased density stratification inhibits vertical mixing, which may result in depletion of dissolved oxygen (DO) in bottom waters. If minimal changes occur in these parameters, then it can be generally assumed that the chemical characteristics of the system will not change significantly. This approach is based on a methodology that permits assessment without requiring extensive data and knowledge of the processes affecting the water quality constituent of direct interest. However, this approach is invalid if preliminary water quality surveys indicate the existence of toxic constituents at concentrations potentially damaging to biotic populations.

Prediction of change in circulation and its effect on the physical parameters can be achieved through comparison with existing projects, physical model studies, and numerical simulation. Changes in salinity may result from the construction of estuarine control works or channel deepening. Construction and operation of locks may cause salinity intrusion in upstream portions of estuaries normally used for freshwater supplies. Also, diversion works may cause normally freshwater portions of an estuary to become saline, or vice versa. If these freshwater supplies are used for municipal, agricultural, or industrial purposes, then the prevention of salinity intrusion can be a controlling factor in the design. Estuarine ecological features also may be influenced by a reduction in salinity as a result of barriers or diversion structures. The decrease in salinity may be detrimental to a seafood industry, affecting such estuarine ecological features as oyster beds or fish and shrimp nurseries. Consideration should be given to both short- and long-term changes in salinity during all seasons of the year, as these changes can have a drastic effect on sensitive ecological features.

14.3 DREDGING

The environmental effects commonly associated with dredging operations are increases in turbidity, resuspension of contaminated sediments, and decreases in DO levels. However, research results indicate that the traditional fears of water quality degradation resulting from the resuspension of dredged material during dredging and disposal operations are for the most part unfounded. More detailed information on the impacts of turbidity and the possible impact of depressed DO levels is given in EM 1110-2-1202 and EM 1110-2-5025.

In some cases, the environmental impact associated with the dredging of uncontaminated sediment may be insignificant. However, the impact of fluid mud dispersal at open-water pipeline disposal operations appears to be significant, at least for short time periods (i.e., months). Regardless of the type of dredging or disposal operations, there are certain environments (e.g., spawning grounds, breeding areas, oyster and clam reefs, areas with poor circulation) and organisms (e.g., coral, sea grasses, benthos) that may be extremely sensitive to high levels of turbidity or burial by dredged material. It is therefore necessary to evaluate the potential impact of each proposed operation on a site-specific basis, taking into consideration the character of the dredged material, the type and size of dredge and its mode of operation, the mode of dredged material disposal, and the nature of the dredging and disposal environment. The seasonal cycles of biological activity and the degree and extent of the potential short- and long-term impacts relative to background conditions in the areas to be dredged also must be evaluated. Although some of these impacts associated have not proved to be as severe as previously alleged, techniques to minimize environmental impacts must be employed.

14.4 DREDGED MATERIAL DISPOSAL

The three main methods of disposal are: (1) open water, (2) upland or off channel, and (3) agitation.

14.4.1 Open Water Disposal

Prediction of physical effects of dredging and disposal is fairly straightforward. Physical effects include removal of organisms at dredging sites and burial of organisms at disposal sites. Physical effects are restricted to the immediate areas of dredging or disposal. In case studies, the recolonization of sites occurs in periods of months to 1 or 2 years. Disturbed sites may be recolonized by opportunistic species that are not normally the dominant species occurring at the site.

Many organisms are very resistant to the effects of sediment suspensions in the water; aside from natural systems requiring clear water, such as coral reefs and some aquatic plant beds, dredging or disposal-induced turbidity is not of major ecological concern. The formation of fluid muds due to disposal is not fully understood and is probably of some environmental concern.

Release of sediment-associated heavy metals and chlorinated hydrocarbons to the water column by dredging and disposal has been found to be the exception rather than the rule. Metals are rarely bioaccumulated from sediments, and then only to low levels. Chlorinated hydrocarbons may be bioaccumulated from sediments, but only very highly contaminated sediments might result in tissue concentrations of potential concern. There is little or no correlation between bulk analysis of sediments for contaminants and their environmental impact.

14.4.2 Upland or off Channel

These disposal areas can be confined or unconfined and are often used for habitat development, which is the establishment of relatively permanent and biologically productive plant and animal habitats.

Four general habitats are suitable for establishment on dredged material: marsh, upland, island, and aquatic. Within any habitat, several distinct biological communities may occur. The determination of the feasibility of habitat development will center on the nature of the surrounding biological communities, the nature of the dredged material, and the site selection, engineering design, cost of alternatives, environmental impacts, and public approval. A decision regarding the type or types of habitats to be developed must be made if this is the selected alternative. The decision will be largely judgmental but, in general, site peculiarities will not present more than one or two logical options.

14.4.3 Agitation Disposal Method

This method is usually applicable when there are strong river currents in the ship channel. The dredge does not remove the sediment but resuspends it to be carried downstream by the river current. Environmental impacts are minimal as this method is usually used following major floods, when the water column is usually very turbid.

14.5 JETTY CONSTRUCTION

A common characteristic of breakwaters and jetties is their location in dynamic, high-energy environments. Physical features of the environment where breakwaters and jetties are typically constructed reflect hydrodynamic and sedimentological conditions that have attained a dynamic equilibrium, a state of continuous change that remains balanced around some average set of conditions. Environmental impacts will occur as the system is initially imbalanced by the presence of the structure(s), and then returns to a new set of dynamic equilibrium conditions. Potential environmental impacts associated with these structures can be sorted into the following categories, all of which are interrelated to some degree: water quality impacts, biological impacts, and socioeconomic and cultural impacts. The magnitude of severity of each type of impact can be expected to vary over time. Each category of impact is briefly discussed here. Because breakwaters and jetties generate essentially similar impacts, they are treated jointly.

14.5.1 Water Quality Impacts

Suspended sediment concentrations may be elevated in water immediately adjacent to the construction of a breakwater or jetty. In many instances, however, construction will occur in naturally turbid estuarine or coastal waters. Plants and animals residing in these environments are generally adapted to, and very tolerant of, high suspended sediment concentrations. However, when construction is to occur in a clear water environment, such as in the vicinity of coral reefs or seagrass beds, precautions should be taken to minimize the amounts of resuspended sediments. Organisms in these environments generally are less tolerant to increased

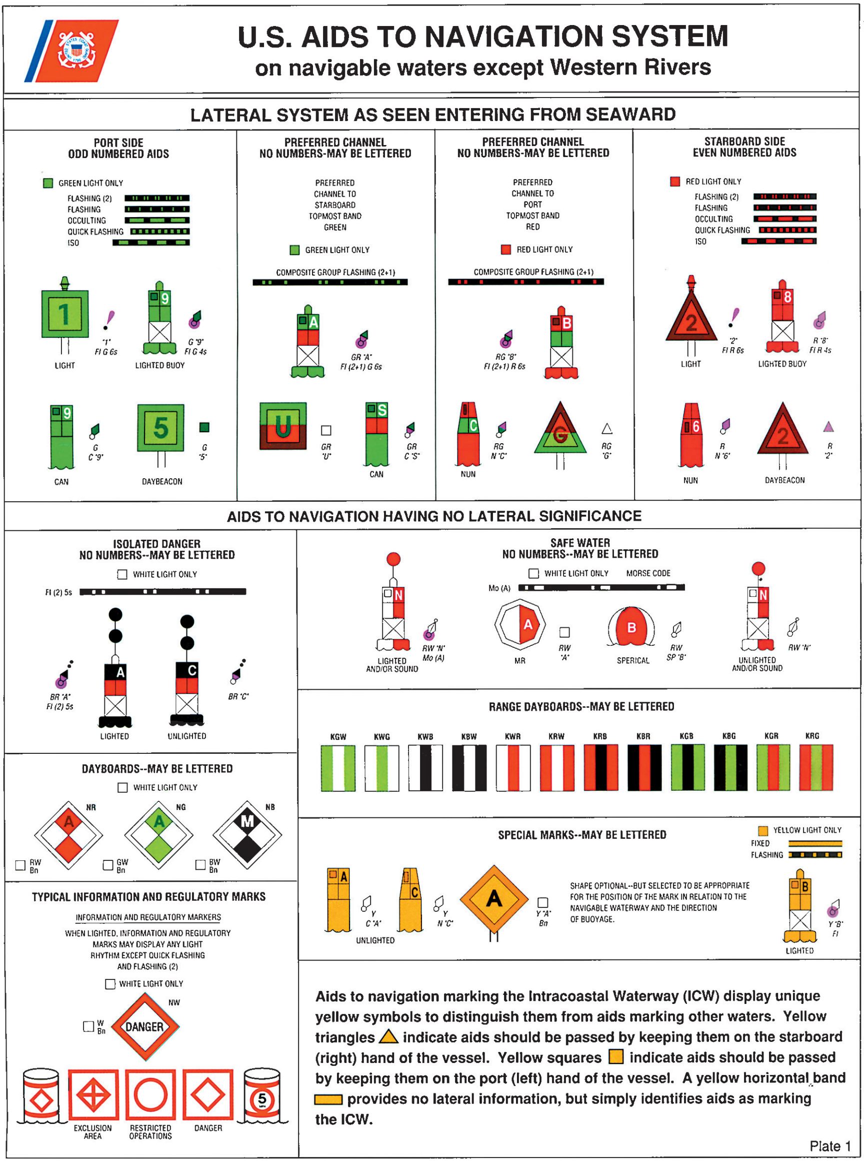


PLATE 1. U.S. Aids to Navigation.

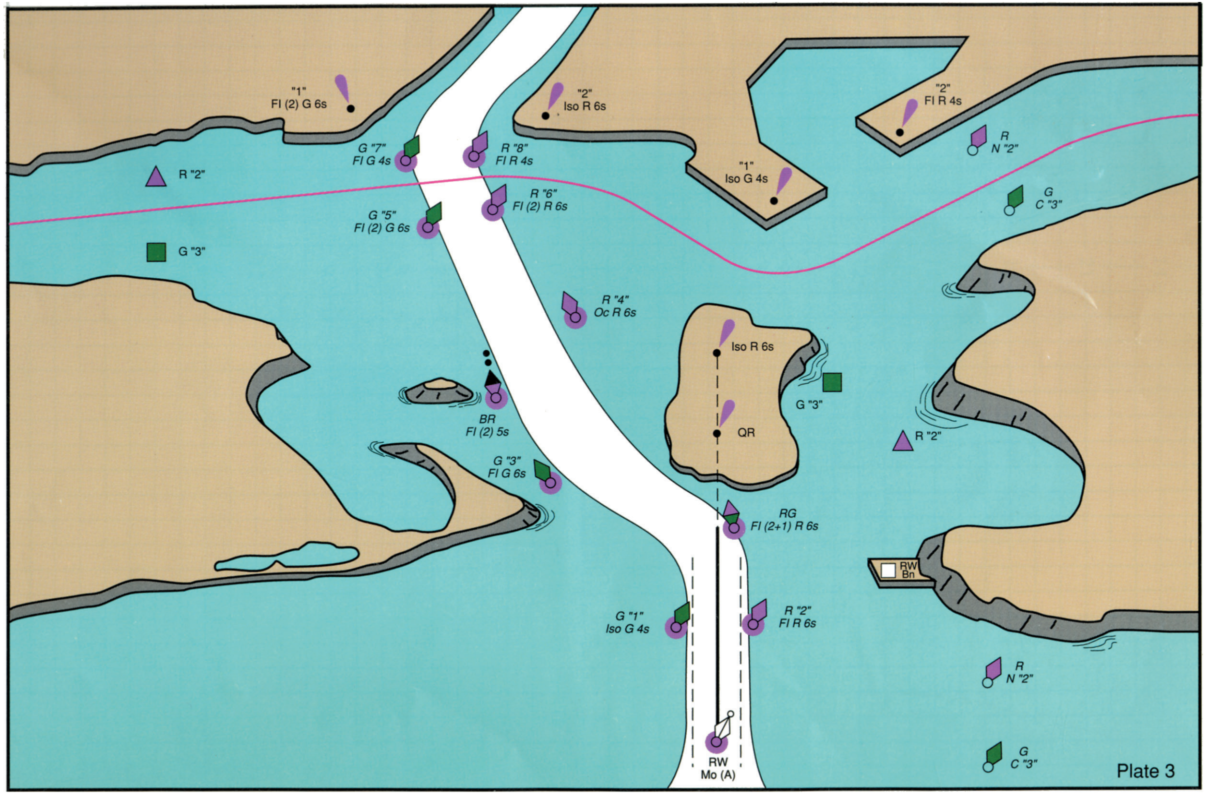


PLATE 2. Aids to Navigation Placement.

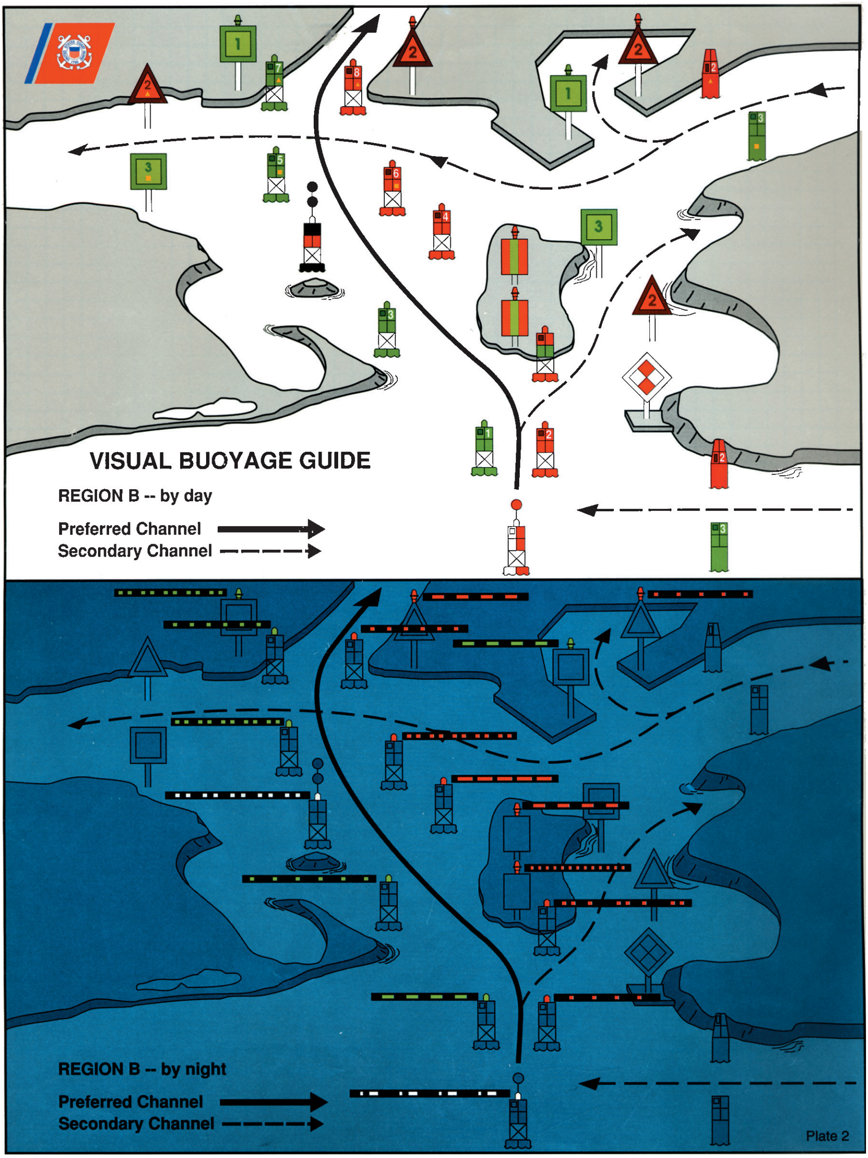


PLATE 3. Visual Buoyage Guide.

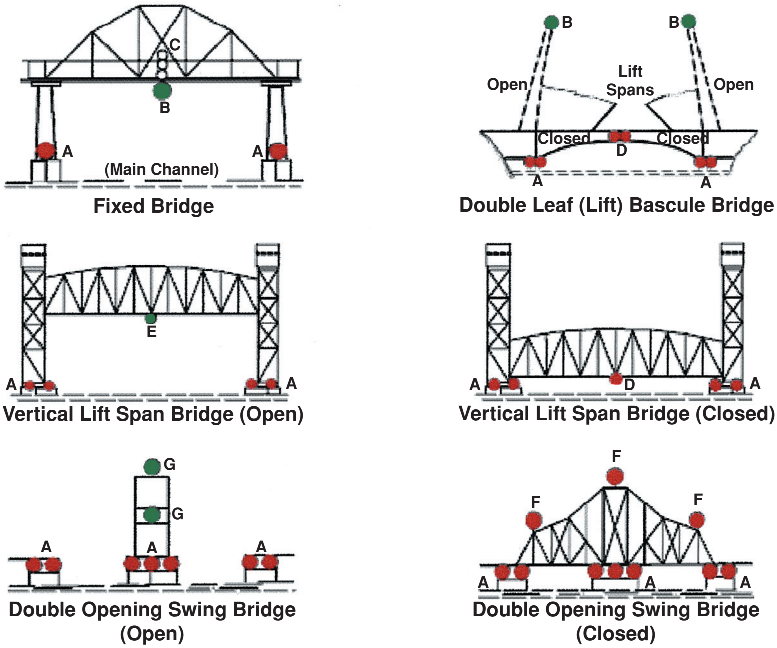


PLATE 4. Combinations of Fixed Lights for Bridges and Structures Extending Over Waterways (from U.S. Coast Guard Digital).

siltation rates, reduced levels of available light, and other effects of elevated suspended sediment concentrations.

14.5.2 Biological Impacts

Biological impacts are inherently difficult to quantify. Impacts, indicated by changes in occurrences and abundances of organisms, may be masked by background "noise" because of seasonal variations in populations, ecological succession events, and natural perturbations (e.g., storms, harsh winters, etc.). The types of biological impacts discussed here range from well established to highly speculative.

Measurable amounts of bottom habitat are physically eradicated in the path of breakwater or jetty construction. Given an example toe-to-toe width of 125 ft, one linear mile of typical rubble structure replaces approximately 15.2 acres of preexisting bottom habitat. This loss of benthic (bottom) habitat and associated benthos (bottom dwelling organisms) is more than offset by the new habitat represented by the structure itself and by the reeflike community that becomes established.

Water currents and turbulence along the base of the structure can produce a scouring action that prevents utilization by most benthic organisms of the habitat area. This effect is largely confined to the bottom immediately adjacent to the structure and may occur along only a portion of the perimeter, such as along the channel side of an inlet's downdrift jetty.

One speculative source of biological concern related to altered hydrodynamic regimes at jettied coastal inlets involves transport of egg and larval stages of fish and shellfish. Eggs and larvae of many important sport and commercial species are almost entirely dependent on water currents for transportation from offshore spawning areas through coastal inlets to estuarine nursery areas. Jetties displace the entrance to an inlet forming a potential barrier to eggs and larvae, particularly those carried by long shore currents. Eddies or lee areas created in the vicinity of jetties may act as sinks in which nonmobile stages become trapped or are delayed. In view of the fact that numerous structures have been in place for quite a long time with no apparent decline in estuarine-dependent species attributable to their presence, a case can be made that such impacts, even if real, are insignificant. Similar concerns have been voiced with regard to the movements of juvenile and adult stages of various fish and shellfish. Because these are generally highly mobile forms, the probability of negative impact is even less significant.

Coastal rubble structures provide substratum for the establishment of artificial reef communities. As such, breakwaters and jetties serve as a focal point for aggregations of fish and shellfish that graze on sources of food or find shelter there. Many species are attracted to the structures in numbers, as evidenced by the popularity of breakwaters and jetties as sport fishing locations.

Potential biological impacts can be summarized as follows:

1. The loss of benthic habitat and benthos in the area covered by the structure(s)
2. The displacement of benthos as a result of scouring effects
3. The development of plant and animal communities on the substratum provided by the structure(s)
4. The altered transport of egg and larval stages of fish and shellfish through coastal inlets
5. The altered movement patterns of juvenile and adult stages of fish and shellfish

14.6 RECENT EXPERIENCE

Following are two examples of environmental consideration for ship channel deepening projects.

14.6.1 Houston Ship Channel

As part of this project, a 118-acre oyster reef was constructed near the ship channel to mitigate for lost habitat when the channel was widened and deepened. The reefs were built from limestone gravel (ranging in size from 1/4 in to less than 3 in). The reef contract was completed in July 2000; tests three months later showed the oysters had started to grow and were about the size of a quarter.

14.6.2 Columbia River Ship Channel

This deepening project (40 ft to 43 ft) has not yet begun. The following are environmental tests required by the state:

- Test for contaminants before dredging outside the 600-ft-wide navigation channel
- Dredge outside the channel only when salmon migration is over
- Monitor to avoid damaging salmon, Dungeness crab, smelt, and sturgeon during dredging

14.7 SOURCE

Information for this chapter came from EM 1110-2-1202, EM 1110-2-1607, EM 1110-2-2904 and EM 1110-2-5025.

Chapter 15
MODEL STUDIES

15.1 GENERAL

Development of deep-draft navigation projects affected by tides or river currents often requires the use of model studies to determine the adequacy of a proposed plan, as well as the need for modifications. Both physical and numerical models can be used to analyze some of the factors that will affect the safety and efficiency of the projects. However, because of the complexity of currents and the effects of wind, waves, tides, and sediment movement, the hybrid modeling approach (which uses both physical and numerical models) is usually required to obtain an accurate evaluation of the conditions that can be expected with each plan and modification considered, particularly in estuarine areas.

15.2 PHYSICAL MODELS

Physical scale models are used to investigate flow patterns when complicated three-dimensional (3-D) effects are necessary. Recent dramatic advances in computer hardware and software have led to the use of numerical models to replace and supplement physical model studies. The following types of navigation investigations can be conducted with physical models:

1. Shoaling and erosion characteristics
2. Salinity intrusion
3. Wave penetration and harbor response
4. Jetty design and armor stability
5. Ship response to waves
6. Channel width in critical navigation reaches
7. Tide heights and current patterns
8. Navigation conditions

ASCE Manual No. 97, *Hydraulic Modeling Concepts and Practic*e (2000), provides details of physical model design, operation, and application.

15.3 NUMERICAL MODELS

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 distinguished by a grid or mesh. Furthermore, testing the numerical results against a prototype data set (verification) is necessary.

Numerical models may be used to replace or supplement physical models, and numerical models can do the following:

1. Provide general circulation patterns for deep- or shallow-draft ship simulator studies
2. Determine shoaling and erosion characteristics
3. Address dredged material disposal issues and other water quality measures
4. Investigate salinity intrusion
5. Study wave penetration and harbor response
6. Evaluate training structure designs

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 can solve hydrodynamics and transport equations simultaneously, whereas others are uncoupled.

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 differential calculus operations over finite distances, which gives an approximation of the governing equations at discrete points. The finite element model 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.

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.

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, and generating presentation- and report-quality graphics, online documentation, and consultation support.

Enlargement of the Galveston-Houston Ship Channel was modeled with the Corps' TABS-MDS numerical modeling system in order to ensure that deepening and widening the channel did not adversely alter salinity or circulation patterns and damage fisheries in Galveston Bay. TABS-MDS uses the finite element method to solve the governing equations for flow of water and transport of salinity, temperature, and sediment. An interagency panel advised the Corps on the validation of the model and found it to reproduce observed tides, velocities, and salinity patterns in the bay system. The panel then selected conditions under which the deepened channel would be tested, including the effects of future planned water diversions that were part of the Texas water development plan. The model showed that enlarging the channel to 45 by 530 ft would not harm and in some areas would enhance conditions for oyster production (Berger, 1995).

15.4 SHIP SIMULATOR MODELS

This model emerged in the 1980s as the best design tool to determine safe channel widths and alignments. This model enables designers to study the interactions of ships with the currents, wind, and banks as they are maneuvered through navigation channels and waterways. Simulators allow the use of both automatic controlled vessel navigation as well as navigation with human pilots with realistic ship/tow controls in a simulated ship-bridge environment. A test scenario is developed for channel design dimension/alignment alternatives and conditions, such as flow rates, tidal conditions, wind, visibility, and navigation marking. Test runs are conducted through the simulated conditions, and can be conducted in real time, simulating the prototype vessel transit speed or fast time (similar to fast forward on a VCR), allowing for more runs. As the vessel is navigated through the test areas, it is subjected to forces resulting from environmental factors and the vessel's motion is determined one step at a time. As the vessel progresses through the scene or changes its orientation, a computer-generated view from the pilot's window is displayed in color on a large screen (Figure 15-1). This allows a pilot to observe the vessel in motion relative to physical objects as would occur in actual vessel transit. In addition, the simulator generates a radar image of the vessel's location. As the vessel progresses through the channel, the scene is updated periodically. Key navigation information also can be displayed on a precision navigation

FIGURE 15-1. Vessel Simulator (COE Waterway Experiment Station).

display. Data pertaining to the ship's motion, location, and orientation in the test area is recorded for later analysis. Tracking of the vessel through the test area can be recorded during the simulation run for immediate evaluation of the test results.

A recent example of vessel simulator use for a channel enlargement project is the Houston, Texas, ship channel, which serves the nation's second largest port. The 400-ft-wide by 40-ft-deep channel was used by 5,400 ships and 50,000 barges in 1996. Ships with beams of 140 to 145 ft used the channel; however, meeting/passing of two such ships was closely monitored and controlled by pilots and not allowed except under certain circumstances.

In some segments of the original ship channel (400 ft wide), the ship pilots developed a risky maneuver called the "Texas Chicken," which allowed the new generation of wide-beam ships to pass in the narrow channel. Both ships sailed along the centerline of the channel. As the approach neared, both ships briefly turned to starboard (right), then returned to the previous course for a port-to-port passing. The hydrodynamic forces of the water compressed between the two ships prevented contact. Following the passing, each vessel would return to the channel centerline. Figure 15-2 shows the "Texas Chicken" maneuver.

The goal of the deepening and widening project was to allow safe transit for these vessels (145 ft beam) and larger vessels.

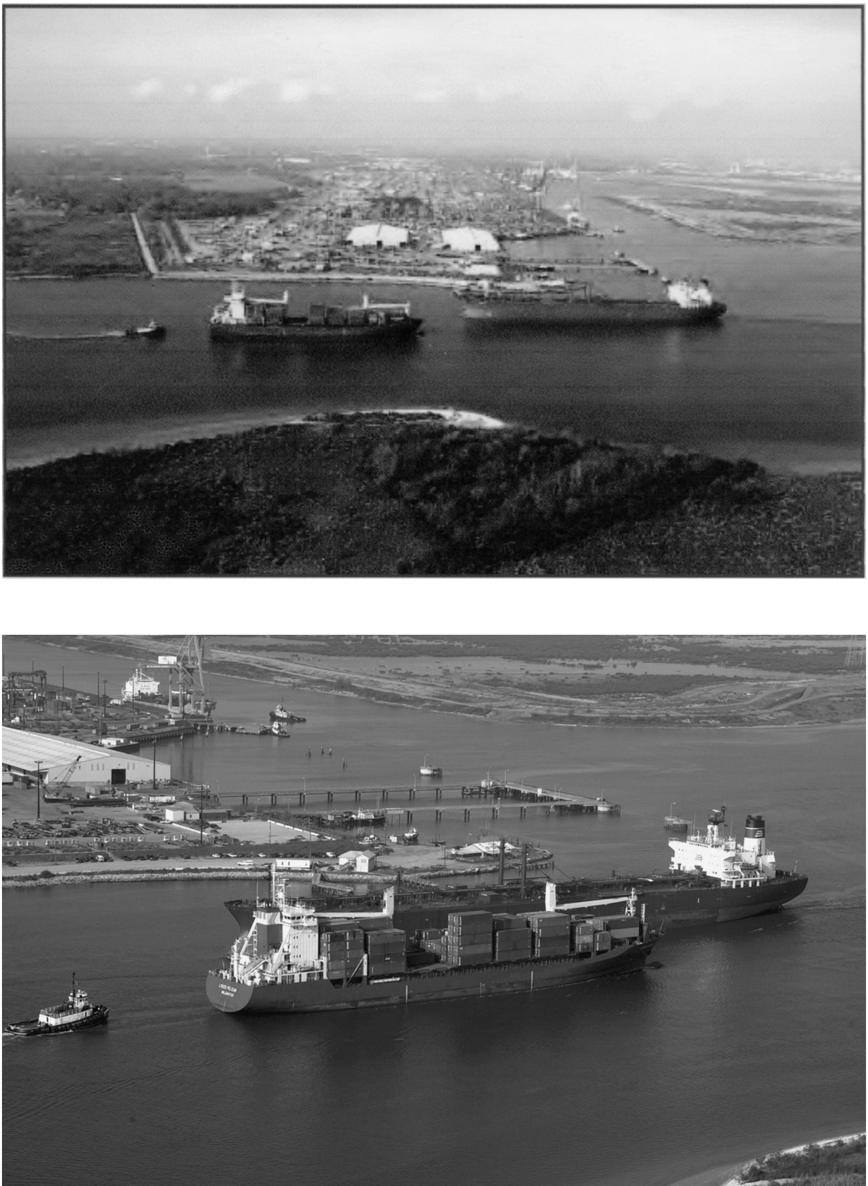


FIGURE 15-2, Top and Bottom: *"Texas Chicken" Maneuver at Barbour's Cut on the Houston Ship Channel; approach and passing sequence. (U.S. Coast Guard Digital). (Continued)*

FIGURE 15-2. (Continued) "Texas Chicken" Maneuver at Barbour's Cut on the Houston Ship Channel; approach and passing sequence. (U.S. Coast Guard Digital).

Ship simulators tested two phases of proposed channel enlargement:

Phase I 530 ft wide by 45 ft deep
Phase II 600 ft wide by 50 ft deep

Ships tested for these channel enlargements were:

Phase I 990 × 156 × 44 & 971 × 140 × 44
Phase II 1,013 × 173 × 49 & 971 × 140 × 44

Tests were conducted in the upper reach where the channel has several bends, as shown in Figure 15-3.

Figure 15-4 shows a typical simulation run for the Phase II condition.

The simulation results confirmed the adequacy of Phase I (530 ft wide) and Phase II (600 ft wide), and recommended some relatively minor modifications on the bends.

Construction started in 1999 on this 1/2-billion-dollar channel dredging project.

Details of the Houston Ship Channel simulation study can be found in the U.S. Army Corps of Engineers WES Technical Report HL-94-3, Ship Navigation Simulation Study, Houston–Galveston Navigation Channels, Texas, Report 2, Houston Ship Channel, Bayou Segment, April 1994.

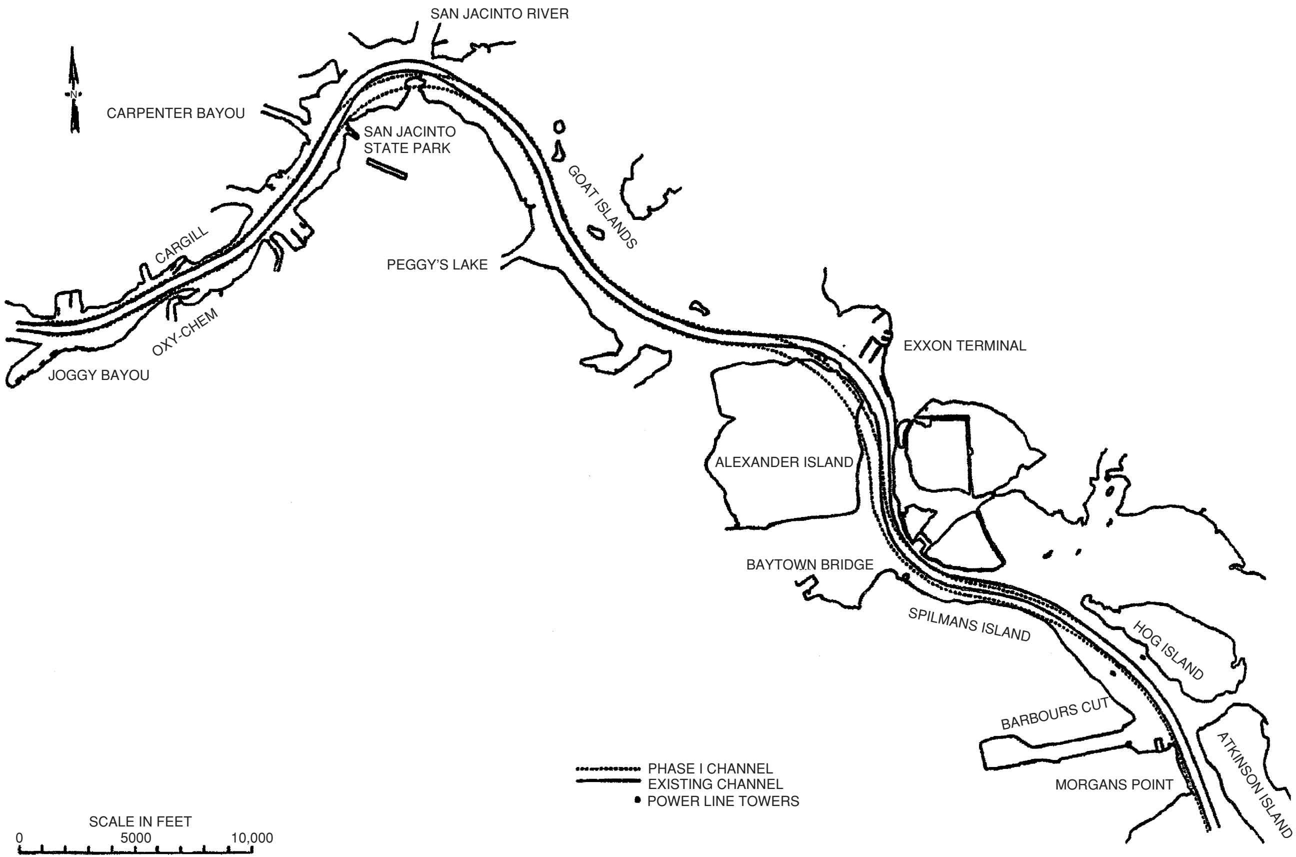


FIGURE 15-3. Houston Ship Channel, Bayou Section Project Map (TR HL-94-3).

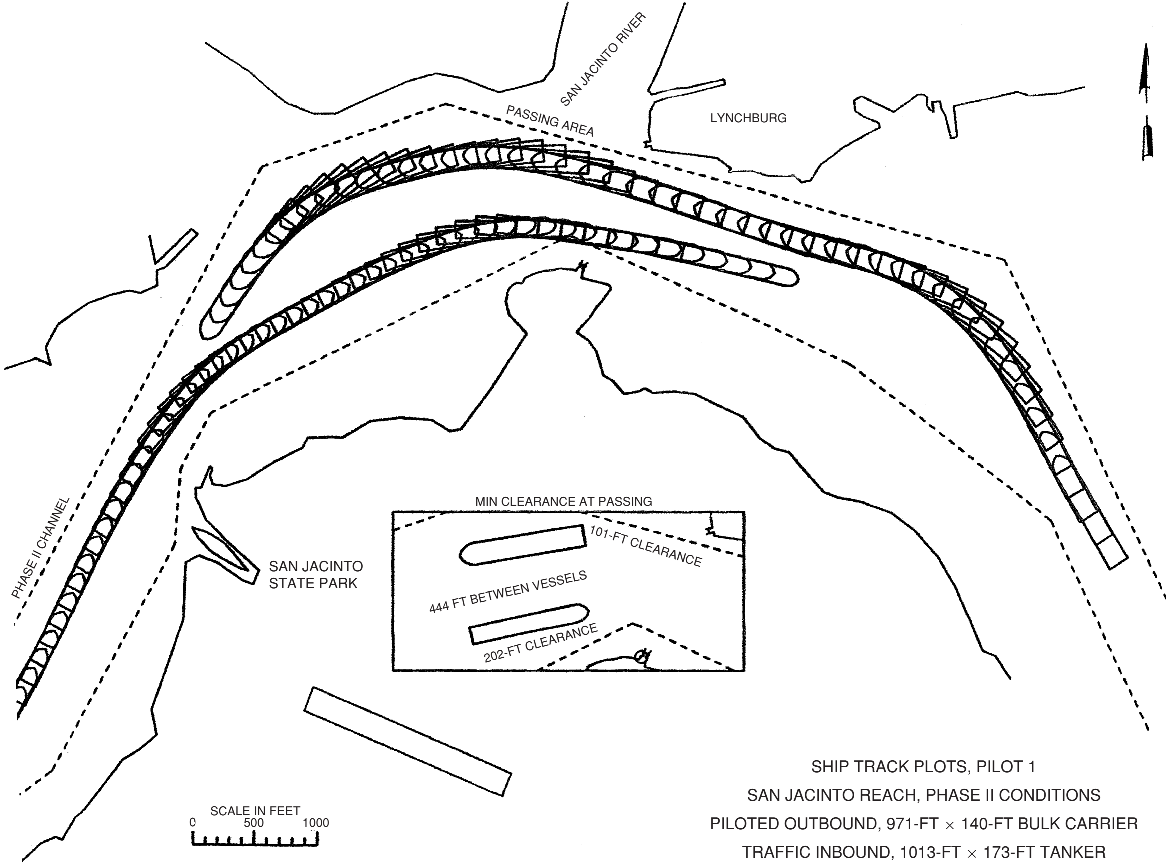


FIGURE 15-4. Simulation of Phase II Passing Conditions (TR HL-94-3).

15.5 VESSEL TRAFFIC FLOW SIMULATION

A traffic flow model (SHIPRISK) has been developed by the Delft University of Technology and Marine Safety Port of Rotterdam to assess the comparative safety of port channel configuration and traffic management scenarios.

This model is particularly applicable to existing ports with vessel tracking systems (VTS).

Two models are used for this simulation:

1. The traffic flow model HARBORISM simulates vessel traffic in the ports and the approaches to the ports taking into account vessel traffic rules (traffic rules in the channels, turning basins, mooring areas, etc.). The output of this model provides the sail schedules of all vessels calling at the port (entrance time, dwell time at the berth, departing time, etc.), and is used as the input file for the SHIPRISK model.
2. The SHIPRISK model is used to estimate the numbers of potential encounters (accidents), to devise alternative scenarios for channel alignment, to plan port facility locations, to check traffic rules, and to plan for weather conditions.

Additional discussion of this vessel traffic flow simulation model and its application to the ports of Rotterdam, The Netherlands, and Puerto America, Venezuela, is presented in Groenveld (2003).

Chapter 16

ICE MANAGEMENT

16.1 GENERAL

In regions where ice formation can be expected, ice-related ship navigation problems 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, the power required to sail, the operation of navigation locks, and the stability of structures. Obviously, the effects of ice on navigation increase with the thickness and extent of ice coverage. Some of the problems encountered with regard to ice include a larger ship-turning radius and greater shippower, which can increase movement of bottom sediment; ice accumulation on ship bottom, which increases 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 EM 1110-8-1.

16.2 DESIGN OF CHANNELS WITH ICE

All vessels, but particularly long cargo ships with vertical sides and a blunt bow, have difficulty turning in ice. Because 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. Local conditions of ice thickness and extent of coverage will be necessary to develop adequate channel designs. It is important to keep turning basins clear to allow ship maneuvers and prevent damage to hulls. It should be noted that conventional commercial ships not specifically designed for ice operation usually are 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. 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 which makes ice breaking 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, and 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 oceangoing ship is empty. Under extremely cold conditions, the brash ice can adhere to the hull of an empty or near-empty vessel. This is because of heat loss as the result of air contact through the sparsely loaded hold. The result of this is increased draft and resistance causing maneuvering difficulties.

16.3 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 and in ASCE Manual No. 94, Inland Navigation: Locks, Dams, and Channels.

Consideration should be given to 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. The depths over the sill should be increased 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.

16.4 EROSION AND SEDIMENT MOVEMENT

Sufficient studies have been done on sediment movement under ice cover in rivers and restricted channels and studies on the Great Lakes 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 the shoreline by gouging, removing protective vegetation, or entraining sediment within the ice. Ice cover tends to damp ship-induced bow and stem waves, which have relatively short periods. However, ice cover has little effect on relatively long 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. High power and propeller rotation will tend to increase scour and bottom sediment movement; these should be considered, particularly when the ship is above underwater cable and pipeline crossings.

16.5 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 against 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.

16.6 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 specially designed ice-breakers. 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 6 in. The maritime insurance companies have specifications by which they will underwrite certain ships operating 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, which could cause 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. Because 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. (The Coast Guard ice breaking mission is discussed in Chapter 20.)

16.7 SOURCE

Most of this information came from EM 1110-2-1612, EM 1110-2-1613, and EM 1110-8-1.

Chapter 17
ECONOMIC OPTIMUM DESIGN

17.1 GENERAL

To achieve the optimum design of a deep-draft navigation project, studies must be made of estimated costs and benefits of various plans, as well as of alternatives on safety, efficiency, and environmental impacts. These studies are used to determine the most economical and functional channel alignment and design with regard to construction, maintenance, and replacement costs for various design levels. The adaptability of each design to future improvements in navigational capability also should be given considerable weight. Economic optimization analysis should consider various elements involved in development and maintenance of the project, including dredging and disposal, structures such as jetties and salinity barriers, and aids to navigation.

17.2 CHANNELS

Channel alignments and dimensions (width and depth) should be studied to determine what is acceptable for safe and efficient navigation. Costs, including initial construction, replacement, and annual maintenance, should be analyzed using a suitable interest rate and should be determined for each alternative. Vessel trip time and tonnage, delays for tides, weather conditions, and effects of reduced depths in channels that have rapid shoaling tendencies should be considered when weighing the benefits of each alternative. The optimum economic channel is selected from a comparison of annual benefits and annual costs for initial construction, replacement, and maintenance for each channel size and alignment. The economic life of a channel, for computing costs and benefits, is usually 50 years. The true design life is as long as the channel is maintained.

17.3 STRUCTURES

Optimization of structures, such as jetties, is accomplished by estimating average annual construction, replacement, and maintenance costs, and average annual benefits for various design levels. The "design level" is related to a specific event with a recurrence interval. For example, a structure could be designed for a 50-year event or a 100-year event. A 100-year event design would usually have a larger and more expensive structure. The elements that are to be considered in an economic optimum or life cycle analysis for structures are:

Project economic life
Construction cost for various design levels
Maintenance cost for various design levels
Replacement cost for various design levels
Benefits for various design levels
Probability for exceedance of various design levels

The construction cost generally will increase as the design level increases.

Maintenance cost generally decreases as design level increases. Replacement cost is less frequent, and the average annual costs of replacement are less as design levels increase. Benefits generally increase as design levels increase because frequency of losses decreases. For example, a jetty with a low crest may overtop occasionally and force closure of the channel because of unsafe wave conditions. The severity or magnitude of design events (such as wave heights, water levels, or ice thickness) has a statistical distribution that can be ordered into a probability of exceedance. The exceedance probability is plotted against the design level (Figure 17-1).

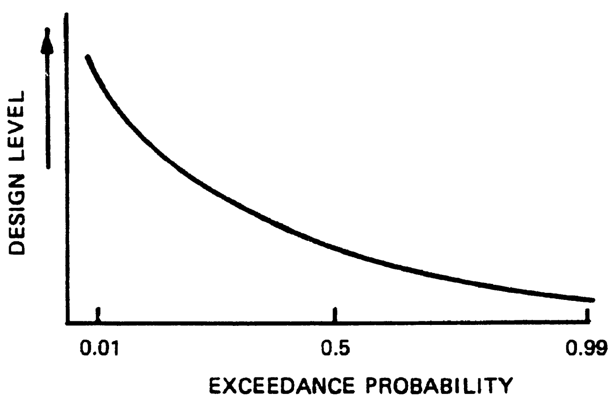


FIGURE 17-1. Exceedance Probability versus Design Level (ASCE Manual No. 80).

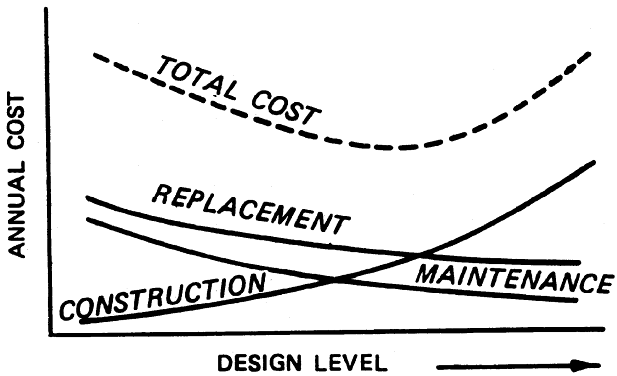


FIGURE 17-2. Project Cost Curves (ASCE Manual No. 80).

A series of project designs and cost estimates are developed for various design levels. For example, a jetty could be designed for wave heights of 14, 16, 18, and 20 ft. Each wave height (design level) would have an exceedance probability similar to that shown in Figure 17-1. In the absence of prototype information, average annual maintenance is often estimated to be 1% of the initial construction cost. However, this approach does not consider exceedance probability of the design level. A more realistic approach would be to estimate average annual maintenance cost by multiplying the exceedance probability of the design level by the construction first cost. This maintenance cost should be compared with maintenance of similar existing projects to assure realistic values. Average annual replacement costs are obtained by estimating the cost of replacement and the year required. The current value of the replacement cost is converted to average annual cost by using an appropriate interest rate and economic project life. The project cost curves generally are similar to those shown in Figure 17-2.

17.4 BENEFITS

Project benefits are compared with project costs to determine the economic optimum design. Achievable project benefits are developed through economic studies, assuming that no constraints exist because of the design level. Achievable benefits are reduced by the benefits lost because the design level is exceeded. Lost benefits are computed by multiplying the annual achievable benefits by the probability of navigation loss for each design studied. The results are typically displayed as shown in Figure 17-3. A comparison of total project cost, actual benefits, and design level is shown in Figure 17-4. The optimum economic design level occurs when net benefits are at the maximum point, as shown in Figure 17-4. Normally, the

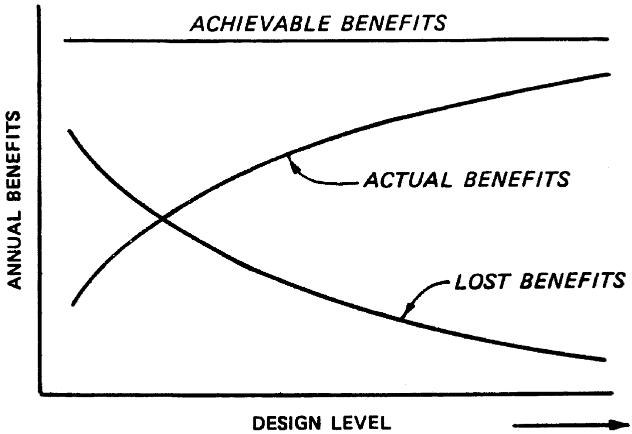


FIGURE 17-3. Benefits versus Design Level (ASCE Manual No. 80).

design level associated with the maximum net benefits will be selected for project design. However, if the net benefit level is not well defined, it may be prudent to select a higher design level to increase the factor of safety.

17.5 TRANSPORTATION SAVINGS

Design benefits are determined by savings in transportation, taking into account ship trip time, cargo capacity, delays for tides, weather conditions, and transit interference from reduced depths in channels that have rapid

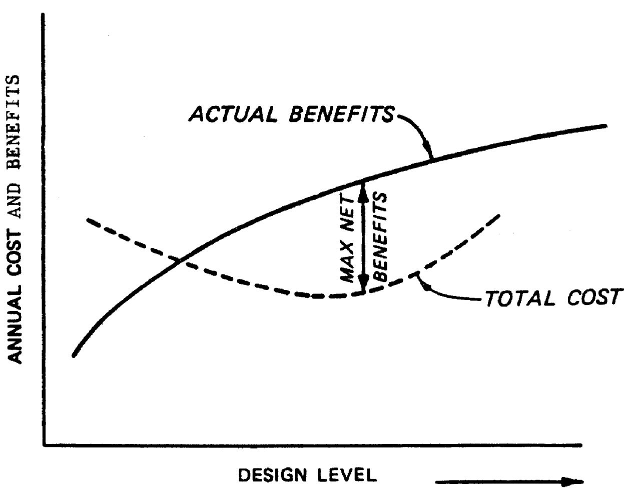


FIGURE 17-4. Cost and Benefits versus Design Level (ASCE Manual No. 80).

shoaling tendencies. Deeper channels will permit the use of larger ships, which are more economical to operate. Some ships with a deeper draft and greater cargo loading could use the channel; this 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 must consider trends in shipbuilding to anticipate future ship sizes and type of ship fleet that will be using the channel. Transportation costs are based on the annual operating costs for each type of ship, including fixed costs and annual operating expenses.

17.6 EVALUATION PROCEDURE

The basic economic benefits from navigation projects include the reduction of costs required to transport commodities and the increase in the value of output for goods and services. These benefits usually are based on costs not included with the proposed project improvements. Project benefits also may 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. Reduction 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

17.7 SOURCE

This information is taken from ASCE Manual 80 (1993 Edition) and EM 1110-2-1613, 2002 Draft (awaiting publication).

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Chapter 18
CONSTRUCTION

18.1 GENERAL

Construction items for ship channels fall into three categories:

1. Dredging
2. Structures
3. Relocations

Dredging is usually scheduled during the spring, summer, and fall, to avoid winter storms that can make dredging operations hazardous. In some projects, such as the Mississippi River ship channel, the flood season can interrupt dredging operations. Fish migration periods are usually avoided to reduce environmental impact.

Structures, such as jetties, are also scheduled for construction during calm wave periods. Figure 18-1 shows jetty rehabilitation work on the Yaquina Bay project. During winter storms, waves can wash over the top of these jetties.

Many of the West Coast jetties were constructed in the late 1800s and early 1900s. Railroad trestles were sunk through the surf and the jetty stone was delivered by train, then placed by cranes mounted on railroad cars. Figure 18-2 shows this type of construction at the Columbia River South Jetty reconstruction in November 1933.

The contemporary method uses mobile cranes operating on a road bed on top of the jetty. The road construction proceeds forward as the jetty is extended into the ocean. Winter waves generally wash away the road surface, so it is desirable to complete the jetty rehabilitation work in one construction season.

Relocation can be a major part of the construction effort. This relocation of underchannel pipelines must precede channel dredging. The Houston ship channel enlargement project had 90 underchannel pipelines that did not meet clearance requirements. The pipelines had to be removed at the owner's cost by authority of navigational servitude. Should the owners

FIGURE 18-1. Yaquina Bay Jetty Rehab (COE, Portland District).

FIGURE 18-2. Trestle Construction Method (COE, Portland District).

wish to replace the pipelines, a new or modified permit from the Army Corps of Engineers is required.

Another constraint on the construction schedule is availability of funds. The Houston ship channel project had 12 separate contracts spread over 6 years. This helped spread the project fund requirement of $719,090,000 over 6 budget cycles.

Construction schedules and activities should always consider the existing channel traffic. Delays and hazards to navigation need to be minimized.

18.2 SOURCE

The Houston-Galveston Navigation Channel project information was taken from the Galveston District Web site www.swg.usace.army.mil.

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Chapter 19
OPERATIONS AND MAINTENANCE

19.1 WEATHER AND CHANNEL CONDITIONS

The safe operation of a ship channel requires an extensive communications network to provide ship captains and pilots with the following information:

Weather predictions
Water levels
Hazards to navigation
Ship movement
Ice conditions
Other relevant navigational information

NOAA provides weather and channel hydraulic (tide and current) predictions. The Coast Guard disseminates information on aids to navigation, hazards, and other maritime-related topics. This information is available on the World Wide Web and on marine radio channels. More information on these subjects can be found in Chapters 20 and 21.

Other channel condition systems are implemented at the port level. The Port of Portland, Oregon, has in place a system called LOADMX, which monitors and reports actual and forecasted river levels. The system allows pilots and ship masters to optimize loaded draft by predicting river and tide levels at various points during the 100-mile long voyage on the river (Beeman, 1985; PIANC Bulletin No. 51).

19.2 SHIP MOVEMENTS

The Coast Guard provides Vessel Traffic Services (VTS) on eight waterways in the continental United States and Alaska. These systems monitor ship movements and provide this information to other vessels in the system. Operational VTS sites for ship channels can be found at the following locations:

Prince William Sound, Alaska
Puget Sound, Washington
San Francisco, California
Los Angeles/Long Beach, California
Houston/Galveston, Texas
Berwick Bay, Louisiana
New York, New York
Sault St. Marie, Michigan

More information on the VTS services can be found in Chapter 20.

19.3 PILOTAGE

Pilots are required in every major seaport in the world. They are responsible for navigating ships safely through the ocean entrance channel. Pilots usually go through a lengthy apprentice period, during which they become knowledgeable about local conditions, as well as proficient in shiphandling.

Many ports have specialized pilots to direct the ship in different segments of the ship channel. The licensed Columbia River bar pilots board an incoming ship in the ocean, and are responsible for navigating the vessel across the 17-mile stretch of river mouth. The bar pilot can delay the ship passage if weather conditions are too severe for a safe crossing. After crossing the river mouth, the bar pilot transfers pilotage to a licensed Columbia River pilot. River pilots are responsible for navigating vessels to their final destination on the 100-mile shipping channel. River pilots also determine the draft of ships that may safely navigate the river.

The pilots of the State of Maryland are examples of specialized pilots. The Chesapeake Bay is the longest pilotage route in the U.S. East Coast; it is nearly 200 miles long. Each ship engaged in foreign trade coming into a Maryland port is required to take on a local ship-handling specialist to navigate the vessel safely into port. There are both bay pilots and docking pilots. Docking pilots are specialized pilots who are uniquely trained to maneuver commercial vessels in close quarters during docking, undocking, and shiftings (with tugboat assistance) within Maryland waters.

Pilots are a valuable resource in channel design. Because of their local knowledge, they can identify problem areas, and are generally asked to participate in ship simulation studies for navigation channel enlargement projects.

19.4 NORMAL MAINTENANCE

Ship channel maintenance falls into two categories: structure repair and channel dredging. Structural repairs are needed on a periodic basis because

FIGURE 19-1. Yaquina Bay, Oregon Jetty Repair (COE, Portland District).

of the constant attack of waves, currents, debris, and ice. For example, in the U.S. West Coast, wave attack is fairly uniform year-round. A typical 12-second-period swell can produce 7,200 wave impacts per day on a jetty. After several years, this constant attack will degrade the jetty, and the outer end wall will need periodic rebuilding. An example of jetty repair is shown in Figure 19-1.

Other ship channel structures that need periodic repair are shoreline revetment and river training structures that are meant to confine flow to keep sediment moving. Floating debris and ice often cause damage to these structures.

Dredging is usually the most costly normal maintenance item. The location and volume of this work can often be predicted based on past experience. Usually, the same river-crossing shoal will require dredging at the same rate, unless an extreme event occurs. Dredging equipment, practice, and disposal alternatives are presented in Chapter 10.

19.5 MAINTENANCE AS A RESULT OF EXTREME EVENTS

Extreme events can lead to significantly greater maintenance efforts and, in some cases, new construction. Extreme events include volcano eruptions, earthquakes, major floods, and hurricanes.

FIGURE 19-2. Mount St. Helens Erupting (COE, Digital Visual Library).

19.5.1 Volcanoes

The Mount St. Helens volcanic eruption on May 18, 1980 (Figure 19-2), resulted in massive sediment and debris flows into the Toutle River, which is a tributary of the Columbia River. This sediment clogged the Columbia River ship channel and required extensive dredging before project depths were reestablished.

A long-term problem remained, that is, increased sediment flow into the ship channel from the massive sediment sources (i.e., Toutle River and the slopes of Mt. St. Helens). The solution was twofold; dredge the Toutle River to preeruption levels (to return the river to its original flood level of protection) and construct a sediment retention structure in the North Fork of the Toutle River. This roller-compacted embankment with a multilevel outlet is working, and the high-level ungated spillway has been successful in stopping large sediment movement to the lower Toutle River and Columbia River ship channel. The sediment retention structure is shown in Figure 19-3.

19.5.2 Earthquake

The 1964 earthquake in Alaska caused a shift in the ocean floor (both upheaval and subsidence). The shift generated a tsunami and several land-slides. This 9.2 magnitude quake was the second most powerful earthquake

FIGURE 19-3. Mount St. Helens Sediment Retention Structure (COE, Digital Visual Library).

ever recorded. The consequences in Alaska were 115 dead and $84 million in damages in 1964 dollars. The damages would be equivalent to $2 billion in 2004 dollars. The effects of the resulting tsunami was felt as far away as San Francisco, California, and Hawaii. The tsunami caused a temporary hazard to ship traffic, as shown in Figure 19-4. The fishing boat in the photo was deposited by the tsunami from the Kodiak boat harbor to Third Street. The Volkswagen near the bow gives an idea of the ship size. The majority of the buildings on First, Second, and Third Streets were destroyed. A longer-term navigation problem was caused by the ocean floor shift, which made all the nautical charts in the region invalid. The fault line ran north and south through Prince William Sound. East of the fault line, the bottom had uplift with a maximum of about 30 ft near Montague Island. Figure 19-5 shows barnacles on the sea floor that had been below the lowest tide level before the earthquake.

The Alaska town of Cordova in Prince William Sound experienced about 6 ft of uplift, as can be seen in Figure 19-6.

The immediate need for chart revisions was achieved by establishing tide gauges near benchmarks that were used in previous hydrographic surveys. Because the sea level had not changed, running a level line from the gauge to the benchmark would determine a new elevation for the benchmark. With this knowledge, charts could be revised for navigation

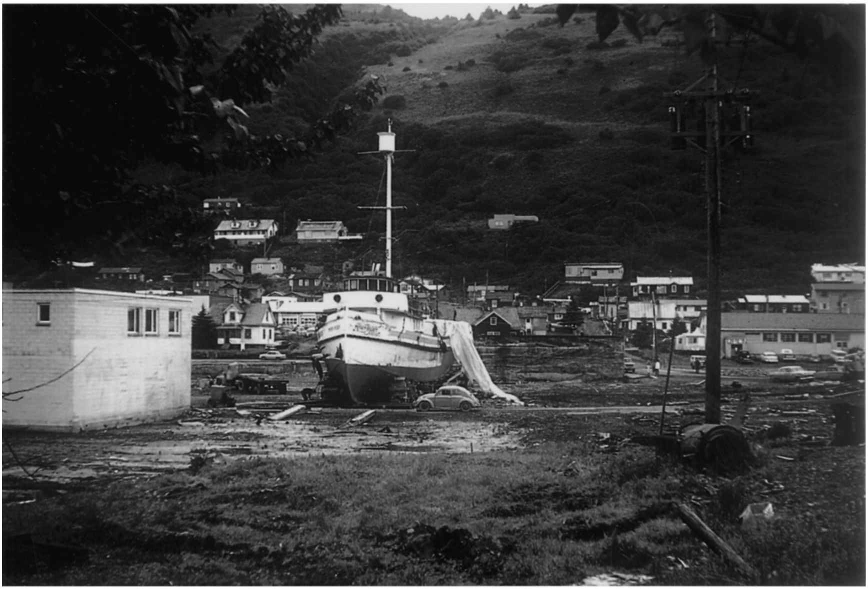

FIGURE 19-4. Fishing Boat in Downtown Kodiak, Alaska (from Lieutenant (jg) B. McCartney).

FIGURE 19-5. MacLeod Harbor Floor, Montague Island After 30 ft of Uplift (1964) (from Lieutenant (jg) B. McCartney).

FIGURE 19-6. Cordova Waterfront After 6 ft of Uplift (1964) (from Lieutenant (jg) B. McCartney).

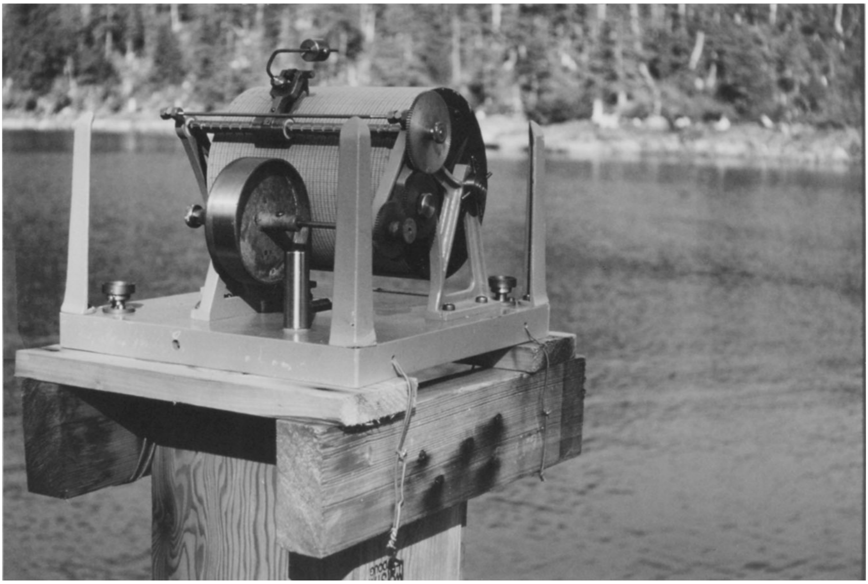

FIGURE 19-7. Typical Tide Gauge, Prince William Sound (1964) (from Lieutenant (jg) B. McCartney).

safety and to determine location and volume of dredging that is needed to re-establish pre-earthquake channel depths.

Figure 19-7 shows a typical portable tide gauge. The drive was powered by a spring with water levels recorded on a revolving drum mounted graph that was wax-coated. The spring needed to be rewound and the graph paper had to be changed about every 7 days.

19.5.3 Major Floods

Major floods can deposit large quantities of sediment in ship channels when high water starts to lower and river current velocities decrease. Dredging following a major flood may be 10 times higher than in normal years. Figure 19-8 shows three hopper dredges working immediately above Head of Passes in the Mississippi River during the March 1999 high water.

FIGURE 19-8. USACE Dredges Essayon, Wheeler, *and* MacFarland *in Mississippi River Ship Channel (COE, Digital Visual Library).*

FIGURE 19-9. Rescue of Grounded Ship (COE, Digital Visual Library).

19.5.4 Hurricanes

Some of the Gulf Coast channels extend several miles out to sea with no protective jetties. These channels are vulnerable to heavy shoaling from passing hurricanes. Large hurricane-generated waves and strong currents can easily deposit sediment in deeper ship channels, a convenient sediment trap.

19.6 ACCIDENTS

Accidents in ship channels are infrequent, but they do occur. These events can be ship to ship, ship to obstruction (e.g., as a bridge or pier), or groundings that are a result of excessive draft, a vessel outside channel boundaries, or channel shoaling. Figure 19-9 shows the *Chemtrans Belocean* set free. Six tug boats were used to free the vessel when it ran aground in the Mississippi River near the Head of Passes.

The agency or agencies responsible for the operation of a ship channel normally have an accident response plan in place, for rapid and appropriate action. This action includes rescue, vessel removal to reopen the channel, and pollution clean up.

19.7 OPERATION AND MAINTENANCE PLAN (O&M)

A comprehensive plan of how the project will be operated and maintained after construction is desirable. The following elements are normally included in the O&M plan:

1. Changes and costs: The predicted physical changes with time after construction and the anticipated O&M costs.
2. Surveillance plan: This plan covers minimum monitoring of the project performance to verify safety and efficiency. Included are the type and frequency of surveys, data collection, and a periodic inspection schedule. Hydrographic surveys, beach profiles, tide and wave records, and jetty stability data collection costs should be used to determine operation costs.
3. Project performance assessment: An assessment of the project performance is desirable. Inspections and analysis of comparative surveys can be used to verify design information, such as rates of erosion, shoaling, and jetty deterioration, as predicted during the design effort.
4. Accident or Emergency Response plan. This plan would identify responsibilities, communication links, and actions to be taken in the event of accidents, oil spills, or other problems that could compromise the waterway operation.

Chapter 20

COAST GUARD ACTIVITIES THAT SUPPORT NAVIGATION

20.1 GENERAL

The Coast Guard carries out numerous safety missions and tasks, including port safety and security, waterways management, and commercial vessel safety. It is responsible for providing a safe, efficient, and navigable waterway system to support domestic commerce, international trade, and military sealift requirements for national defense. The services the Coast Guard provides include long- and short-range aids to navigation; charting; tide/current/pilotage information through "Notices to Mariners"; vessel traffic services; domestic and international icebreaking and patrol services; technical assistance and advice; vessel safety standards and inspection; and bridge administration standards and inspection. These services can be consolidated into five fundamental roles:

Maritime Mobility
Maritime Safety
Maritime Security
National Defense
Protection of Natural Resources

Many Coast Guard missions benefit more than one of its roles. For example, whereas the aids to navigation mission primarily supports the service's maritime mobility role by facilitating the movement of people and goods, the system of aids also supports the Coast Guard's role of keeping maritime safety and protecting natural resources by preventing accidents.

20.2 MARITIME MOBILITY

The U.S. marine transportation system facilitates America's global reach into foreign markets and engagement in world affairs, including protection of U.S. national interests through a national and international regulatory framework governing trade and commerce. This system includes the waterways and ports through which more than 2 billion tons of America's foreign and domestic freight and 3.3 billion barrels of oil move each year, as well as the intermodal links that support economic and military security. It also includes international and domestic passenger services, commercial and recreational fisheries, and recreational boating. The Coast Guard's primary missions for providing a safe and efficient marine transportation system include:

Aids to Navigation
Icebreaking
Bridge Administration
Waterways Management/Vessel Traffic Service

20.2.1 Aids to Navigation

The waters of the United States and its territories are marked to assist navigation by the U.S. Aids to Navigation System. This system employs a simple arrangement of colors, shapes, numbers, and light characteristics to mark navigable channels, waterways, and obstructions. Figure 20-1 shows the types of aids used on the navigable waters of the United States.

The goal of the U.S. Aids to Navigation System is to promote safe navigation on waterways. Aids to Navigation can provide a boater with the same type of information drivers get from street signs, stop signals, road barriers, detours, and traffic lights. These aids include lighted structures, beacons, day markers, range lights, fog signals, and landmarks, as well as floating buoys. Each aid has a purpose, and helps in determining location, how to get from one place to another, or how to stay out of danger.

The U.S. Aids to Navigation System is intended for use with nautical charts, one of the most important tools used by boaters for planning trips and safely navigating waterways. Charts show the nature and shape of the coast, buoys and beacons, depths of water, land features, directional information, marine hazards, and other pertinent information. This valuable information cannot be obtained from other sources, such as a road map or atlas. Figure 20-2 shows a sample nautical chart.

The primary components of the U.S. Aids to Navigation System are beacons and buoys.

Beacons are aids to navigation structures that are permanently fixed to the earth's surface. They range from lighthouses to small single-pile structures and may be located on land or in the water. Lighted beacons are called lights; unlighted beacons are called daybeacons. Beacons exhibit a daymark to make them readily visible and easily identifiable against background conditions.

Buoys are floating aids that come in many shapes and sizes. They are moored to the seabed by concrete sinkers with chain or synthetic rope

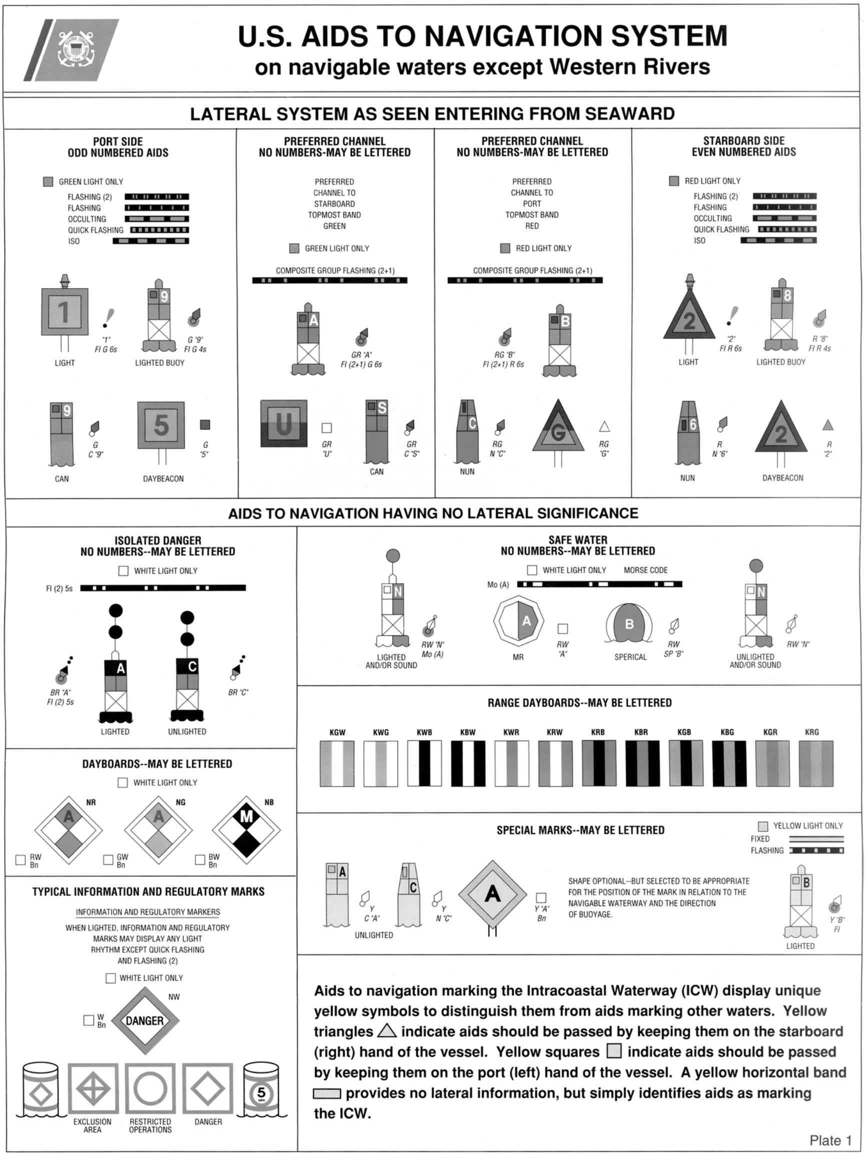

FIGURE 20-1. U.S. Aids to Navigation. (See also Plate 1, following page 130.)

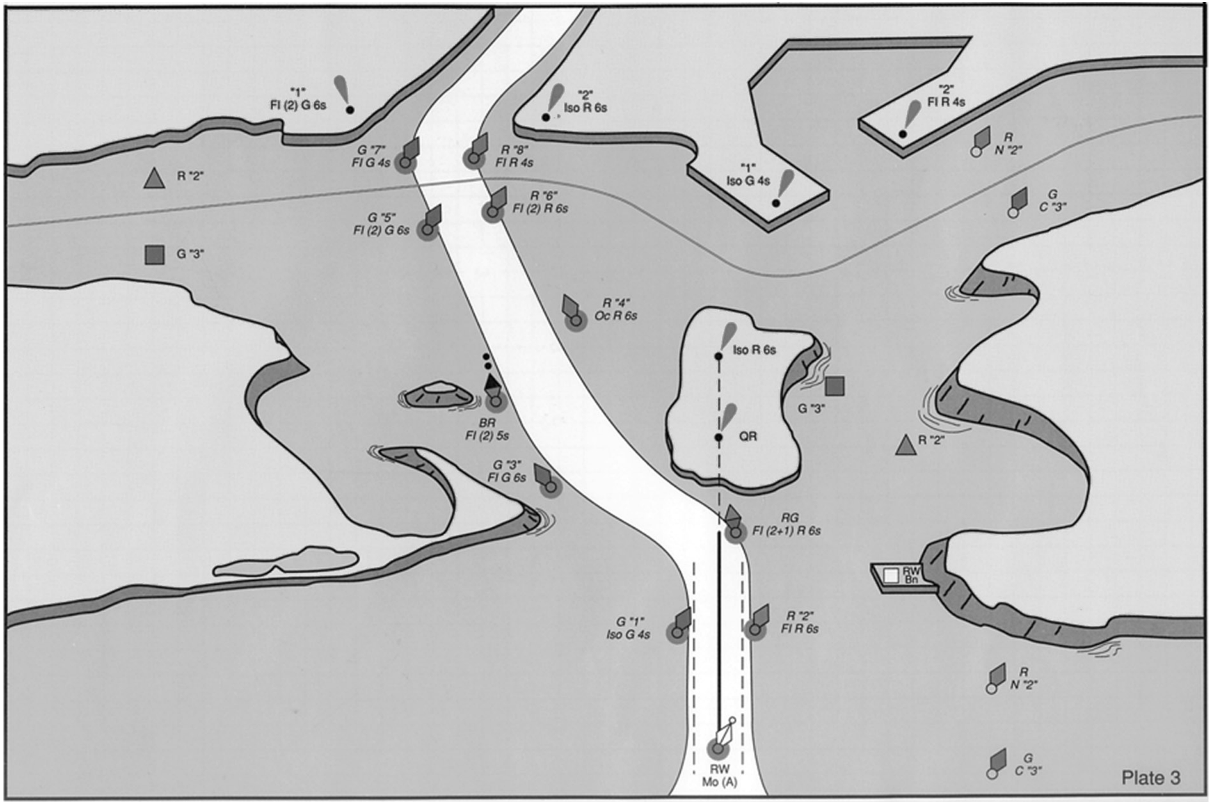

FIGURE 20-2. Aids to Navigation Placement. (See also Plate 2, following page 130.)

moorings of various lengths. They are intended to convey information to the boater by their shape or color, by the characteristics of a visible or audible signal, or a combination of two or more such features.

20.2.2 Private Aids to Navigation

A Private Aid to Navigation is a buoy, light, or daybeacon owned and maintained by any individual or organization other than the U.S. Coast Guard. These aids are designed to allow individuals or organizations to mark privately owned marine obstructions or other similar hazards to navigation. For further information, contact your local Coast Guard District Aids to Navigation Office.

The U.S. Army Corps of Engineers regulates the placement of mooring buoys in all navigable U.S. waters. Those wishing to establish mooring buoys must contact their local Army Corps of Engineers office.

20.2.3 Western Rivers Marking System

The Western Rivers Marking System was merged with the U.S. Aids to Navigation System in 2003; and as of December 31, 2003, the Western Rivers Marking System was discontinued. However, until the transition is complete, both systems can still be found on the Western Rivers.

Western Rivers Marking System is a variation of the standard U.S. Aids to Navigation System (ATONS) and is found on the Mississippi River and tributaries above Baton Rouge, as well as on certain other rivers that flow toward the Gulf of Mexico. Figure 20-3 shows the types of navigation aids used on the Western Rivers and by states. Red daybeacons, lights, and buoys mark the starboard banks and limits of channels as vessels "return for sea" or proceed upstream. Green daybeacons, lights, and buoys mark the port banks and limits of navigable channels when going upstream. The Western Rivers Marking System varies from the standard U.S. system in the following ways:

1. Buoys are not numbered.
2. Passing daybeacons are not numbered but normally have an attached "Mile Marker" board that indicates the distance in statute miles from a fixed point (normally the river mouth).
3. Diamond-shaped nonlateral dayboards checkered red-and-white or green-and-white, similar to those used in the U.S. Aids to Navigation System, are used as crossing daybeacons where the river channel crosses from one bank to the other.
4. Lights on green buoys and on beacons with green daymarks show a single flash, which may be green or white.
5. Lights on red buoys and on beacons with red daymarks show a double flash [Group Flashing (2)], which may be red or white.
6. Isolated danger marks and safe water marks are not used.

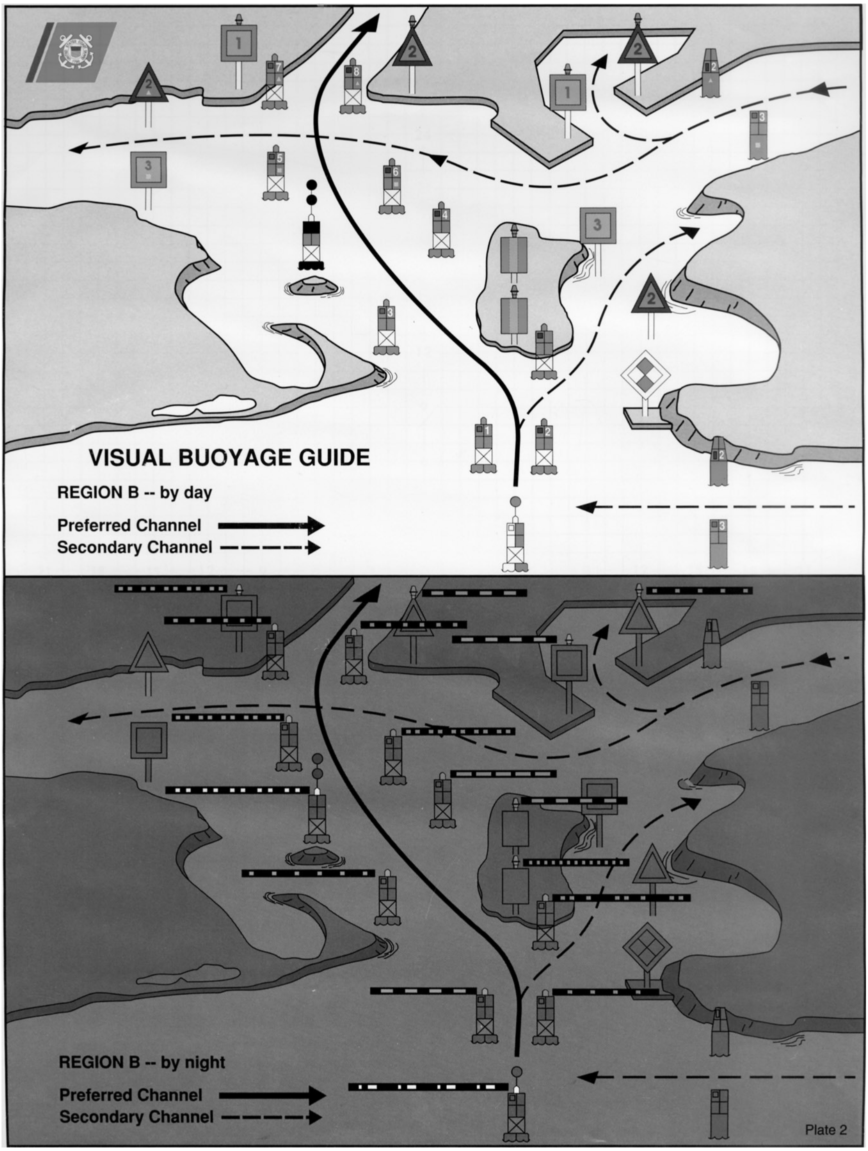

FIGURE 20-3. Visual Buoyage Guide. (See also Plate 3, following page 130.)

20.2.3.1 River Bank Names. When travel is downstream, the banks are named "right" and "left." The right bank has green aids and the left bank has red aids; thus, the west bank of the Mississippi is its right bank and has green aids. To avoid confusion, commercial river traffic often calls the right bank the right descending bank, and the left bank, the left descending bank.

20.2.3.2 Mile Markers. These markers are some of the most useful aids on a river. They are attached to daybeacons or displayed in other easily seen places. Because the U.S. Corps of Engineers erects them, they show distance in statute miles rather than in nautical miles. With the exception of the Ohio River, mile markers indicate the distance upstream from the mouth of a river. Ohio River markers start at its headwaters and indicate the distance downstream. Mile Markers also help a vessel operator locate his/her position on a river chart.

20.2.3.3 Crossing Daybeacons. Because the navigable channels of rivers swing from bank to bank as the river bends, diamond-shaped crossing daybeacons are used to assist river traffic by indicating where these channels change from one side of the river to the other. Crossing daybeacons are always on the opposite side of the river. When a diamond-shaped crossing daybeacon is sighted, the vessel operator should head for the "diamond," and treat the color of the daybeacon as a channel mark (i.e., keep red mark to the left bank when traveling downstream).

20.2.3.4 River Buoys. Changes in river channels caused by fluctuations in water level, current speed, and shifting shoals make buoys maintenance a continuous task for the Coast Guard. In wintertime when rivers freeze, buoys can be lost or can move. Because of their somewhat temporary nature, river buoys do not have letters or numbers and usually are not shown on river charts.

20.2.4 Notice to Mariners

The Coast Guard has statutory and treaty obligations to make navigation information available to the public. Local Notices to Mariners (LNMs) are the primary means for communicating information pertaining to individual Coast Guard Districts (Figure 20-4). LNMs, which are available free of charge, provide important safety information that is not available anywhere else. LNMs appear on the Coast Guard Navigation Center's Web site at http://www.navcen.uscg.gov/lnm/default.htm. Historically, LNMs were printed and distributed to the public via a free subscription service; however, a revision to the Coast Guard's Aids to Navigation (ATON) Manual (COMDTINST M16500.7) authorized elimination of printed LNMs. The last printed LNMs were distributed on April 1, 2004.

20.2.5 Ice Breaking

For decades, the U.S. Coast Guard has provided both domestic and international icebreaking services. Section 2 of Title 14, of the U.S. Code, requires the Coast Guard to operate icebreaking facilities on domestic and international waters. In 1965, the Coast Guard and the Department of the

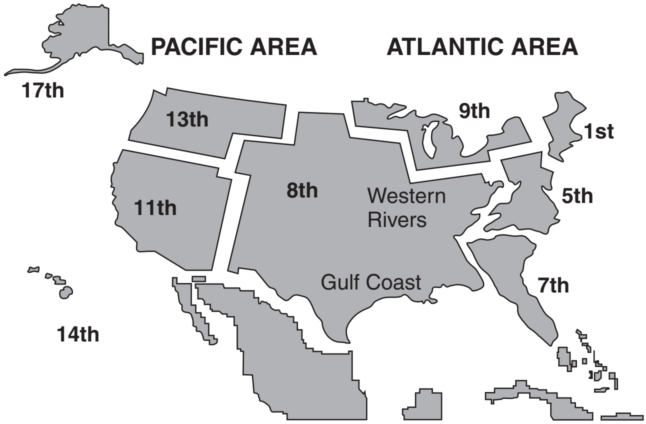

FIGURE 20-4. Coast Guard Districts (uscg.mil/units).

Navy signed a Memorandum of Agreement that requires the Coast Guard to maintain and operate all U.S. icebreakers in wartime as well as undertake seasonal deployments to the Arctic and Antarctic in support of national interests. A typical ice breaker is shown in Figure 20-5.

Domestic ice-breaking operations are performed on U.S. navigable waters in support of national and international maritime transportation, commerce, and safety. Geographically, domestic ice breaking is conducted in two regions, on the East Coast, from Maine to Virginia, and on the Great Lakes. The Coast Guard's fleet of ice capable ships includes both icebreaking cutters and buoy tenders. In domestic waterways, the Coast Guard conducts icebreaking operations to keep certain shipping routes and ports open during the winter to meet the demands of commerce. The Coast Guard responds to a vessel operator's requests for assistance if they are disabled or stranded in ice-covered waters.

The Coast Guard has a policy of noninterference with commercial icebreaking services. However, few commercial icebreaking services have developed in areas where the Coast Guard has icebreaking vessels, because the Coast Guard promptly responds to all assistance requests and provides its services free of charge.

20.2.5.1 East Coast Domestic Ice Breaking. The Coast Guard deploys 14 vessels that are designed primarily to perform icebreaking services along East Coast waterways between Maine and Virginia. Two 140-foot icebreaking tugs are stationed in New Jersey and another is stationed in Rockland, Maine. These small cutters are specially configured for icebreaking along U.S. coastal waters. These vessels incorporate an advanced hull design and engineering plant, along with a "bubbler" hull air lubrication

FIGURE 20-5. Coast Guard Polar Icebreaker Polar Star *(WAGB 10) (U.S. Coast Guard Digital Library).*

system, for effective icebreaking and winter flood-relief operations. The bubbler system pumps air through openings in the hull below the waterline reducing ice friction, allowing the cutter to pass easily though ice fields. Eleven 65-ft small harbor tugs, which are engaged in icebreaking services during the winter, operate along the East Coast. One tug is stationed in Portsmouth, Virginia, to service the Chesapeake Bay; two are stationed in Pennsylvania; three in Bayonne, New Jersey; one in New Haven, Connecticut; one in Boston, Massachusetts; and three in Maine. During severe weather, the Coast Guard can move ice-capable vessels, mainly buoy tenders (stationed in more southerly locations) to northern areas to assist in ice-breaking activities.

Figure 20-6 shows CGC *Sturgeon Bay,* a 140-foot ice-breaking tug homeported in Bayonne, New Jersey, preparing to make tracks in the ice for a tug and barge, and attempting to transit the Cape Cod Canal, about 65 miles south of Boston. Nearly 70% of home heating oil bound for New England arrives there via the Cape Cod Canal.

20.2.5.2 Great Lakes Ice Breaking. There are 10 icebreaking-capable vessels assigned to the Great Lakes to maintain a 42-week shipping season. Three 140-foot Bay Class tugs are stationed in Michigan; one is stationed in Sturgeon Bay, Wisconsin; and one in Cleveland, Ohio. The Coast Guard Cutter *Mackinaw* is the only heavy icebreaking vessel assigned to the Great Lakes. This vessel is currently stationed in Cheboygan, Michigan, and is scheduled for decommissioning in fiscal year 2006. Four other buoy tenders stationed in Michigan and Minnesota also are used to keep Great Lakes shipping lanes open during the winter.

On the Great Lakes, there are seven key waterways that must be kept navigable during the winter, when ice formation restricts or prohibits ship movements. In an average year, over 100 million metric t of domestic cargo moves on the Great Lakes. During most winters, the Great Lakes icebreaking program allows shipping to continue for an additional 6-8 weeks, enabling an additional 10-12 million t of cargo to be shipped over ice-covered waters.

The Coast Guard Cutters *Biscayne Bay* (WTGB 104) and *Katmai Bay* (WTGB 101) are shown on Figure 20-7, breaking ice in the Straits of Mackinac (Figure 20-7).

20.2.6 Bridge Administration

In 1967, the Bridge Program was transferred from the Army Corps of Engineers to the Coast Guard. The Coast Guard is responsible for approval of the location and plans of bridges and causeways constructed across navigable waters of the United States. In addition, the Coast Guard is responsible for approval of the location and plans of international bridges

FIGURE 20-6. CGC Sturgeon Bay *USCG (U.S. Coast Guard Digital Library).*

and the alteration of bridges found to be unreasonable obstructions to navigation. Authority for these actions is found in the following statutes: 33 U.S.C 401, 491, 494, 511–524, 525, and 535a, 535b, 535c, 535e, 535f, 535g, and 535h (Note: these are all separate sections, not subsections of 535). Section 535 and following is popularly known as the International Bridge

FIGURE 20-7. Coast Guard Cutters Biscayne Bay *(WTGB 104) and* Katmai Bay *(WTGB 101) Break Ice in the Straits of Mackinac (U.S. Coast Guard Digital Library).*

Act of 1972. To implement these statutes, the Coast Guard has published the following regulations in 33 CFR Chapter I, Subchapter J (Bridges):

1. Part 114—General;
2. Part 115—Bridge Locations and Clearances; Administrative Procedures;
3. Part 116—Alteration of Obstructive Bridges;
4. Part 117—Drawbridge Operation Regulations; and
5. Part 118—Lighting of Bridges.

20.2.6.1 Bridge Lighting and Other Signals. In U.S. waters, the Coast Guard prescribes certain combinations of fixed lights for bridges and structures extending over waterways (Figure 20-8). In general, red lights (A) are used to mark piers and supports and green lights (B) mark the centerline of the navigable channel through a fixed bridge. If there is more than one channel through the bridge, the preferred route is marked by three white lights (C) placed vertically. Red lights (D) also are used on some lift bridges to indicate the lift is closed, and green lights (E) are used to indicate that the lift is open to vessel traffic. Double-opening swing bridges are lighted

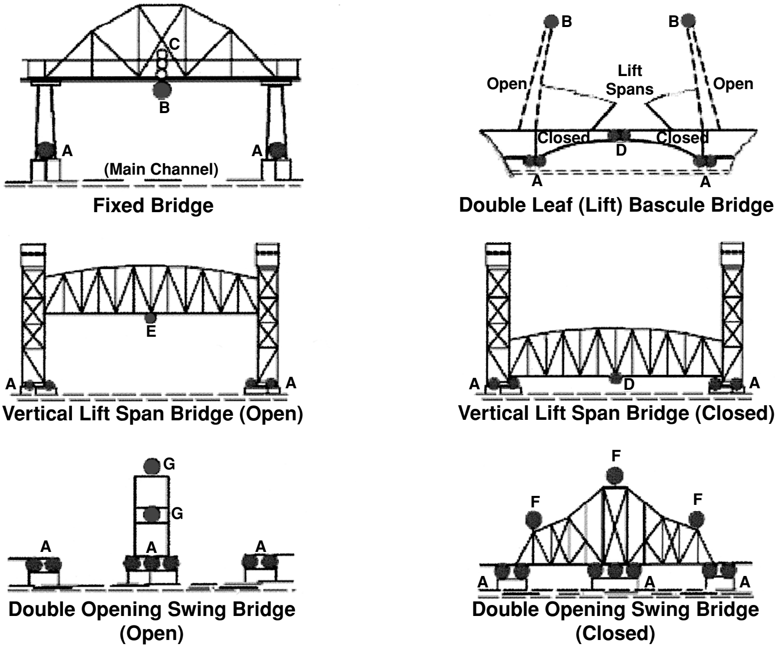

FIGURE 20-8. Combinations of Fixed Lights for Bridges and Structures Extending over Waterways (uscgboating.org). (See also Plate 4, following page 130.)

with three lanterns on top of the span structure; when viewed from an approaching vessel, the swing span when closed will display three red lights (F) and when open for navigation will display two green lights (G).

Clearance gauges are extremely valuable to vessel operators because they indicate the vertical distance (clearance) between the "low steel" of the bridge channel span and the waterline. (They do not indicate the depth of water under the bridge.) These gauges, located on the right side of the channel facing approaching vessels, are permanently fixed to the bridge pier or structure. Each gauge is marked by black numbers and foot marks (lines) on a white background board.

Further information on drawbridge regulations and opening signals for bridges over the Navigable Waterway can be found in the U.S. Coast Pilot books.

20.2.7 Waterways Management/Vessel Traffic Service

The Coast Guard has a statutory responsibility under the Ports and Waterways Safety Act of 1972 (PWSA), Title 33 USC §1221, to ensure the

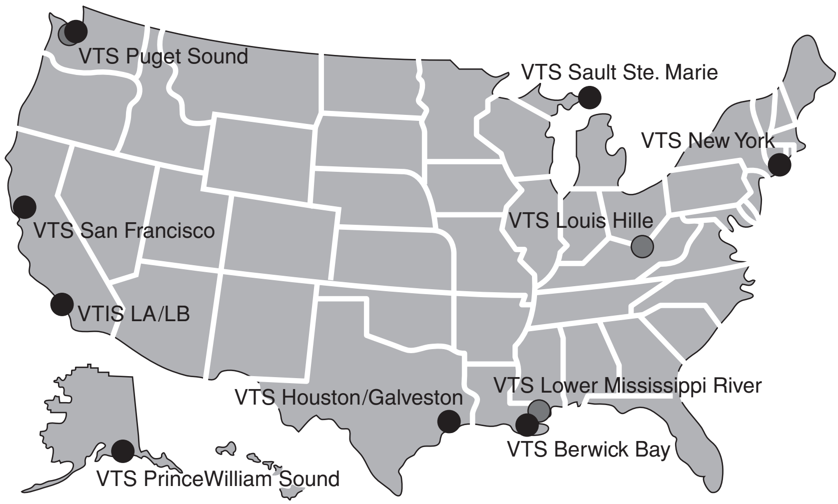

FIGURE 20-9. Coast Guard VTS Locations (navcen.uscg.gov).

safety and environmental protection of U.S. ports and waterways. The PWSA authorizes the Coast Guard to "... establish, operate and maintain vessel traffic services in ports and waterways subject to congestion." It also authorizes the Coast Guard to require the carriage of electronic devices necessary for participation in the VTS system. The purpose of the act was to establish good order and predictability on U.S. waterways by implementing fundamental waterways management practices.

The VTS system at each port has a Vessel Traffic Center that receives vessel movement data from the Automatic Identification System (AIS), surveillance sensors, other sources, or directly from vessels. Meteorological and hydrographic data is also received at the vessel traffic center and disseminated as needed. AIS technology relies on global navigational positioning systems (GPS), navigation sensors, and digital communication equipment operating according to standardized protocols (AIS transponders) that permit the voiceless exchange of navigation information. AIS transponders can broadcast vessel information such as name or call sign, dimensions, type, GPS position, course, speed, and navigation status. This information is continually updated and received by all AIS-equipped vessels in the vicinity. An AIS-based VTS reduces the need for voice interactions; enhances the ability to navigate; improves situational awareness; and assists in the performance of duties, thus reducing the risk of collisions.

Figure 20-9 illustrates the location of current Coast Guard VTS areas.

20.2.7.0.1 VTS New York. The control center is located at Fort Wadsworth in Staten Island, New York. In 1995, Coast Guard Activities, New York, assumed operational control of the VTS, which has the responsibility of coordinating vessel traffic movements in the busy ports of New York and New Jersey. The VTS New York area includes the entrance to the harbor via Ambrose and Sandy Hook Channels, through the Verrazano Narrows Bridge to the Throgs Neck Bridge in the East River, to the Holland Tunnel in the Hudson River, the Kill Van Kull including Newark Bay and all of Arthur Kill, and Raritan Bay.

20.2.7.0.2 VTS San Francisco. The San Francisco Vessel Traffic Center is located at Yerba Buena Island in San Francisco Bay. VTS San Francisco is responsible for the safety of vessel movements along approximately 133 miles of waterway from offshore to the ports of Stockton and Sacramento. On May 3, 1995, federal regulations established regulated navigation areas within the San Francisco Bay Region. These regulations, developed with input from the Harbor Safety Committee of the San Francisco Bay Region, were designed to improve navigation safety by organizing traffic flow patterns; reducing meeting, crossing, and overtaking situations in constricted channels; and limiting vessels' speeds. VTS San Francisco also operates an Offshore Vessel Movement Reporting System (OVMRS), which is completely voluntary and operates using a broadcast system with information provided by participants.

20.2.7.0.3 VTIS Los Angeles/Long Beach. Vessel Traffic Information Service (VTIS) Los Angeles-Long Beach (LA/LB) is jointly operated by the Coast Guard and Marine Exchange of LA/LB from the Vessel Traffic Center located in San Pedro. The VTIS assists in the safe navigation of vessels approaching the ports of LA/LB in an area extending 25 miles out to sea from Point Fermin (LAT 33 42.3′N LONG 118 17.6′W). The LA/LB VTIS developed a unique partnership with the state of California, the Coast Guard, the Ports of Los Angeles-Long Beach, the Marine Exchange, and the local maritime community. With start-up funds provided by the ports of Los Angeles and Long Beach, the VTIS operations are supported by fees assessed against commercial vessels operating in the LA/LB area. VTIS LA/LB came on line in March 1994.

20.2.7.0.4 VTS Puget Sound. The Vessel Traffic Center is located at Pier 36 in Seattle and monitors the Strait of Juan de Fuca, Rosario Strait, Admiralty Inlet, and Puget Sound south as far as Olympia. Since 1979, the U.S. Coast Guard has worked cooperatively with the Canadian Coast Guard in managing vessel traffic in adjacent waters. Through the Cooperative Vessel Traffic Service (CVTS), two Canadian Vessel Traffic Centers work hand in hand with Puget Sound Vessel Traffic Service. Tofino Vessel Traffic Service manages the area west of the Strait of Juan de Fuca. North of the Strait of

Juan de Fuca, through Haro Strait, to Vancouver, British Columbia, is managed by Vancouver Vessel Traffic Service. The three Vessel Traffic Centers communicate via a computer link and dedicated telephone lines to advise each other of vessels passing between their respective zones.

20.2.7.0.5 VTS Houston-Galveston. The Vessel Traffic Center is located in the upper reaches of the Houston Ship Channel within the city of Houston. The VTS operating area is the Houston Ship Channel from the sea buoy to the turning basin at the upstream end of the channel (a distance of 53 miles) and the side channels to Galveston, Texas City, Bayport, and the Intracoastal Waterway.

20.2.7.0.6 VTS Prince William Sound. The Prince William Sound Vessel Traffic Center is located in Valdez. Geographically, the area is comprised of deep open waterways surrounded by mountainous terrain. The Coast Guard has installed a dependent surveillance system to improve its ability to track tankers transiting Prince William Sound, and requires these vessels to carry position and identification reporting equipment. The ability to supplement radar with dependent surveillance bridges the gap in areas in which conditions dictate some form of surveillance and radar coverage is impractical. Once the dependent surveillance information is returned to the vessel traffic center, it is integrated with radar data and presented to the watchstander on an electronic chart display. VTS Prince William Sound is required by the Trans-Alaska Pipeline Authorization Act (Public Law 93-153), pursuant to authority contained in Title 1 of the Ports and Waterways Safety Act of 1972 (86 Stat. 424, Public Law 92-340). The southern terminus of the pipeline is on the south shoreline of the Port of Valdez. Port Valdez is at the north end of Prince William Sound.

20.2.7.0.7 VTS St. Mary's River. The St. Mary's River Vessel Traffic Center is located at Coast Guard Group Sault Ste. Marie, Michigan. In October 1994, it became a mandatory system operating year-round with an area of responsibility along the entire length of the St. Mary's River (approximately 80 miles). Within the VTS area the water level drops approximately 21 ft from the level of Lake Superior to the level of the lower lakes. The Soo Locks were constructed and are presently maintained by the Corps of Engineers. In most areas of the river there is adequate room for vessels to maneuver or anchor during periods of low visibility, or when other problems hinder safe navigation. However, three areas are extremely hazardous to transit or anchor in low visibility: West Neebish Channel (downbound traffic only), Middle Neebish Channel (upbound traffic only), and Little Rapids Cut (two-way traffic). During periods of low visibility, it is customary to close the entire river.

20.2.7.0.8 VTS Berwick Bay. The Berwick Bay Vessel Traffic Center is located at Coast Guard Marine Safety Office Morgan City, Louisiana. VTS Berwick Bay manages vessel traffic on one of the most hazardous waterways in the United States due to strong currents and a series of bridges that must be negotiated by inland tows traveling between Houston, Baton Rouge, and New Orleans. The area of responsibility encompasses the junction of the Atchafalaya River (an outflow of the Mississippi River), the Gulf Intracoastal Waterway, the Port Allen-Morgan City Alternate Route, and several tributary bayous. Narrow bridge openings and a swift river current require the VTS to maintain one-way traffic flow through the bridges. During seasonal high-water periods, the VTS enforces towing regulations requiring inland tows transiting the bridges to have a minimum amount of horsepower based on the length of tow. VTS Berwick Bay is unique among Coast Guard Vessel Traffic Services because it maintains direct control of vessel traffic.

20.2.7.0.9 VTS Louisville. The Louisville Vessel Traffic Center is located at Coast Guard Group Ohio Valley in Louisville, Kentucky. VTS Louisville is a vessel movement reporting system designed to enable vessel operators to better cope with problems encountered during high water on the Ohio River between miles 592.0 and 606.0. The VTS has no active surveillance equipment such as radar or cameras. It monitors traffic via VHF Channel 13 communications only. The VTS is activated when the upper river gauge at the McAlpine Lock and Dam is approximately 13 ft and rising. It remains in 24-hr operation until the upper river gauge falls below 13 ft. River conditions vary widely, especially during springtime. A series of thunderstorms can, at times, necessitate activation of the VTS in a matter of hours.

20.3 MARITIME SAFETY

One of the most basic responsibilities of the U.S. government is to protect the lives and safety of Americans. In the maritime realm, the lead responsibility falls to the Coast Guard. In partnership with other federal agencies, state and local governments, marine industries, and individual mariners, the Coast Guard preserves safety at sea through a focused program of prevention, response, and investigation.

20.3.1 Prevention

Safety prevention activities include developing commercial and recreational vessel standards, enforcing compliance with these standards, licensing commercial mariners, operating the International Ice Patrol to protect ships transiting the North Atlantic shipping lanes, and educating the public. The Coast Guard develops operating and construction criteria for many types of vessels from commercial ships to recreational boats. The Coast Guard is America's voice in the International Maritime Organization (IMO), which promulgates measures to improve shipping safety, pollution prevention, mariner training, and certification standards. The Coast Guard is the agency primarily responsible for developing domestic shipping and navigation regulations.

Navigation and shipping regulations are published in Chapter I of Titles 33 and 46, Code of Federal Regulations (CFR). These regulations provide detailed guidance for the design and operation of inspected vessels, and establish minimal requirements for uninspected vessels.

The Coast Guard ensures compliance with safety regulations in many ways. Members of the Coast Guard inspect U.S. flag vessels and mobile offshore drilling units and marine facilities; examine foreign-flag vessels based on the potential safety and pollution risk they pose; review and approve plans for vessel construction, repair, and alteration; and document and admeasure U.S. flag vessels. The Port State Control program is aimed at eliminating substandard foreign-flagged vessels from U.S. ports and waterways. Port State Control is a key element in the safety enforcement program because 95% of large passenger ships and 75% of cargo ships operating in U.S. waters are foreign-flagged.

20.3.2 Response (Search and Rescue)

Mishaps will occur despite the best prevention efforts. As the lead agency for maritime search and rescue (SAR) in U.S. waters, the Coast Guard coordinates the SAR efforts of sea and airborne Coast Guard units, as well as those of other federal, state, and local responders. In addition, they also leverage the world's merchant fleet to rescue mariners in distress around the globe through the Automated Mutual-Assistance Vessel Rescue (AMVER) system.

The statutory authority for the U.S. Coast Guard to conduct SAR missions is contained in Title 14, Sections 2, 88, and 141 of the U.S. Code. The code states that the Coast Guard shall develop, establish, maintain, and operate SAR facilities, may render aid to distressed persons, and protect and save property on and under the high seas and waters subject to the jurisdiction of the United States. These waters generally include all navigable waters subject to the jurisdiction of the United States but also include international waters stretching far into the Atlantic and Pacific Oceans and the Gulf of Mexico.

The mission and purpose of the Coast Guard's SAR Program is to prevent death or injury to persons and loss or damage to property in the marine environment. SAR functions and the hierarchy of response can be broken down into two parts:

1. **Search:** An operation normally coordinated by a rescue coordination center (RCC), rescue subcenter (RSC), or group/activities operations center, using available and appropriate personnel, facilities, and resources to locate persons or property in distress.
2. **Rescue:** An operation with the primary purpose of retrieving persons in distress and delivering them to a place of safety. This may include providing for certain medical care or other critical needs. Rescue operations also may be performed for the purpose of preventing or mitigating property loss or damage. However, missions shall not normally be performed for the purpose of salvage or recovery of property when those actions are not essential to the saving of life. Beneficial secondary consequences of a rescue operation may be to prevent environmental damage or remove hazards to navigation, but these are not considered part of the rescue operation's objective.

The rescue of persons in distress is the highest priority SAR mission. Missions *solely* for saving property or for other purposes such as preventing environmental damage will always give way to saving a person's life.

The Coast Guard does dangerous work in a perilous environment. Their heritage is based in large part on the selfless acts of courageous men and women who use their tools and their judgment under the most demanding conditions to save the lives of others.

20.3.3 Casualty Investigations

An important purpose of marine casualty investigations is to obtain information to prevent similar casualties, as far as is practicable. It is necessary for the causes of casualties to be determined as precisely as possible so that factual information will be available for program review and statistical studies. It is not sufficient to know only *how* a casualty occurred; it also must be clear *why* it happened. Based on this information, the Coast Guard may develop appropriate corrective measures, regulations, and standards of safety. In addition, legislation for marine safety may be recommended, if needed. An equally important purpose of these investigations is the determination of whether there is any evidence of violation of law or regulation, any basis for the institution of civil penalty action under any of the laws administered by the Coast Guard, or suspension and revocation (S&R) proceedings under 46 U.S.C. 7703.

The Coast Guard has the jurisdiction to investigate the following:

1. A marine casualty or other accident involving any vessel on the navigable waters of the United States, or involving U.S. vessels wherever they may be.

2. An incident involving the destruction of, or damage to, any bridge or other structure on or in the navigable waters of the United States, or any land structure or shore area immediately adjacent to those waters.
3. An incident involving a major fire, an oil spill, or any injury occurring as a result of operations conducted pursuant to the Outer Continental Shelf Lands Act (OCSLA), including allegations of unsafe working conditions or violations of safety regulations.
4. Water pollution by oil or other hazardous substance or the threat thereof to the "waters of the United States" (anywhere in the hydrologic chain).
5. Acts of misconduct, incompetence, negligence, unskillfulness, or willful violation of law committed by any licensed, certificated, or documented individual.
6. Boating accidents.
7. Casualties or accidents that occur to any component of a deep-water port.

The primary purpose of an investigation is to ascertain the cause(s) of an accident, casualty, or personnel misbehavior to determine if remedial measures should be taken; and to determine whether any violation of federal law or regulation has occurred. It should be clearly understood that the Coast Guard does not conduct investigations to determine civil liability in disputes between private litigants. Rather, its investigations are a means to promote safety of life and property and to protect the marine environment.

20.4 MARITIME SECURITY

Maritime law enforcement and border control are the oldest of the Coast Guard's numerous responsibilities, dating back as the Revenue Marine in 1790. Congress established the Revenue Marine specifically to patrol the coasts and seaports to frustrate smuggling and enforce the customs laws of the fledgling republic. The Coast Guard's maritime law enforcement role and the task of interdicting ships at sea provide the foundation on which the much broader and complex present-day mission set has been built. Maritime Security Missions include:

General Maritime Law Enforcement
Drug Interdiction
Alien Migrant Interdiction
EEZ and Living Marine Resource Law/Treaty
Enforcement

20.4.1 General Maritime Law Enforcement

As the nation's primary maritime law enforcement service, the Coast Guard enforces or assists in enforcing federal laws, treaties, and other international agreements on the high seas and waters under U.S. jurisdiction. They possess the authority to board any vessel subject to U.S. jurisdiction to make inspections, searches, inquiries, and arrests. The Coast Guard wields extraordinarily broad police power primarily to suppress violations of drug, immigration, fisheries, and environmental laws. No other U.S. armed service or federal agency possesses this combination of law enforcement capabilities and responsibilities together with the legal authorities to carry them out.

The Coast Guard's ability to fulfill its roles (i.e., saving lives and property at sea; protecting America's maritime borders and suppressing violations of the law; protecting the marine environment; providing a safe, efficient marine transportation system; and defending the nation) makes the Coast Guard truly a unique instrument of national security.

20.4.2 Drug Interdiction

As the designated lead agency for maritime drug interdiction under the National Drug Control Strategy and the co-lead agency with the U.S. Customs Service for air interdiction operations, the Coast Guard defends America's seaward frontier against a virtual torrent of illegal drugs. For more than two decades, Coast Guard cutters and aircraft, forward deployed off South America and in the transit zone, have intercepted many t of cocaine, marijuana, and other illegal drugs that otherwise would have found their way to American streets.

20.4.3 Alien Migrant Interdiction

Coast Guard alien migrant interdiction operations are also law enforcement missions with a significant humanitarian dimension. Migrants typically take great risks and endure significant hardships in their attempts to flee their countries and enter the United States. In many cases, migrant vessels interdicted at sea are overloaded and unseaworthy, lack basic safety equipment, and are operated by inexperienced mariners. The majorities of alien migrant interdiction cases handled by the Coast Guard actually begin as SAR cases, once again illustrating the interwoven nature of the Coast Guard's roles and missions. Between 1980 and 2000, the Coast Guard intercepted 290,000 migrants, mostly from Cuba, Dominican Republic, People's Republic of China, and Haiti.

20.4.4 EEZ and Living Marine Resource Law/Treaty Enforcement

In 1976, Congress passed what is now known as the Magnuson-Stevens Fishery Conservation and Management Act. By creating an Exclusive Economic Zone (EEZ), this act pushed out the U.S. maritime border to 200 nautical miles. In the years that followed, international fisheries agreements went even further, extending U.S. jurisdiction to high seas areas beyond the EEZ. Today, the Coast Guard patrols these areas, as well as the EEZ—where they focus primarily on maritime boundary areas such as the U.S./Russian Convention Line in the Bering Sea—to uphold U.S. sovereignty and protect America's precious resources.

20.5 NATIONAL DEFENSE

Throughout American history, the Coast Guard has served alongside the U.S. Navy in critical national defense missions, beginning with the Quasi-War with France in 1798, through the Civil War, World Wars I and II, to the Vietnam War and the Persian Gulf War. A 1995 agreement between the Secretaries of Defense and Transportation assigned the Coast Guard five specific national defense missions in support of the Unified Commanders-in-Chief (CINCs) in addition to their general defense operations and polar icebreaking duties. These missions (i.e., maritime interception operations; military environmental response operations; port operations, security, and defense; peacetime military engagement; and coastal sea control operations) require the Coast Guard to execute essential military functions and tasks in support of joint and combined forces in peacetime, crisis, and war.

20.6 PROTECTION OF NATURAL RESOURCES

The Coast Guard's protection of natural resources role dates to the 1820s, when Congress required the Revenue Marine to protect federal stocks of Florida live oak. As the exploitation of the nation's valuable marine resources—whales, fur-bearing animals, and fish—increased, the Coast Guard was given the duty to protect these resources as well. Today, with the U.S. EEZ supporting commercial and recreational fisheries worth more than $30 billion annually, the Coast Guard serves as the primary agency for at-sea fisheries enforcement. This role has expanded over the last few decades to include enforcing laws intended to protect the environment as a public good. As a result, the Coast Guard now actively protects sensitive marine habitats, marine mammals, and endangered marine species, and enforces laws protecting U.S. waters from the discharge of oil and other hazardous substances.

The Coast Guard conducts a wide range of activities (e.g., education and prevention, enforcement, response and containment, and recovery) in support of its primary environmental protection mission areas: maritime pollution enforcement, offshore lightering zone enforcement, domestic fisheries enforcement, and foreign vessel inspection. They are usually the first responders to environmental disasters on the seas and are typically the lead agency for any ensuing response effort. Under the National Contingency Plan, Coast Guard Captains of the Port (COTP) are the predesignated Federal On-Scene Coordinators (FOSC) for oil and hazardous substance incidents in all coastal and some inland areas. The FOSC is, in reality, the president's designated on-scene representative. As such, the FOSC is responsible for forging a well-coordinated and effective response operation involving a diverse set of government and commercial entities in many emotionally charged and potentially dangerous emergency situations.

20.6.1 Pollution Response

The Coast Guard's concerns extend to pollution and threats of pollution in the coastal zone. This zone includes U.S. waters subject to the tide, U.S. waters of the Great Lakes, specified ports and harbors on inland rivers, and the contiguous zone and waters on the high seas out to 200 miles. There are four elements involved in assessing discharges and releases to ensure appropriate response:

1. Preventing spills whenever possible
2. Ensuring that responsible parties clean up discharges of oil and releases of hazardous substances
3. Mitigating the effects of spills that do occur
4. Reducing the potential for spills or operational discharges outside U.S. waters from entering U.S. waters or fouling U.S. coastlines

These elements are considered in all cases of pollution or threatened pollution that arise from deep-water ports or outer continental shelf activities.

To respond to major discharges, the Commandant has established the National Strike Force (NSF). This consists of teams of highly trained personnel that are prepositioned on the Atlantic, Gulf, and Pacific coasts to assist on-scene coordinators (OSC's) of federal response activities. Strike Teams are at the following locations: GULF Strike Team, Mobile, Alabama; NATIONAL Strike Force, Elizabeth City, North Carolina; PACIFIC Strike Team, Novato, California; and ATLANTIC Strike Team, Fort Dix, New Jersey. In addition, the NSF has assisted foreign governments on request in major international pollution cases.

The Coast Guard operates the National Response Center (NRC) around the clock to receive notification of pollution incidents and to ensure that information is passed to the predesignated Coast Guard or EPA OSC for response. The NRC provides a toll free number (800-424-8802) for making pollution reports from anywhere in the United States.

20.6.2 Enforcement

The federal responsibility for the removal of discharged oil and hazardous substances is shared by the Coast Guard and the EPA. The federal agencies cannot require anyone to clean up an oil spill; however, if federal funds are used for the clean up, the costs (up to certain limits) are passed to the owner or operator of the discharging vessel or facility or, under certain circumstances, to the person causing the discharge.

20.7 SOURCE

This chapter was authored by Eric P. Christensen, Commander, U.S. Coast Guard.

Chapter 21

NOAA ACTIVITIES THAT SUPPORT NAVIGATION

21.1 NATIONAL OCEAN SERVICE (NOS)

Marine navigation tools are necessary to ensure safe and efficient marine transportation and commerce, offshore engineering projects, naval operations, and recreational activities. The Office of Coast Survey, which is part of NOAA's National Ocean Service (NOS), is responsible for providing these tools, such as nautical charts and hydrographic surveys. These must be kept accurate and up to date at all times.

21.2 AUTHORIZING MANDATE

The mandate to create nautical charts of the nation's coasts dates back to 1807, when President Thomas Jefferson ordered a survey of the young nation's coast. The Organic Act of 1807 authorized the newly formed coastal survey agency to construct and maintain the nation's nautical charts. This agency, the Office of Coast Survey (OCS), is the oldest scientific organization in the United States. It has been a part of NOS since 1970, when the National Oceanic and Atmospheric Administration was created.

21.3 NAUTICAL CHARTS

OCS remains the primary agency responsible for constructing and maintaining the nation's nautical charts. The U.S. Army Corps of Engineers produces "navigational maps" for some inland rivers, primarily the Mississippi, Ohio, Tennessee, Columbia, and their tributaries. NOAA charts are available from NOAA field offices and a network of local sales agents. Corps of Engineers river charts are available from district offices. Nautical charts contain information about the nature and form of the coast, the depth of the water, and general character and configuration of the sea

FIGURE 21-1. NOAA Ship Surveyor *(NOAA Photo Library).*

bottom, locations of dangers to navigation, the rise and fall of the tides, locations of navigational aids, and characteristics of the earth's magnetism. The charts are compiled by using a fleet of hydrographic vessels that operate in the coastal waters of the continental United States and Alaska and Hawaii. A typical NOAA ship is shown in Figure 21-1.

NOS collects marine hydrographic data (depth soundings) to construct and maintain more than 1,000 nautical charts. In addition, NOS makes available a historical map and chart collection—more than 20,000 maps and charts dating from the late 1700s. The collection includes nautical charts, hydrographic surveys, topographic surveys, geodetic surveys, city plans, and Civil War battle maps.

NOAA's National Geographic Data Center (NGDC) is the repository of all NOAA (and many other organizations) hydrographic and bathymetric data. NGDC and the collocated World Data Center for Marine Geology & Geophysics compile, maintain, archive, and distribute data from extensive databases in both coastal and open ocean areas. Key data types include bathymetry and gridded relief, trackline geophysics (gravity, magnetics, seismic reflection), sediment thickness, data from ocean drilling and seafloor sediment and rock samples, digital coastlines, and data from the Great Lakes. In addition to operating the collocated World Data Center for Marine Geology & Geophysics, part of the International Council of Scientific Unions (ICSU) World Data Center system, NGDC

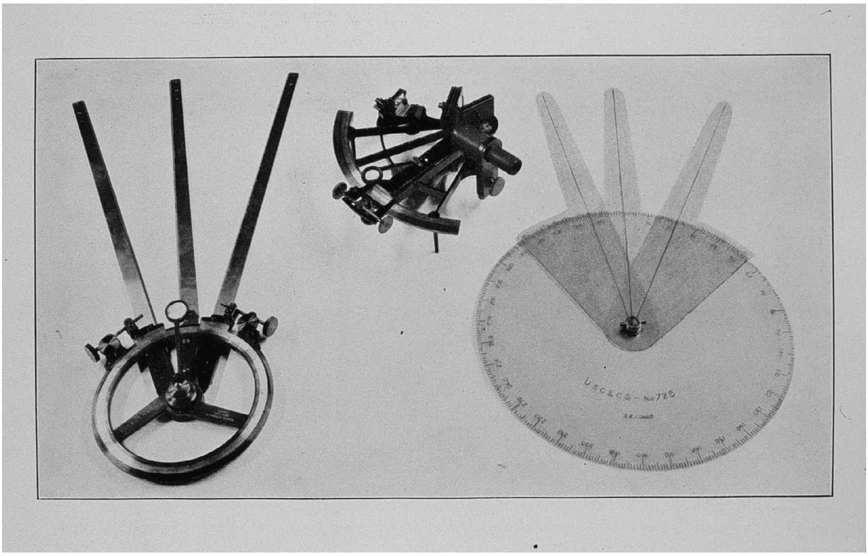

FIGURE 21-2. Sextant and Three-Arm Protractors Used for Chart-Making (NOAA Photo Library).

also operates the International Hydrographic Organization Data Center for Digital Bathymetry (IHO-DCDB) on behalf of the Member Nations of the International Hydrographic Organization. Additional information on NGDC is available at http://www.ngdc.noaa.gov/mgg/mggd.

Coastal nautical charts initially were developed using two sextant angles shooting three known landside objects to establish the sounding vessel location. The depth was measured by a lead line. The lead line was replaced by electronic depth measurement equipment (fathometer) in the mid-20th century. A sextant is shown in Figure 21-2. The sextant method of positioning was still used until the 1970s and 1980s, when it was replaced by electronic ground positioning equipment. The present-day hydrographic surveys are completely automated from positioning, depth measurement, and plotting of results.

21.4 TIDES AND CURRENTS

NOAA's National Ocean Service (NOS) has been monitoring sea level variations for many years. For some U.S. locations, sea level records exist for more than 100 years. Water level data is used for a variety of practical purposes, including hydrography, nautical charting, maritime navigation, coastal engineering, and tsunami and storm surge warnings. Mariners use the information to time their approach to and exit from ports. Long-term applications include marine boundary determinations, tidal predictions, monitoring sea level trends, oceanographic research, and climate research. Bridge, breakwater, and deep-water channel construction also are affected by tidal and current changes.

Within NOS, the Center for Operational Oceanographic Products and Services (CO-OPS) is primarily responsible for predicting and measuring water levels and currents, and disseminating this information. CO-OPS collects, analyzes, and distributes such data to maintain safe maritime navigation and waterborne commerce. This real-time information is provided to shipmasters and pilots to help avoid groundings and collisions. The information provided includes water levels, currents, and other oceanographic and meteorological data from bays and harbors via telephone voice response and the Internet.

CO-OPS also manages the nation's National Water Level Observation Program (NWLON). NWLON provides basic tidal information to determine U.S. coastal marine boundaries and to create nautical charts. It also supports climate monitoring activities, tsunami and storm surge warning systems, coastal processes, and tectonic research. It consists of 175 continuously operating water level measurement stations along the U.S. coasts and in the Great Lakes regions. Many of these stations have been operational and transmitting data for 19 years.

FIGURE 21-3. Temporary Tide Gauge, Prince William Sound, Alaska (from Lieutenant (jg) B. McCartney).

Tide gauge stations are separated into two types: long-term, which are usually located in major harbors, such as Seattle and San Francisco; and temporary (operating for a few months), which support fieldwork, such as hydrographic surveys or current surveys. An example of this temporary tide gauge is shown in Figure 21-3.

The center also provides tidal and storm surge information online for U.S. coastal areas and the Great Lakes region. The Web site is updated every 10 minutes to reflect changing conditions. In addition, the center provides products that supply predictive information about tides and currents for more than 3,000 tide stations.

21.5 CURRENTS

Water currents are more difficult to measure. In the past, observations of currents were made for only a few days at a time at any particular location. More recently, however, continuous current observations have been made at several locations along the nation's coasts. However, these observation stations are subject to corrosion, marine fouling, and other damage, and are expensive to maintain.

An example of survey equipment in the 1960s is shown in Figure 21-4. The meter is suspended 15 ft below a surface buoy and records current

FIGURE 21-4. Current Survey Buoys on Board, USC&GS Hodson *in Puget Sound, Washington, 1964 (from Lieutenant (jg) B. McCartney).*

speeds and direction. Speed is measured by a rotating impeller at the front of a torpedo-shaped instrument, and magnetic direction is also recorded.

Current measurements are now usually taken by acoustic Doppler meters, which emit an acoustic signal from either a boat- or bottom-mounted transmitter. The signal is reflected from sediment or other particles transported by the flow and recorded. The reflected signal is analyzed to detect the Doppler shift in frequency, yielding a measure of flow velocity in three dimensions. The instruments can be constructed to measure velocity at a point or to profile a waterway, with regard to depth or width.

21.6 GLOBAL POSITIONING

The Global Positioning System (GPS) includes a constellation of 24 satellites, launched and operated by the U.S. Air Force, which transmits radio signals. When used according to standardized procedures, GPS receivers can determine positional coordinates to centimeter-level accuracy anywhere on the surface of the earth. The first GPS satellite was launched in 1978, and the system was declared fully operational for civilian applications in December 1993.

Augmenting this space-based system is a network of Continuously Operating GPS Reference Stations (CORS), which serve as the foundation for the National Spatial Reference System (NSRS). NSRS is a coordinate system that defines position (latitude and longitude), elevation, distance and direction between points, strength of gravitational pull, and the way in which these values change over time. This information is essential for ensuring the reliability of transportation and communication systems, boundary and property surveys, land record systems, mapping and charting, and many scientific and engineering applications. NSRS provides the positional integrity that allows use of GPS for many modern positioning applications.

The National Geodetic Survey (NGS), part of NOAA's National Ocean Service, coordinates a network of more than 400 CORS stations, which receive GPS radio signals 24 hours a day, seven days a week. The GPS data collected at these stations allow GPS users to determine more accurate positions through computation after the data are collected. Numerous federal, state, and local government agencies, as well as universities and commercial organizations, operate CORS stations. They are established and maintained according to rigorous standards developed by NGS to provide the most accurate GPS information available. CORS standards cover factors such as location and stability of the GPS-receiving antenna, and transmitting and computing GPS data.

21.7 COAST PILOT

The U.S. Coast Pilot consists of a series of nautical books that covers information important to navigators of coastal and intracoastal waters and the Great Lakes. Issued in nine volumes, these books contain supplemental information that is difficult to portray on a nautical chart.

Topics in the Coast Pilot include channel descriptions, anchorages, bridge and cable clearances, currents, tide and water levels, prominent features, pilotage, towage, weather, ice conditions, wharf descriptions, dangers, routes, traffic separation schemes, small-craft facilities, and federal regulations applicable to navigation. Coast Pilot publications are available through NOAA-authorized network nautical agents.

21.8 PORTS

The Physical Oceanographic Real-Time System (PORTS) is an information acquisition and dissemination technology developed by the NOS in cooperation with a number of ports throughout the United States. The first permanent, fully integrated, operational PORTS was deployed in Tampa Bay during 1990 and 1991. The system is managed, operated, and maintained under a cooperative agreement with NOS. PORTS includes the integration of real-time currents, water levels, winds, and water temperatures at multiple locations with a data dissemination system that includes telephone voice response as well as modem dial-up and dedicated modem displays. PORTS consists of acoustic Doppler current profilers (ADCPs) with water temperature sensors, a "nowcast" of currents at other locations, water level gauges with anemometers, packet radio transmission equipment, a data acquisition system, and an information dissemination system (IDS).

The traditional prediction tables that are updated annually by the NOAA provide information about the astronomical tides, currents, river flow, and other meteorological forces. Real-time measurements, enriched by nowcasts, were identified as critical requirements for safe navigation.

PORTS is a public information system that provides real-time information to the general public and provides essential information for safe and cost-effective navigation, search-and-rescue, hazardous material and oil-spill prevention and response, and scientific research. PORTS also provides NOAA's Global Ocean Observing System with coastal ocean measurement and dissemination components. All data is continuously archived and is available to the public. PORTS data is broadcast over NOAA Weather Radio hourly by the National Weather Service and is available on a priority basis for trajectory modeling in support of the U.S. Coast Guard.

PORTS systems are operational at the following locations:

San Francisco Bay
New York/New Jersey Harbor
Houston/ Galveston
Tampa Bay
Chesapeake Bay
Narragansett Bay

Soo Locks
Los Angeles/Long Beach
Delaware River and Bay
Port of Anchorage

21.9 MARINE AND COASTAL WEATHER SERVICES

The NOAA Weather Radio network provides voice broadcasts of local and coastal marine forecasts on a continuous cycle. The forecasts are produced by local National Weather Service forecast offices. Coastal stations also broadcast predicted tides and real-time observations from buoys and coastal meteorological sensors operated by NOAA's National Data Buoy Center. Recorded voice broadcasts have been largely supplanted by a computer-synthesized voice. Channel numbers (e.g., WX1, WX2) have no special significance but often are so designated in consumer equipment. Other channel numbering schemes also are prevalent. The NOAA Weather Radio network provides near continuous coverage of the coastal United States, the Great Lakes, Hawaii, and the populated Alaska coastline. Typical coverage is 25 nautical miles offshore, but it may extend much further in certain areas.

21.10 SOURCE

NOAA Web pages provided most of this information; the 1964 photos were taken by Lieutenant (jg) B. McCartney.

Chapter 22
CASE HISTORIES

This chapter revisits and updates the 3 case histories presented in ASCE Manual 80, 1993. These case histories are intended to show the application of design principles presented in earlier chapters. The unique features of these navigation projects are briefly summarized with more detail provided in the later part of the chapter.

22.1 CASE HISTORY 1—GRAYS HARBOR, WASHINGTON

This project involves the enlargement of an existing 26-mile-long channel. The channel starts in the Pacific Ocean and ends at the Port of Aberdeen, Washington. The channel provides one-way traffic for ocean-going cargo ships. The design included physical hydraulic models, ship simulation models, sediment studies, mitigation for fish and crabs, and dredge material disposal in confined estuary and ocean sites.

22.2 CASE HISTORY 2—NORFOLK HARBOR, VIRGINIA

This project involves the enlargement of an existing channel. The channel starts in the Atlantic Ocean and ends in the Elizabeth River. It provides access to terminals at Newport News, Norfolk, and terminates along the Elizabeth River. The new channel uses the "notched" concept with the outbound lane deeper than the inbound lane. The design included physical hydraulic models, ship simulation models, and numerical sediment models.

22.3 CASE HISTORY 3—SAVANNAH HARBOR, GEORGIA

This project involves the widening of a 5-mile section of an existing channel along the Savannah waterfront. The project purpose is to provide

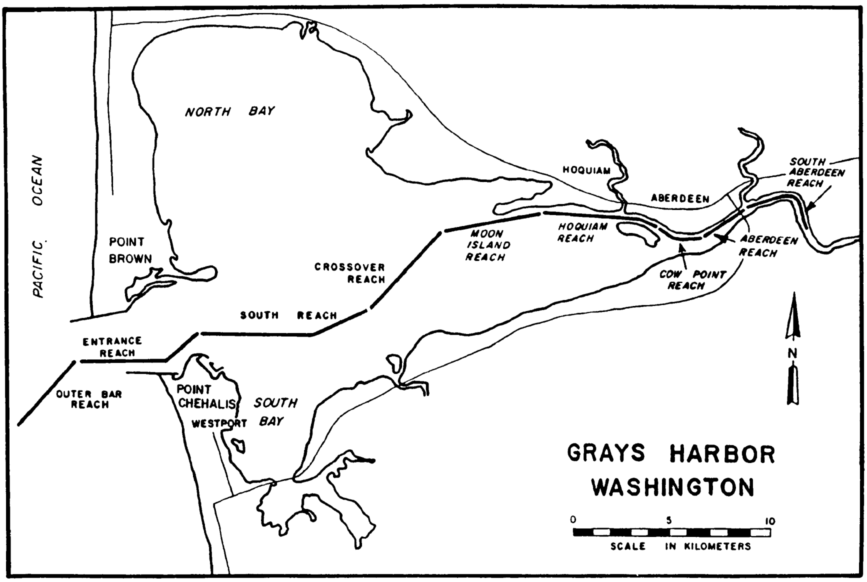

FIGURE 22-1. Grays Harbor, Washington (ASCE Manual No. 80).

a safer passing zone along this congested river reach. The final design consists of a ship simulation study to evaluate the safety benefits for the wider channel.

22.4 CASE HISTORY 1—GRAYS HARBOR, WASHINGTON

22.4.1 Project Description

Grays Harbor (Figure 22-1) is on the west coast of Washington State. It is 45 miles north of the Columbia River and 110 miles south of the Straits of Juan de Fuca. The estuary is 15 miles long and 11 miles wide, with a surface area that varies between 97 square miles at mean higher high water (MHHW) to 33 square miles at mean lower low water (MLLW). Two jetties protect the ocean entrance.

A 26-mile-long channel extends from the Pacific Ocean to the port facilities at the cities of Hoquiam, Aberdeen, and Cosmopolis. The channel, in 1989, was 350 ft wide and 30 ft deep with some 200-ft-wide segments at the upstream end. The desire to enlarge the channel came from the increasing number of vessels that were lightloaded to use the channel. In 1975, fewer than 40% of vessels had drafts exceeding the 30-ft depth.

By the mid-1980s, about 80% of the vessels had drafts exceeding 30 ft. The U.S. Army Corps of Engineers completed a study in 1989 to evaluate the need for an enlarged channel to accommodate the deeper-draft vessels. This study included the following: channel design; physical hydraulic model ship simulations; dredging and disposal; economic and environmental impacts; mitigation; sedimentation; and relocations.

22.4.2 Proposed Channel Improvements

The before and after channel dimensions follow:

Channel Reach	Original Project, in Feet	Enlarged Project, in Feet
Ocean bar	30 × 600 (not dredged)	46 × 1000
Entrance	30 × 600 (not dredged)	46-38 × 1000-600
Outer harbor	30 × 350	36 × 350
Inner harbor	30 × 200	36 × 300-250

22.4.3 Hydrodynamic and Wind Conditions

The channel traffic is exposed to three different hydraulic conditions. The ocean bar and entrance experience large waves, tidal currents, and strong winds. The estuary reach has mild waves, currents, and winds, and the river reach has river currents and a confined channel with some sharp bends. The tide range for this project follows.

	Elevation in Feet Referred to MLLW	
Data Plane	Pt. Chehalis	Aberdeen
Highest tide (estimated)	14.00	14.90
Mean higher high water	9.00	10.10
Mean sea level	4.60	5.38
Mean lower low water	0.00	0.00
Lowest tide (estimated)	–3.50	–2.90

The strongest winds are from the west, southwest, and south. These winds can reach 70 miles per hour from April to September.

Significant wave heights of 20 to 30 ft can be expected each year off Grays Harbor. Swells generally approach the coast southwest to northwest. The majority of the swell periods are 12 to 18 s. Sea conditions often have a more southerly approach in winter and north-northwest approach in the summer. Wind-generated waves in the estuary can reach 5 ft, although 1- to 3-ft-high waves are more common.

22.4.4 Design Vessel

There were two design vessels selected for this enlargement study. The design vessel for the lower harbor has a loaded draft of 37 ft, a length of 625 ft, and a beam of 100 ft. The upper harbor design vessel is 600 ft long, with a l00-ft beam and a draft of 37 ft.

22.4.5 Channel Depth Design

The channel depths were designed to consider the factors outlined in EM 1110-2-1613 (1983). The vessel operation scenario assumes only outbound transits are loaded; outbound transits are normally made during floodtide; and maximum allowable wave height of 8 ft for outbound transit.

Information on wave effects for the Grays Harbor ocean entrance was taken from a study of 53 vessel transits over the Columbia River bar conducted between May 1978 and April 1980. The data showed the maximum excursion of the ship's bow will be less than 14 ft, 95% of the time, for the limiting 8-ft wave height. The 8-ft wave constraint is for pilot safety when boarding an incoming ship. Table 22-1 shows the channel depths selected for the various channel reaches.

TABLE 22-1. Summary of Channel Depths for Design Vessel (ft).

(1)	Above Bridges (2)	Inner harbor (3)	Outer* harbor (4)	Entrance* channel (5)	Outer* bar (6)
Design ship draft	37.0	37.0	37.0	37.0	37.0
Minimum safe clearance	2.5	2.5	3.0	4.0	4.0
Freshwater sinkage	0.5	0.5	0	0	0
Trim	0.5	0.5	0	0	0
Squat	1.0	1.0	0.5	0	0
Snip motion due to waves	0	0	2.0	4–14	14.0
Tide	−6.0	−6.0	−6 to −7	−7 to −8	−9.0
Totals – channel depths	35.5	35.5	36.5–35.5	38–46	46.0
Recommended depths	36.0	36	36	38-46	46

*For severe wave design conditions, vessels are assumed to be evenly trimmed (bow excursion is critical) and pilots will reduce vessel speed and/or time transits for near high tide.

In addition to these depths, an allowance of 2 ft for dredging tolerance and 2 ft for advanced maintenance were included in initial and future maintenance dredging work.

22.4.6 Channel Width and Alignment Design

Guidance from EM 1110-2-1613 (1983) was used for preliminary design on this project. During the detailed design of this project, ship simulation studies were used to determine channel alignment and widths, including bend widening.

With the relatively small number of vessels arriving and leaving Grays Harbor, design for two-way traffic is not warranted. Certain portions of the estuary, such as north of Point Chehalis and Moon Island Reach, have adequate room for passing of vessels. Under most passing conditions, light-loaded inbound vessels can find adequate water depths either at the channel bend widenings or in naturally deep areas along the channel. Pilots are equipped with ship-to-ship radio and passing situations are discussed between pilots.

The deeper-draft channel alignment is generally along the existing channel with minor modifications to take advantage of naturally deep parts of the estuary. The channel follows the thalweg of the Chehalis River and is generally aligned with existing current patterns in the estuary, minimizing annual maintenance dredging and maximizing safe navigation for ships. Ship sizes and speeds were considered in the degree of turns in the alignment, but alignments are generally governed by the existence of deep water. The entrance channel is aligned through deep water off Point Chehalis and along the south jetty. The outer bar channel is aligned along a southwest azimuth because of pilot preference and to minimize initial and maintenance dredge quantities. Outgoing ships will quarter or be abeam to most swell along this alignment. Discussions with pilots at Grays Harbor indicate that they are more concerned about being set by the currents and wind and by vessel pitch than roll of the vessel. Present bar transits are usually made in a southwest direction. Incoming vessels are empty or light-loaded and can usually navigate safely with quartering or stern seas, and because of relatively deep water over other parts of the outer bar do necessarily follow the designated outer bar channel into the harbor. Ship simulation studies (Hewlett, Eagles, Huval, and Daggett, 1991) were conducted at the U.S. Army Waterways Experiment Station (WES) Hydraulic Laboratory, and simulation runs were made by all four Grays Harbor pilots.

The simulator was developed from bathymetric condition surveys. Current data obtained from the Grays Harbor estuary model were supplemented by field measurements of currents, photographs, pilot discussions, and from an outbound transit experience made by WES and district personnel. Two reaches of channel were tested, 8.5 miles of the outer channel from Moon Island through the south reach and about 4 miles of the inner channel reaches Aberdeen and South Aberdeen. Vessels tested were a 535-ft-long by 34-ft design draft ship for existing channel conditions and a 625-ft-long by 36.5-ft design draft ship for improved channel conditions. All outbound simulations were run with fully loaded vessels. Inbound simulations were made with light-loaded vessels transiting through the bridges and turning at Elliott Slough. Summary of the test results follows.

22.4.7 Outer Harbor Simulations

The crossover and south reach channels were authorized at 400 ft and as a study alternative to this width were simulated at 350 ft width. The simulation showed pilots could "safely" navigate a 350-ft-wide channel with the 625-ft-long vessel except for major turns in the channel reaches. After exiting Moon Island Reach, pilots all tended to drift to the outside of the channel. An outside widening of 100 ft to a 450-ft channel width is recommended for the first 3,000 ft of crossover with an additional 1,800 ft of taper back to the 350-ft-wide channel.

Similarly, after the exit of crossover, pilots would drift to the outside of upper South Reach. Outside widening of 100 ft is also recommended for the upper south reach. Length of this widening is 2,500 ft with a taper back to 350 ft of an additional 1,000 ft. These bend-widening areas are generally in locations of naturally deep waters and require little dredging.

22.4.8 Inner Harbor

The Aberdeen and South Aberdeen reaches were authorized at 250 ft wide along with the replacement of an existing railroad bridge, which would increase the horizontal clearance through the railroad bridge and adjacent upstream highway bridge from 125 to 195 ft. The maximum-size vessel considered for economic analysis during feasibility studies was a 600-ft-long by 90-ft beam vessel with a draft of 34 ft. In an investigation to determine if larger vessels commonly used by carriers could transit this reach, the 625-ft by 100-ft beam with loaded draft of 36.5 ft was tested. Simulation results showed this transit could be made "safely" if the channel from Elliott Slough to the bridges was 300 ft wide and if minor widening allowances just upstream of the highway bridge were made, including removal of two old bridge piers.

22.4.9 Hydrodynamic and Sediment Studies

The following hydrodynamic and sediment studies were made for this project.

1. Physical hydraulic model to assess changes in salinity, circulation, flushing rates, and currents. This information was used to estimate changes in water quality for the environmental-impact assessment.
2. Field studies of near-bottom currents using drogue observations. This information was used in sediment-movement analysis and selection of disposal sites.
3. Analysis of past dredging records and disposal site performance. This information was used to estimate future dredging requirements and select disposal locations.

22.4.10 Dredge Material Disposal

There are three categories of disposal sites: ocean, entrance channel, and confined upland. There are two ocean sites: one beyond the 90-ft contour about 3 miles southwest of the south jetty and the other in about 150 ft of water 8 miles west of the south jetty.

The entrance channel disposal sites are in two dispersive locations off Point Chehalis, which have been used in the past for dredge disposal. Two upland sites are near the Port of Grays Harbor facility in Aberdeen.

22.4.11 Mitigation

The channel enlargement causes an impact on crabs and fish habitat. Several crab mitigation sites were selected in North and South Bays. The mitigation consisted of placing oyster shells in the site to allow cover and reduced predation on young crabs. The fish mitigation consisted of creating additional habitat in the river above the navigation channel.

22.4.12 Relocations

The relocations for this project consist of moving utility lines crossing under the channel and replacing a railroad bridge. The existing railroad bridge has a 125-ft horizontal clearance between piers. The options were to replace the bridge with a longer span or remove the bridge. Bridge removal was selected. With removal of the railroad bridge, the highway bridge would become the width constraint with its 195 ft of horizontal clearance.

22.4.13 Project Status

The dredging of the bar, entrance, and outer harbor channels took place between April 1990 and February 1991. The railroad bridge was removed in 1997.

22.5 CASE HISTORY 2—NORFOLK HARBOR AND CHANNELS, VIRGINIA

22.5.1 Project Description

Norfolk Harbor (Figure 22-2) is on the east coast of Virginia on the southern parts of Chesapeake Bay. The Chesapeake Bay is over 200 miles long and is the largest estuary in the United States. The navigation channels start in the Atlantic Ocean and serve both Norfolk and Newport News harbors. A channel enlargement was desired to accommodate large bulk carriers, up to 150,000 deadweight t.

22.5.2 Proposed Channel Improvements

The before-and-after channel dimensions and other features are listed in Table 22-2.

TABLE 22-2. Before-and-After Channel Dimensions.

Channel Reach	Original Project, in Feet	Final Enlarged Project, in Feet*
Atlantic Ocean	None	60 × 1300
Thimble Shoal	45 × 1000	55 × 1000
Norfolk Harbor	45 × 800 to 1500	55 × 800 to 1500
Newport News	45 × 800	55 × 800
North Segment Elizabeth River	40 × 375 to 750	45 × 375 to 750
South Segment Elizabeth River	35 × 250 to 500	40 × 250 to 500
End of South Segment Elizabeth River	None	40 × 800 turning basin
Varied	None	3 new fixed mooring and anchoring facilities

*Project will be built in stages with outbound lanes deepened first.

22.5.3 Hydrodynamic and Wind Conditions

The tidal cycle in the project area is semidiurnal, with two high tides and two low tides occurring in a 24-hr period. The mean tidal range varies between 2.5 ft at Norfolk Harbor and 3.5 ft at the Atlantic Channel. The combined effect of tide and wind has produced water levels between −0.3 and +10.0, referred to as mean low water.

The prevailing wind direction is north and northeasterly during February, March, September, and October, and south or southwest for the remainder of the year. The speed of the fastest wind occurring in every

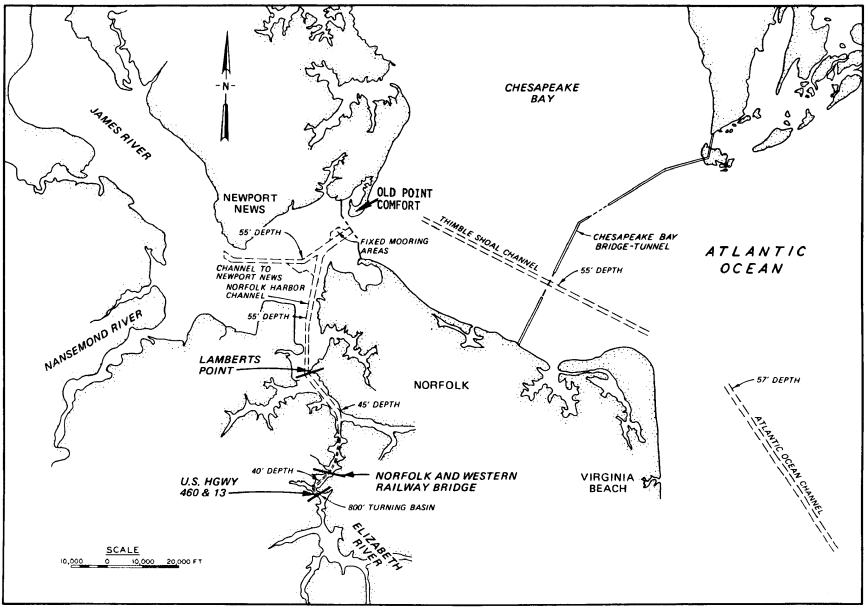

FIGURE 22-2. Norfolk Harbor, Virginia (ASCE Manual No. 80).

month of the year has been over 50 miph, with a maximum speed on record of 80 miph.

Wave climate throughout the project region is generally mild, except during abnormal weather conditions. Under normal conditions, wave action causes few navigation problems throughout the project area. The mildest wave conditions prevail throughout Norfolk Harbor and Hampton Roads, where the surrounding topography minimizes development of substantial waves. The representative wave climate of Hampton Roads and vicinity follows.

Wave Climate of Hampton Roads and Vicinity

Wave Height (1)	Percentage of Time (2)
Less than 2 ft	78%
3 to 4 ft	16%
5 to 9 ft	5%
Greater than 10 ft	1%

The wave climate of lower Chesapeake Bay is characterized by conditions more inclement than that of Hampton Roads. Wave information typical of lower Chesapeake Bay is shown below.

Wave Climate of Lower Chesapeake Bay.

Wave Height (2)	Percentage of Time (2)
Less than 2 ft	75%
3 to 4 ft	18%
5 to 9 ft	6%
Greater than 10 ft	1%

The largest waves in the project area occur in the vicinity of the Atlantic Ocean Channel. At this location, severe wave heights, often associated with northeasters and hurricanes, can cause navigational problems. Normally, this wave action comes from the northeast. A study of 20 years of wave data offshore of Cape Henry was used to develop the following information.

Wave Climate of Atlantic Ocean Channel and Vicinity.

Wave Height (1)	Percentage of Time (2)
Less than 2 ft	56%
3 to 4 ft	35%
5 to 9 ft	07%
Greater than 10 ft	02%

22.5.4 Design Vessels

The design vessels were selected on the basis of an engineering analysis of the principal vessels comprising the vessel fleet, future trends in bulk cargo vessels, and coordination with the U.S. Coast Guard, U.S. Maritime Administration, and the Virginia Pilots Association. The primary design vessel used for simulation studies and design computations had the following characteristics:

Vessel type	Bulk Carrier (Collier)
Length overall	915 ft
Beam	145 ft
Draft-loaded	52 ft
Draft-ballasted	40 ft
(representative of a 150,000 deadweight t vessel)	

A secondary design vessel was used for simulation studies as a sensitivity test for vessel size and maneuverability and had the following characteristics:

Vessel type	Wide Beam Bulk Carrier
Length overall	1,085 ft
Beam	178 ft
Draft-loaded	53 ft
Draft-ballasted	40 ft

22.5.5 Channel Design Simulation Studies

Computer-aided channel design simulation studies were made for the Atlantic Ocean Channel, Thimble Shoal Channel, Norfolk Harbor Channel, the Channel to Newport News, and the connecting waters between the Norfolk Harbor Channel on the Thimble Shoal Channels.

22.5.6 Channel Depth Design

The feasibility study identified the Thimble Shoal Tunnel as a limiting factor to practical channel depth for the Norfolk Harbor and Channels deepening project. As a consequence, a project depth of 55 ft was established for the Norfolk Harbor Channel, Channel to Newport News, Thimble Shoal Channel, and the deep-draft anchorages. Ship hydrodynamic investigations indicate that the design vessel is capable of operating with a 52-ft draft under the maximum credible port condition of a 40-knot wind and a current velocity of 0.5 knots. These conditions will permit the majority of vessels to operate in an unrestricted manner. A small number of very large bulk carriers will be unable to fully load with a 55-ft project depth; however, the total project economics makes this unavoidable. The channel depths are as follows:

Channel	Interior Channels	Atlantic Ocean
Vessel draft	52 ft	52 ft
Safety clearance	2 ft	2 ft
Heave, pitch, roll, squat, and trim	1 ft	6 ft
	55 ft	60 ft

Dredging tolerance and advance maintenance allowances are in addition to these depths.

22.5.7 Channel Width Design

Selection of channel width for outbound (loaded) and inbound (ballasted) vessels was made by a ship simulation study. The simulation scenarios were developed jointly with the U.S. Coast Guard district and the Virginia Pilots Association. More than 25 pilots participated in running the ships from the various simulation transits. The resulting channel width and depths for the four-phase construction plan are listed in Table 22-3.

TABLE 22-3. Phased Construction Plan.

		Outbound Lane		Inbound Lane	
Phase	Channel Segment	Width in Feet	Depth in Feet	Width in Feet	Depth in Feet
1st	Atlantic Ocean	Natural (not dredged)			Natural (not dredged)
	Thimble Shoal	650	50	350	45
	Norfolk Harbor	650	50	350	45
	Newport News	800	50	Constructed full width	
2nd	Atlantic Ocean	650	60	650	Natural (not dredged)
	Thimble Shoal	650	55	350	45
	Norfolk Harbor	650	55	350	45
	Newport News	800	55	Constructed full width	
3rd	Atlantic Ocean	No change from second phase			
	Thimble Shoal	650	55	350	50
	Norfolk Harbor	650	55	350	50
	Newport News	No change from second phase			
4th (final)	Atlantic Ocean	No change from second phase			
	Thimble Shoal	650	55	350	55
	Norfolk Harbor	650	55	350	55
	Newport News	No change from second phase			

In addition to the depths shown here, an additional 2 ft was provided for dredging tolerance and advanced maintenance.

22.5.8 Hydrodynamic and Sedimentation Studies

A physical hydraulic model was used to evaluate the impacts of the proposed deepened channels. This model measured changes in current velocities, water surface elevation, and salinity.

Sedimentation evaluation consisted of an extensive bottom sampling program and a sedimentation investigation (Berger et al., 1985). This sedimentation study estimated a total increase in annual shoaling of 23% for the Norfolk Harbor Channel and little change in the Newport News Channel, a 20% increase for the Thimble Shoal Channel and 200,000 cu yd annually of maintenance dredging for the Atlantic Ocean Channel. As of 1992, the actual sedimentation has been much less than predicted by the sedimentation study.

22.5.9 Dredge Material Disposal

Two disposal sites were selected for this project: an ocean location south of the Atlantic Ocean Channel, and an existing confined disposal area located west of the Norfolk Channel segment.

22.5.10 Mitigation

Extensive environmental-impact studies determined that there were no mitigation requirements for this project. These environmental studies included the following:

Benthic invertebrates
Finfish
Plankton
Phytoplankton
Zooplankton
Sediment quality
Sediment movement in both the ocean and the estuary
Water quality

22.5.11 Relocations

Relocations investigations identified water lines, tunnels, power lines, and a ship-degaussing range for the Navy in the project area. The power lines were a minimum of 75 ft below MLW in the Norfolk Channel so that they were not affected by the deepening project.

The two water lines under the Norfolk Channel are at 52 ft and 60 ft MLW and will need relocation. The Navy degaussing range in the Norfolk Channel will need relocation.

The Thimble Shoal Channel tunnel (part of the Chesapeake Bay Bridge Tunnel) has a top clearance of 63 ft below MLW. There is a minimum earth cover of 10 ft over the top of the tunnel. This channel-deepening project will put the new channel bottom at 57 ft below MLW (55 ft authorized depth, 2 ft of over-depth dredging); this will encroach on the cover over the tunnel and risk damage to the tunnel structure. A protective rock blanket was recommended for this channel segment over the tunnel. See Table 22-4 for further details.

TABLE 22-4. Project Status (from Norfolk District, 2000).

Channel Segment	Original Project	Current Project	Project Status 2000
Atlantic Ocean	Natural depths over 50 ft 11.1 mi. length	57 ft × 1000 ft width Subsequently recommended 60 ft deep, 1,300 ft wide	No dredging– channel marked at 1,300 ft wide
Thimble Shoals	45 ft × 1,000 ft 13.4 mi. length	55 ft deep, 1,000 ft wide	Outbound element 50 ft deep, 650 ft wide Remaining 350 ft width maintained at 45 ft
Norfolk Harbor	45 ft × 800 ft 2 mi. from I-64 bridge	55 ft × 1,500 ft width Subsequently recommended 1,000 ft width	50 ft depth, 1,000 ft width
	45 ft × 800 ft 4.3 mi. to Norfolk International Terminal	55 ft × 1500 ft width Subsequently recommend 1,000 ft width	Outbound element 50 ft depth, 650 ft width Remaining 350 ft width maintained at 45 ft
Newport News 6 mi.	45 ft × 800 ft	55 ft × 800 ft	50 ft × 800 ft

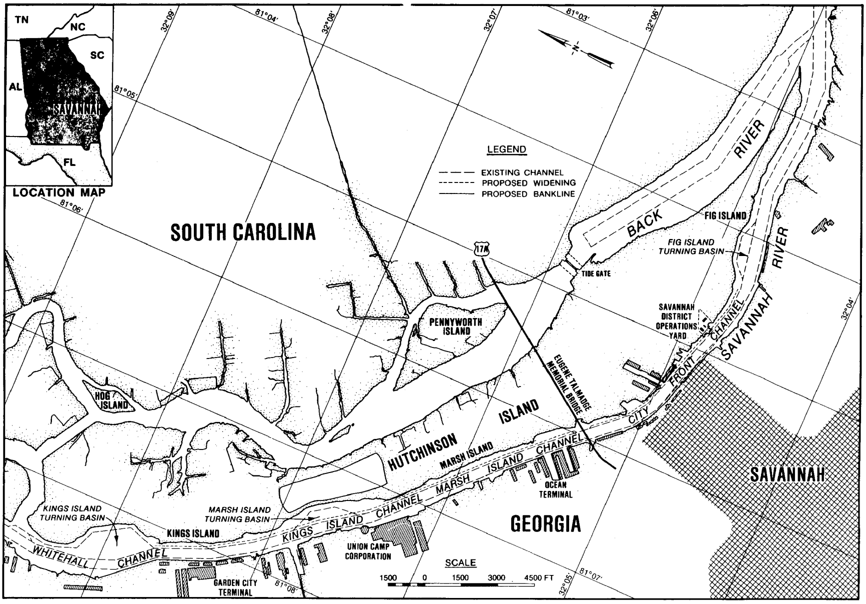

FIGURE 22-3. Savanna Harbor, Georgia (ASCE Manual No. 80).

22.6 CASE HISTORY 3—SAVANNAH HARBOR WIDENING PROJECT SAVANNAH, GEORGIA

22.6.1 Project Description

Savannah Harbor (Figure 22-3) comprises the lower 213 miles of the Savannah river in Chatham County, Georgia. In general, the harbor channel is a narrow winding river subject to both freshwater inflow and tidal action. Industrial development starts around mile 10 on the south bank and extends to the end of the harbor. Major development includes the city of Savannah, petroleum terminals, container terminals, chemical plants, paper mills, a sugar refinery, cement plants, a shipyard, and many smaller industrial activities. On the north bank there are more oil terminals, the operations yard for the U.S. Army Corps of Engineer District, Savannah, a large pulp mill effluent aeration lagoon, and numerous dredged material disposal sites. Despite this development, the major portion of the north bank remains fairly open, consisting of brush lands and saltwater marsh. Much of this north bank land is used for dredge disposal. Because of the large amount of industrial activity in the harbor, the Port of Savannah recently recorded a larger increase in total tonnage than most other harbors in the United States.

22.6.2 Proposed Channel Improvements

The proposed widening is to involve the 5.6-mile section between the upstream end of Fig Island Turning Basin and the downstream end of King Island Turning Basin.

Currently, the channel is maintained at a depth of 38 ft and a width of 400 ft. The Georgia Department of Transportation removed the north pier of the "old Talmadge Bridge" in 1992. The replacement bridge is now open to traffic. Removal of the old bridge pier allows a 500-ft channel width for the entire length. The project depth will remain at 38 ft. Above the bridge, the widening required removing small amounts of bank line to maintain the channel's side slope. Below the bridge, however, large portions of developed land on the north bank required removal, including the Savannah District staging yard and other old docking areas, as well as some World War I–era slips. A summary of project pertinent data follows.

Project location:
  distance above mouth of Savannah River: 13.1 to 18.5 mi
Channel dimensions widened section:
  length: 28,340 ft
  Bottom width: 500 ft
  Side slopes: 1 on 3
  Harbor line from edge of channel: 100 to 150 ft
Construction quantities:
  material dredged from channel: 1,894,000 cu yd

22.6.3 Hydrodynamic Conditions

The Savannah River is one of the largest rivers in the southeastern United States, with an average freshwater inflow calculated at the boundary of the study area of 12,000 cu ft per s. The river is subject to mean tidal ranges on the order of 6 to 9 ft that produce current speeds through the study area of around 2.5 to 3.0 knots on the ebbing tide. The flooding tide usually produces currents a little smaller than those in the ebbing tide. Previously, the main controlling factor of the strong ebb tide was the tide gate structure located on the north side of Hutchinson Island in the Back River. This structure was constructed by the U.S. Army Corps of Engineers to aid in sediment flushing through the main shipping channel in the Front River. The tide gate was removed and a closure structure was put in place in February 1992. Removal of the gate was for fisheries enhancement.

22.6.4 Design Vessels

Originally, this investigation was to run simulations using a number of vessels including three container ships, two LASH ships, two bulk carriers, and a liquid tanker. Because of limited time, it was desirable to test only worst-case conditions; therefore, the scope of testing was restricted to the United States Lines Inc. 950-ft New York class container ships. This particular ship was determined to be the best design case for the following reasons:

1. It is the largest ship in Savannah Harbor. According to comments made by pilots, the 950s have better mechanical response than smaller ships; however, the length of the ship causes greater control problems in opposing currents.
2. Discussion with pilots confirmed that the 950s caused them the most stress.
3. Actual simulator testing by pilots and simulator employees used a few models of smaller ships. These ships were observed to cause no greater difficulties than did the 950s.

22.6.5 Channel Design

The U.S. Army Corps of Engineers Waterways Experiment Station (WES) Hydraulics Laboratory conducted a ship simulation study concerning the effect of proposed improvements on navigation. The objective of the ship simulator investigation was to compare the existing and planned (proposed) channels to determine any change in ship controllability and operational safety.

Required data included channel geometry, bottom topography, currents for both existing and planned channels, a numerical model of a ship, and photographs of the scene along the river banks. A numerical hydrodynamic model was used to generate the channel currents. Prototype data were used for boundary conditions and verification of the model of the existing channel.

Boundary conditions for the planned channel were obtained from the laterally averaged numerical model which was generated for the sediment and salinity intrusion studies. A reconnaissance trip was carried out to observe an inbound and outbound transit through the study area to obtain some familiarity with prototype conditions. Video recordings and still photographs were taken during the transits to aid in generation of the simulated visual scene.

In keeping with the objective of testing only the worst case, it also was decided to run simulation in spring tide conditions and, in so doing, subject the ship to extreme currents. The tidal range to generate these currents was approximately 10.5 ft. Results of the Savannah Harbor ship simulation study reveal these conclusions:

1. A slight but consistent improvement was noted in vessel controllability in the planned channel.

2. Passage through the immediate vicinity of the bridge appears to be unaffected by the plan.
3. A significant improvement was evident in the mean south bank clearance in the planned channel especially in the city-front area.
4. The area between Marsh Island Turning Basin and Kings Island Turning Basin is a potential area for an accident, exhibited by the high incidence of groundings in the simulator runs.
5. In their comments and questionnaire ratings, the pilots consistently judged the planned channel an improvement.
6. Pilots often commented that the planned channel would afford them safer passing zones, especially in the straight reach between Talmadge Bridge and Marsh Island. This possible advantage of the planned channel was not tested by the simulator.
7. The study also quantified another problem in the Marsh Island area; that is, ships tied up at the Amoco Dock upstream of Union Camp Corp. All the pilots voiced apprehension that the channel was too close to this dock when tankers were moored.

22.6.6 Project Status

This channel-widening project was completed in February 1992.

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Appendix B

DIMENSIONS OF SELECTED U.S. DEEP-DRAFT NAVIGATION ENTRANCE CHANNELS IN 1993

Harbor (1)	Depth, Ft (2)	Width, Ft (3)
East Coast		
New York, N.Y.	45	2000
Baltimore, MD	50	1000
Wilmington, NC	40	500
Charleston, SC	35	1000
Port Everglades, FL	45	500
Miami, FL	38	500
Great Lakes		
Milwaukee, WI	30	800
Green Bay, WI	26	500
Gulf Coast		
Houston, TX	40	400
Galveston, TX	42	800
Mississippi River, LA	45	600–750
Mobile, AL	47	600
Panama City, FL	42	450
Tampa, FL	46	700
San Juan, P.R.	48	500
West Coast		
Grays Harbor, WA	46	1,000
Mouth of Columbia River, WA	55	2,000
Coos Bay, OR	45	700
San Francisco, CA	45	2,000
Los Angeles, CA	40	1,000
San Diego, CA	42	800
Honolulu, HI	45	500

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Appendix C

ESTUARY WATERWAY PROJECTS LESSONS LEARNED

During the last 100 years, the U.S. Army Corps of Engineers built, and continues to maintain, over 300 navigation projects in tidal waters. These projects include deep-draft ship channels, small boat harbors, and intracoastal waterways for barges. The majority of these projects function very well with minimal maintenance cost. However, a few experience higher-than-expected shoaling rates and require considerable maintenance dredging.

The Corps' Committee on Tidal Hydraulics has studied these problem projects since 1950 and has identified a list of dos and don'ts for estuary navigation projects. These generic lessons involve two categories—entrance channels and interior channels. These were identified during a detailed review of 24 of the 109 projects in which the committee had provided advice. Case histories for each of the reviewed projects included an analysis of the various lessons that were learned. The study was published by the Committee on Tidal Hydraulics in 1995.

Some of the lessons are obvious and may seem too trivial to list. However, the experience of the committee is that such lessons tend to become lost and must then be relearned by subsequent generations. Restating those lessons in this manual will make relearning them somewhat more likely.

C.1 ENTRANCE CHANNELS

1. Parallel jetties are less prone to shoaling because of their configuration, which confines the ebb flow, raising ebb velocities and, thereby, flushing sediment seaward (Figure C-1).
2. Although curved jetties also can be designed to produce nondepositional velocities (e.g., Umpqua River entrance), flow concentrations on the outside of the curve can cause the undermining of the jetty and make a channel alignment difficult to navigate (Figure C-1).

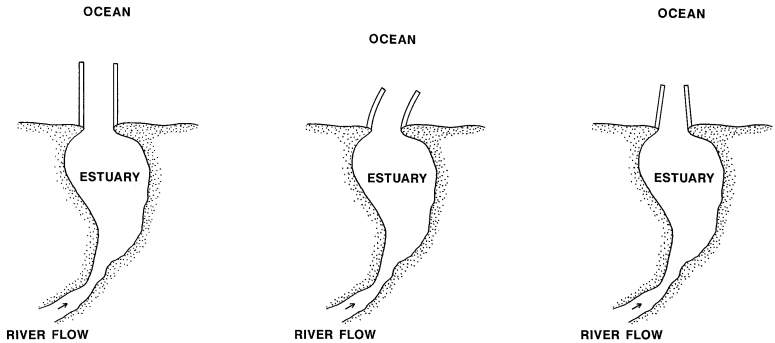

FIGURE C-1. Straight Parallel, Curved Parallel, and Arrowhead Jetties.

3. Entrance channels with arrowhead jetties frequently shoal rapidly because ebb flow is not confined enough to produce scouring velocities inside the jetties (Figure C-1). This also can allow or cause channel migration. Examples: Mouth of the Columbia River and Galveston Bay entrance.
4. Jetties should be long enough to prevent littoral transport around the jetty ends and into the navigation channel (Figure C-2). Model studies of the Rogue River, Oregon, jetties have shown that an extension would substantially reduce channel shoaling.
5. Jetties should be sealed to prevent a significant portion of the littoral drift from passing through the jetty (Figure C-3). Sealing and rehabilitation of the Umpqua River, Oregon, jetties reduced channel shoaling.

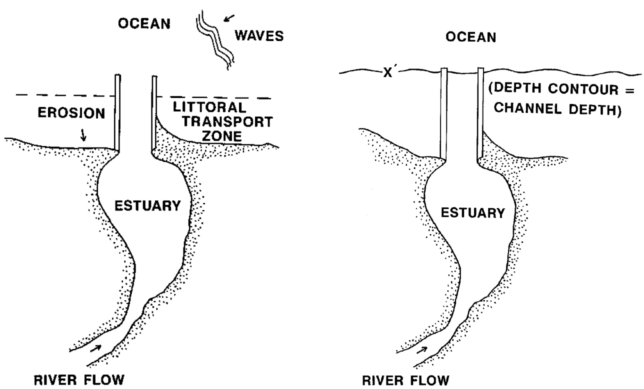

FIGURE C-2. Jetty Length.

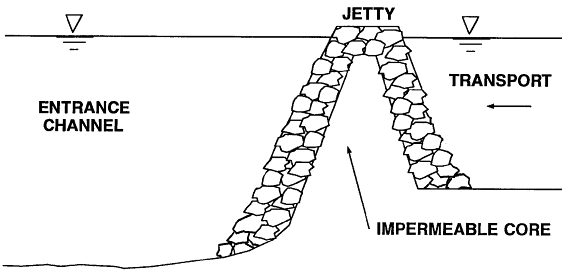

FIGURE C-3. Jetty Sealing.

6. The outer ends of jetties should be submerged at high tide, unless their primary function is to protect from waves. This position will reduce the capacity of flood tide to carry littoral materials into the channel, and still train the ebb tide flow to flush sediments seaward (Figure C-4). Example: Grays Harbor, Washington.
7. Separation of river flow from the harbor entrance can reduce navigation channel shoaling by isolating the channel shoaling (Figure C-5). The separated entrance of Mission Bay, California, is an example.
8. Shoaling in an entrance channel that is confined by jetties can be reduced by diminishing the jetty space (Figure C-6). Too narrow a spacing, however, can cause a hazardous navigation condition or scouring velocities, which can undermine adjacent jetties. Model studies of the Tillamook Bay, Oregon, entrance were used to optimize jetty spacing with regard to both channel shoaling and navigation safety.
9. Channels will migrate toward the jetty on a single jetty entrance, which can cause undermining of the jetty (Figure C-7). For example,

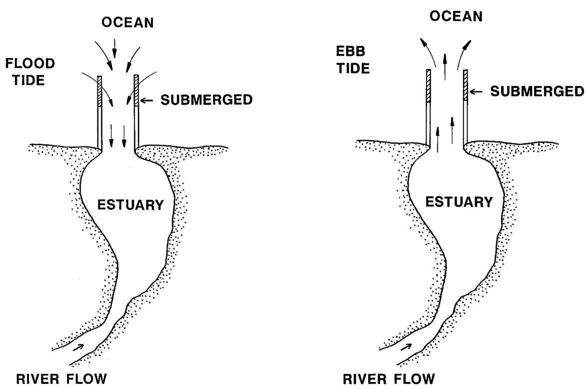

FIGURE C-4. Submerged Jetty Ends.

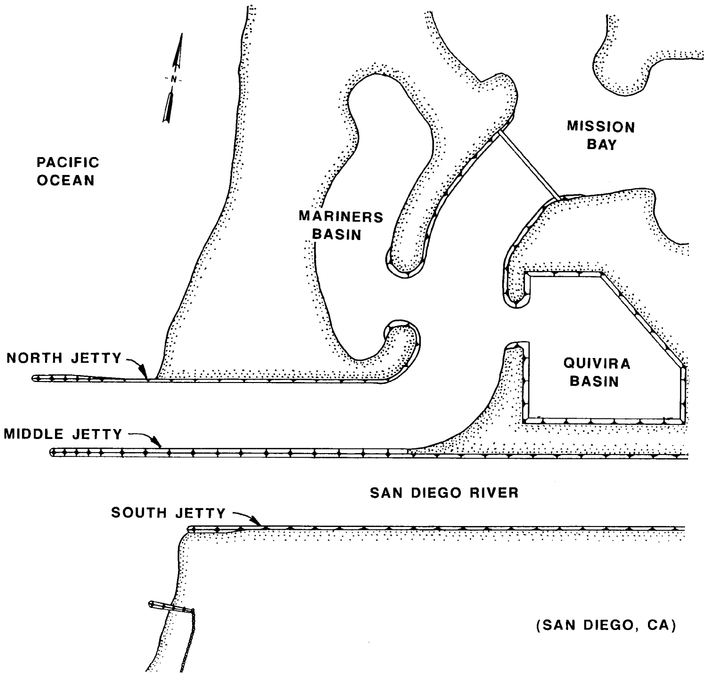

FIGURE C-5. Mission Bay Separated Entrances.

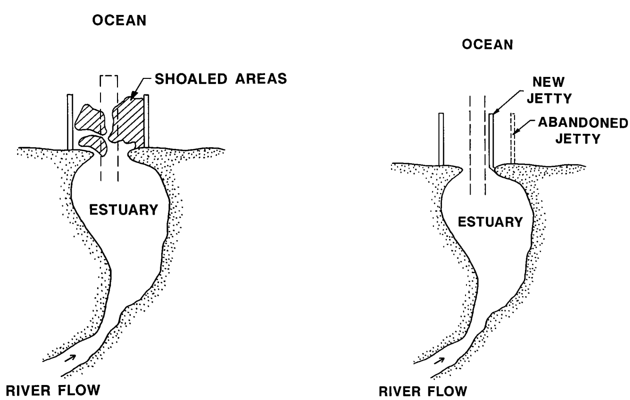

FIGURE C-6. Reduced Jetty Spacing.

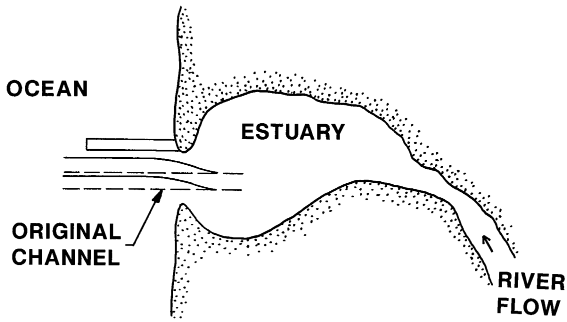

FIGURE C-7. Single-Jetty Channel Migration.

before 1969, Tillamook Bay, Oregon, was a single-jetty system. The north jetty was constructed in 1933 and the south jetty in 1969.

10. Some jetty systems may take many years, possibly a century or more, to reach equilibrium (Figure C-8). Example: Galveston Bay entrance.
11. After construction of a new channel, adjustments (sloughing) of side slopes can require several years. The sloughed material is a source of material for channel shoaling (Figure C-9). This lesson also applies to interior channels. Example: Mouth of the Columbia River; Matagorda ship channel.
12. Agitation dredging and in-channel disposal can be effective, where strong ebb-flow dominance exists over the entire water column (Figure C-10). On the other hand, if the currents are weak, the agitated material may immediately return to the channel, thus increasing the volume to be dredged. Example: Mississippi River southwest pass. This is a lesson that also applies to interior channels.

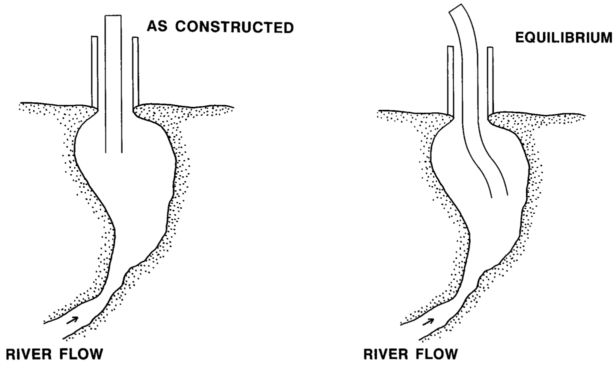

FIGURE C-8. Jetty System Adjustments.

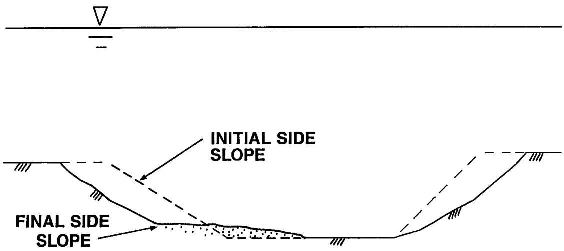

FIGURE C-9. Adjusting Channel Side Slopes.

13. Open-water disposal should be in a dispersive site (scour hole) where sediment movement is out to sea (Figure C-11). Nondispersive disposal sites accumulate sediments. Thus, they will have a finite life if sediments are not removed periodically to make room for additional dredged material. Example: San Francisco Bay, Alcatraz disposal site.
14. Repairs to an undermined jetty should be made by first locating the new jetty on the ocean side of the original jetty. The undermined jetty then serves as the channel-side toe for the new jetty (Figure C-12). Example: South jetty at Grays Harbor, Washington.

C.2 INTERIOR CHANNELS

1. Dredged channels or harbor facilities in naturally shallow water usually require frequent maintenance dredging to maintain their depths (Figure C-13). Examples are the U.S. Navy Military Ocean Terminal, Sunny Point, Cape Fear River; Matagorda Bay ship channel; Mississippi River–gulf outlet. Where possible, they should be located in naturally deep water.
2. Expansions of harbor width will reduce velocities that can induce rapid shoaling (Figure C-14). Example: Brunswick Harbor, Delaware River.

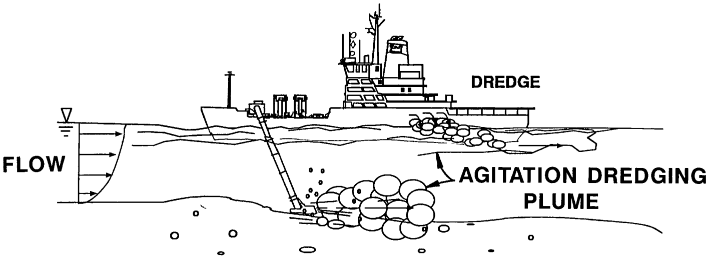

FIGURE C-10. Agitation Dredging in Ebb Flow Dominance.

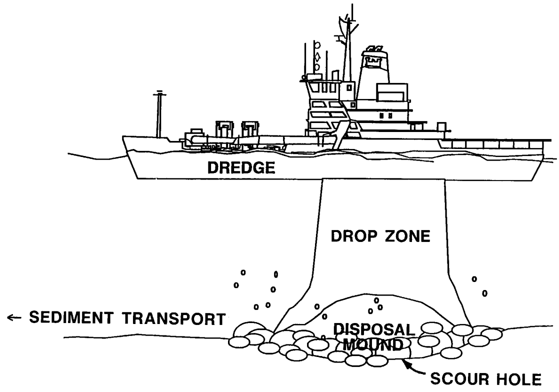

FIGURE C-11. Disposal in Scour Hole.

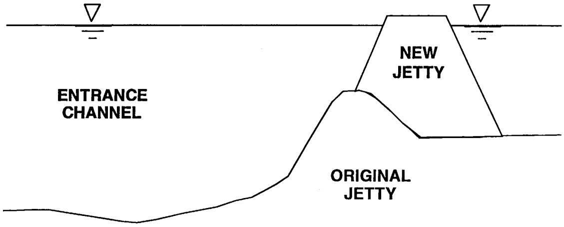

FIGURE C-12. Jetty Repair.

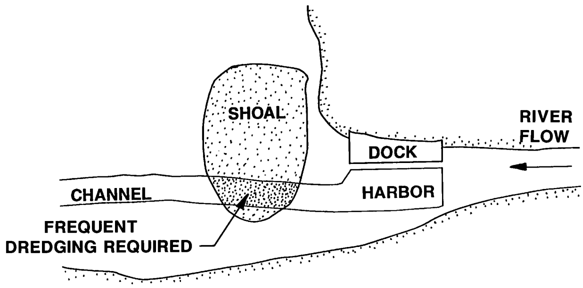

FIGURE C-13. Channel Dredging through Shoals.

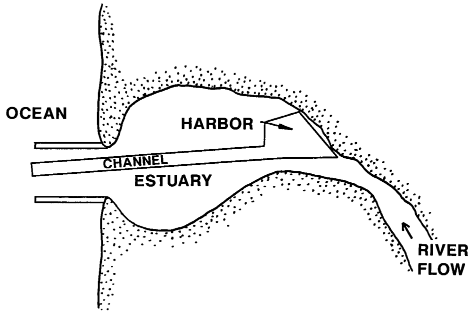

FIGURE C-14. Rapid Shoaling in Harbor Expansion.

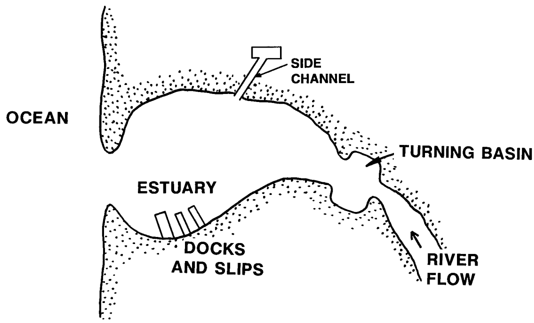

FIGURE C-15. Side Channels, Basins, and Pier Slips as Sediment Traps.

3. Side channels, basins, and pier slips in estuaries can be effective sediment traps (i.e., they will be subject to a higher rate of shoaling than surrounding areas) (Figure C-15). Examples: New York Harbor; U.S. Navy Military Ocean Terminal, Sunny Point, Cape Fear River.
4. Piers on pilings create eddies that increase the shoaling rates of sediments (Figure C-16). Example: New York Harbor and San Francisco Bay.
5. Increased river discharge by diversion can increase sediment load available for shoaling in the estuary (Figure C-17). The increased sediment load can be introduced into the system with the increased flow velocity that causes more bank and bed erosion. Example: Santee-Cooper diversion project, Charleston Harbor.
6. Isolation of the channel from sediment inflow by structures can reduce maintenance dredging requirements (Figure C-18). Examples: Gastineau Channel, Alaska; Colorado River, Texas; Mississippi River–gulf outlet.
7. Access channels and harbor areas off the main navigation channel should be streamlined to reduce eddies and dead-water areas where shoaling can occur (Figure C-19). Example: U.S. Navy Military Ocean Terminal, Sunny Point, Cape Fear River. Where possible, they should be open at both ends to permit through flow.
8. Sediment traps in connecting channels can be used to control the location of dredging (Figure C-20). Such sediment traps can be

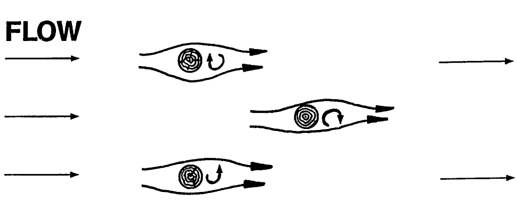

FIGURE C-16. Eddies Around Pilings.

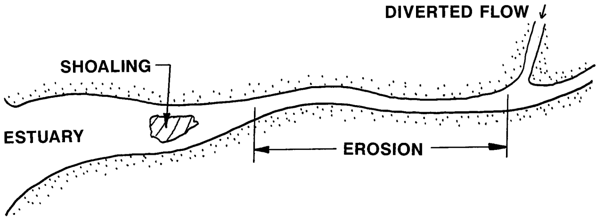

FIGURE C-17. Diversion Caused Shoaling.

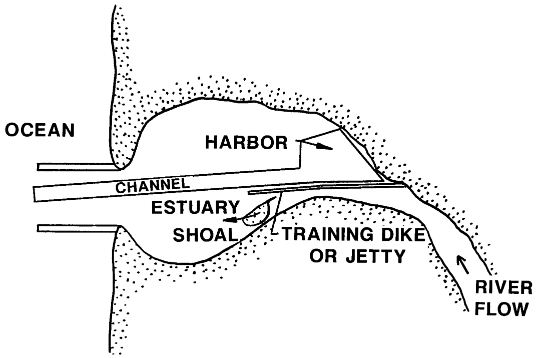

FIGURE C-18. Isolated Sediment from Channel.

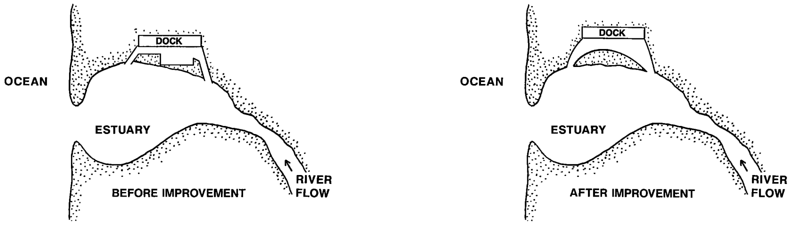

FIGURE C-19. Access Channel Streamlining.

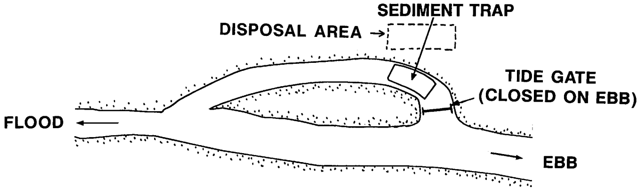

FIGURE C-20. Sediment Trap Controls Dredging Location.

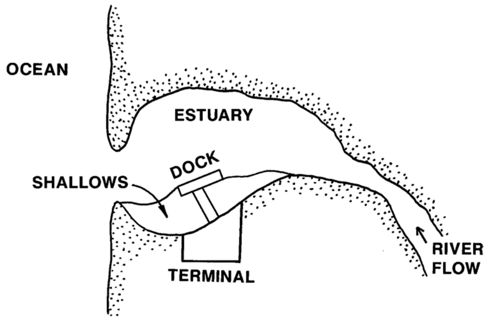

FIGURE C-21. Dock in Deep Water.

particularly effective when they are combined with a tide gate, allowing sediment-laden water into the trap and forcing cleaner water (after deposition during slack tide) into the main channel to enhance flushing in a problem area. Example: Savanna Harbor. Such a scheme can be used to relocate deposition areas closer to dredged material disposal sites.

9. Docks should be located in naturally deep water, where possible (Figure C-21). For example, the approach channel to a marginal wharf at Anchorage Harbor is incised into a natural shoal that is about half as deep as the channel. It experiences heavy shoaling.
10. Harbors should be located on the outside of river bends because the inside of bends will shoal (Figure C-22). Example: Gold Beach Harbor, Rogue River, Oregon.
11. Abandonment or relocation of harbor projects should be considered when rapid shoaling prevents effective maintenance (Figure C-23). Example: Gastineau Channel, Alaska.
12. Confined disposal—either in upland or diked in water sites—will prevent the return of dredged materials to the channel, thereby reducing future channel shoaling (Figure C-24). Example: Delaware Bay.

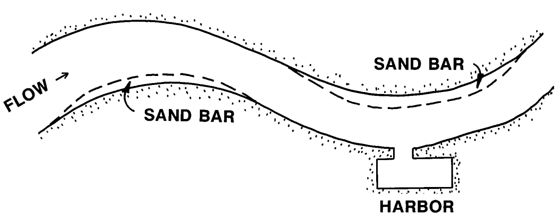

FIGURE C-22. Site Harbors on Outside of River Bend.

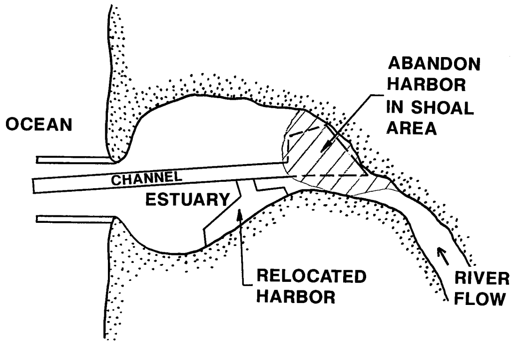

FIGURE C-23. Rapid Shoaling Forces Abandonment or Relocation.

13. Open-water (unconfined) disposal that is remote from the channel or in areas of low bottom current will limit the return of dredged material to the channel (Figure C-25). Example: Chesapeake and Delaware Canal. Open-water disposal operations that are too close to the channels in Matagorda Bay and the Mississippi River–gulf outlet allow substantial return of the material to the channels.
14. Mounds formed by disposal of dredged material should have flat side slopes to reduce the potential for erosion. This will, in turn, reduce the return of materials to the active sediment system (Figure C-26). Example: Mississippi River–gulf outlet.
15. Controlled dredging (e.g., covered dredge head) and disposal (e.g., silt curtain or tremie disposal on bottom) practices can reduce the

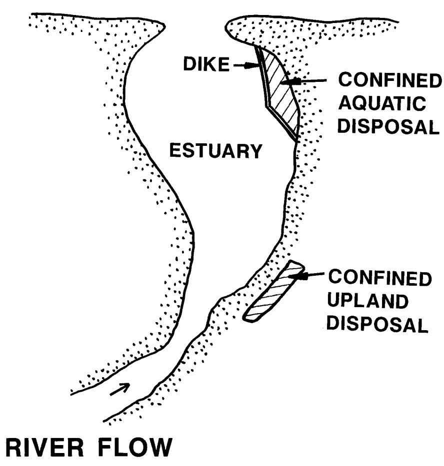

FIGURE C-24. Confined Disposal Area.

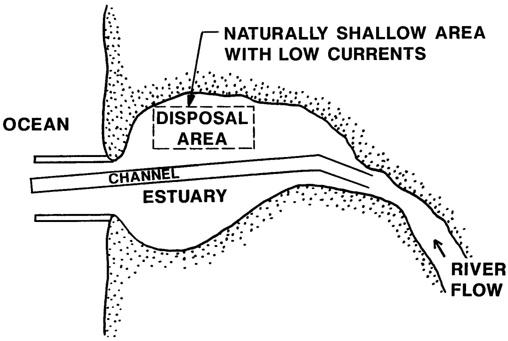

FIGURE C-25. Remote Disposal Area.

volume of sediment placed back in suspension, thereby reducing the rate of channel shoaling (Figure C-27).

16. Null zones will cause shoaling and should be avoided as harbor sites. In a null zone, which is usually caused by salinity stratification, no (tidal) net flow occurs at the bottom (Figure C-28). Example: Mississippi River. The location of such null zones can be altered through upstream flow regulation.
17. An increase in channel depth usually will allow greater penetration of the saltwater wedge, which will move the shoaling location upstream (Figure C-29). Example: Savannah Harbor.
18. A decrease in freshwater inflow (e.g., due to upstream dam regulation) can increase the length of salinity intrusion and change the location of shoaling (Figure C-30). Controlled model tests of Delaware Bay clearly demonstrated this phenomenon.
19. An increase in freshwater inflow (e.g., due to upstream flow diversion) can cause salinity stratification and shoaling in a previously well-mixed estuary (Figure C-31). Example: Charleston Harbor.
20. Suspended clay sediments will flocculate and enhance shoaling with the proper combination of salinity, water temperature, and flow conditions. Example: Savannah Harbor; Delaware Bay.

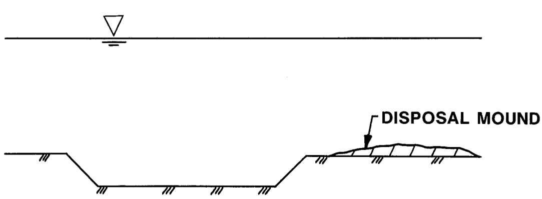

FIGURE C-26. Low, Flat Disposal Mound.

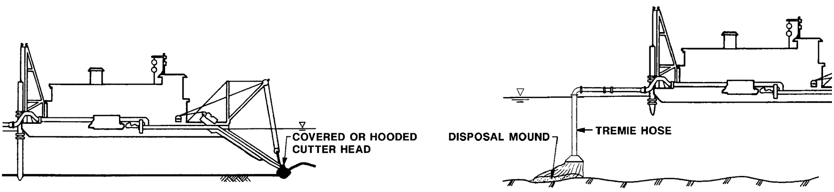

FIGURE C-27. Controlled Dredging and Disposal.

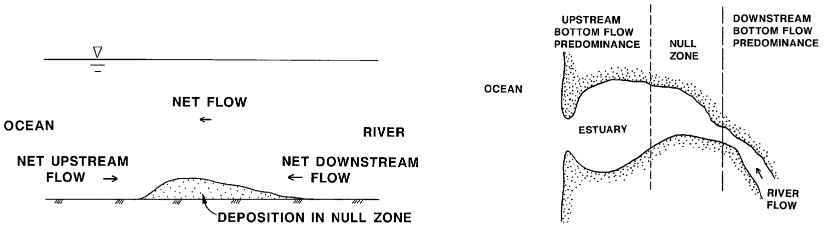

FIGURE C-28. Null Zones Will Cause Shoaling.

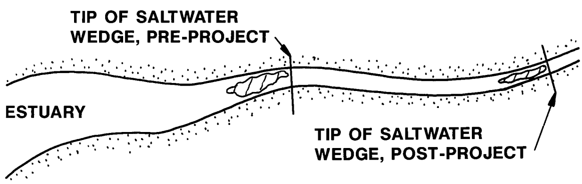

FIGURE C-29. Saltwater Wedge and Shoaling Shifts Upstream with Deeper Channel.

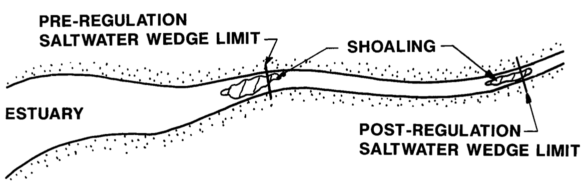

FIGURE C-30. Decreased Freshwater Inflow Moves Shoaling Location Upstream.

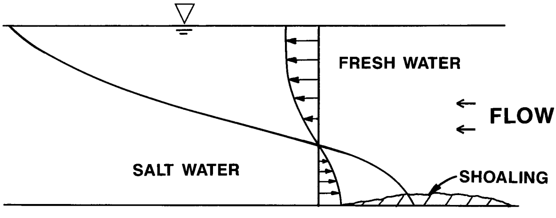

FIGURE C-31. Shoaling Caused by Salinity Stratification.

21. Unconfined disposal of clean material usually has no adverse long-term effects on the biological population. The dredged channel and submerged disposal site will re-colonize in a short time; 1 or 2 years is a normal period.

The following tabulation summarizes the most pertinent information pertaining to lessons that were learned from the 23 case studies considered by the CTH.

Project: **Anchorage Harbor, Alaska**

Problem: Shoaling in wharf area adjacent to interior channel.
Cause: Reduced currents in expansion off main channel.
Solution: a. Continue dredging.
b. Relocate wharves to deep water.
Remarks: a. Present practice is to continue dredging.
b. Relocating wharves not economical at the present time.

Project: **Brunswick Harbor, Georgia**

Problem: Interior-channel shoaling after channel enlargement.
Cause: Reduced currents in enlarged channel.
Solution: a. Continue dredging.
b. Construct closure dams at the head of side channel to reduce sediment influx and shoaling in harbor.
Remarks: a. Continue dredging.
b. Construction of first dam seemed to reduce shoaling but second dam seemed to increase shoaling.

Project: **Cape Fear River, Sunny Point Terminal, North Carolina**

Problem: Shoaling in harbor adjacent to interior channel.
Cause: Reduced currents in harbor off main channels.
Solution: Realign and streamline channels and eliminate one of the channels leading to the wharves.
Remarks: Being considered by Army.

Project: **Charleston Harbor, South Carolina**

Problem: High shoaling rate in interior channel following diversion of river into estuary.
Cause: a. Increased velocity eroded up-stream banks, which deposited in channel.
b. Fresh river water created a stratified system with the salinity wedge causing shoaling.
Solution: a. Redivert river out of estuary.
b. Redivert river out of estuary.

Remarks: a. Rediversion plan is under way.
b. Rediversion plan is under way.

Project: Chesapeake and Delaware Canal, Delaware/Maryland
Problem: Evaluate overboard disposal for interior channel.
Cause: N/A
Solution: N/A
Remarks: A prototype study of overboard disposal showed no long-term adverse effects on biota after 1 to $1\frac{1}{2}$ years.

Project: Colorado River, Texas
Problem: a. Feasibility of jettied entrance channel.
b. Interior-channel shoaling.
Cause: a. Substantial littoral drift.
b. Large sediment contribution during floods and naturally shallow depths.
Solution: a. Jetties are required to prevent excessive shoaling.
b. Separate flood and navigation channels.
Remarks: a. Not yet constructed.
b. Not yet constructed.

Project: Columbia River, Oregon/Washington

1. Problem: Entrance channel shoaling.
Cause: a. Littoral drift, river sediment load, and upstream bottom flow predominance.
b. Arrowhead jetty configuration.
c. Side slope adjustment (sloughing).
Solution: a. Dredging.
b. Construct spur jetty.
c. Dredging.
Remarks: a. Present practice.
b. Too expensive.
c. Present practice.

2. Problem: Interior channel shoaling.
Cause: River sediment load and adjustment of dredge-cut slope.
Solution: a. Dredging.
b. Construction with dikes.
Remarks: a. Present practice.
b. Present practice.

3. Problem: Rehabilitation needs for entrance jetties.
Cause: Deterioration with time.
Solution: a. South jetty repair. Leave outer end submerged to minimize channel shoaling.
b. North jetty repair and sealing.

Remarks: a. Completed in 1964, except for outer 1.2 miles.
b. Not accomplished to date.

Project: Delaware Estuary, Pennsylvania/New Jersey/Delaware
Problem: Interior-channel shoaling.
Cause: a. Heavy sediment inflow and open-water disposal near channel in shallow bay.
b. Substantial enlargement of cross section by construction of an anchorage area significantly reduced velocities.
c. Null point resulting from salinity stratification.
Solution: a. Eliminate agitation dredging and dispose in confined area.
b. Dredging.
c. Dredging.
Remarks: a. Implemented with success.
b. Present practice.
c. Present practice.

Project: Duwamish River, Washington
Problem: Determine impact of each channel closing on shoaling and circulation.
Cause: N/A
Solution: CTH recommended not closing each channel because of probable reduced flushing.
Remarks: Closure not implemented at this time.

Project: Galveston Entrance Channel, Texas
Problem: Channel shift toward north jetty endangered north jetty stability and complicated navigation by making sharper bends.
Cause: Maintenance dredging followed channel migration toward north jetty. Excessive jetty spacing and arrowhead configuration contributed to migration.
Solution: Change channel alignment to midpoint between jetty and hold during future maintenance work.
Remarks: Implemented with success.

Project: Gastineau Channel, Alaska
Problem: Rapid shoaling in small boat half-tide channel.
Cause: Large sediment inflow in shallow bay.
Solution: a. Isolate sediment from channel by parallel dike.
b. Abandon project.
Remarks: a. Recommended by model study but too expensive.
b. Project has not been maintained and is effectively abandoned.

Project: **Georgetown Harbor, South Carolina**

Problem: Interior-channel shoaling.

Cause: a. Deep channel through shallow bay with inflow from two large sediment-bearing rivers.
b. Upstream bottom flow predominance.

Solution: a. Dredge or abandon.
b. Dredge.
c. Divert sediment-laden inflow.

Remarks: a. Presently maintained by dredging.
b. Present practice.
c. Not implemented.

Project: **Grays Harbor, Washington**

1. Problem: Extent of jetty rehabilitation needed.

Cause: Deterioration with time.

Solution: a. Rehabilitate south jetty above the water line; leave outer 5,000 ft degraded.
b. Total length of north jetty to be rehabilitated.

Remarks: a. Was accomplished in 1966; has not worked very well.
b. Recommended by model. Accomplished in 1975; has worked very well.

2. Problem: Interior-channel shoaling and poor navigation alignment.

Cause: Channel alignment through high shoaling area with several turns.

Solution: Relocate channel.

Remarks: Accomplished in 1978. Reduced shoaling by 300,000 cu yd per year as predicted by model.

3. Problem: Open-water disposal location.

Cause: Recirculation of disposal material by flood currents into navigation channel.

Solution: Relocate disposal to deep scour hole between jetties.

Remarks: Recommended by model studies and implemented.

Project: **Hudson River, New York Harbor, New York**

Problem: a. Interior-channel shoaling.
b. High shoaling rates at pier slips.

Cause: a. Filling of deep scour hole with rock increased bottom turbulence and changed flow predominance.
b. Pier slips serve as sediment traps.

Solution: a. Remove rock to re-establish natural cross-sectional area.
b. Abandon high shoaling area slips.
Remarks: a. Recommended by model study. Not yet implemented.
b. Slips have been abandoned.

Project: Jacksonville Harbor, Mill Cove, Florida
Problem: Interior small-boat-channel shoaling.
Cause: Natural flow in the area was reduced by dredged material disposal islands.
Solution: Enlarge entrances to allow more flow through flushing action.
Remarks: Proposed solution by District.

Project: Matagorda Ship Channel, Texas
1. Problem: Interior-channel shoaling.
Cause: Adjustment of dredge cuts and erosion of disposal mounds near the channel caused high initial shoaling.
Solution: Dispose of dredged material in a site remote from the channel.
Remarks: Present practice.
2. Problem: Cross currents have adverse impact on ships.
Cause: Ebb flow from Matagorda Bay crosses new deep navigation channel.
Solution: Channel realighment or widening.
Remarks: Not proposed at this time.
3. Problem: Predicted bank erosion of new entrance channel.
Cause: High velocities.
Solution: Preplaced riprap in trenches at desired stable bank locations.
Remarks: Successfully implemented.

Project: Mississippi River–Gulf Outlet, Louisiana
Problem: Entrance-channel shoaling.
Cause: a. Lateral currents and waves in shallow water carry sediment into deep channel.
b. Return of dredged material placed adjacent to the channel.
Solution: a. Dikes or land-connected jetties to prevent sediment from reaching channel.
b. Dispose dredged material at a site remote from channel.
Remarks: a. 50% of dike system is completed and is presently being evaluated.

b. Dredged material apparently is placed too close to the channel.

Project: Mississippi River, Southwest Pass, Louisiana

1. Problem: Entrance channel shoaling.
   Cause: Location of saltwater wedge during high flows.
   Solution: a. Agitation dredging, which releases materials in areas of strong ebb flow dominance.
   b. Entrance channel realignment.
   Remarks: a. Present practice.
   b. Constructed as recommended by model study; works well.
2. Problem: Interior-channel shoaling.
   Cause: Heavy river-sediment load settles, in reach of reduced velocities and salinity wedge interface.
   Solution: a. Dredging.
   b. Confinement of channel to maintain high velocities.
   Remarks: a. Present practice with agitation dredging and in-channel disposal is effective.
   b. Present practice with dike and groin system.

Project: Rogue River, Oregon

Problem: Entrance-channel shoaling that blocks small boat harbor entrance.
Cause: a. Floods deposit large sediment load in entrance. Winter waves return flood sediment and littoral drift into channel.
b. Harbor located on inside of bend, where river currents will not flush out sediment brought in by waves.
Solution: a. Extend jetties to prevent littoral drift from entering channel.
b. Separate harbor from river with separate ocean entrances.
Remarks: a. Model tests showed partly effective but shoal still migrated to boat harbor entrance.
b. Recommended by model studies.

Project: San Francisco Bay, California

Problem: Interior-channel shoaling.
Cause: Large sediment inflow and recirculation of unconfined, disposed dredged material.
Solution: Dispose at a dispersive site, which minimizes return of material to channel.

Remarks: Proven effective by District experience and field tests.

Project: Savannah River, Georgia

Problem: Interior-channel shoaling.

Cause: a. Deepening of channel and regulation of upland freshwater inflow by dams. This caused shoaling to move upstream as a result of salinity wedge advance and ideal sediment flocculation conditions.
b. Open-water dredged material disposal and dredging practice that created large quantities of suspended sediment.

Solution: a. Create tide gate and sediment trap in a branch channel. Tide gate forced ebb flow back to main channel.
b. Use confined disposal areas. Change dredging methods to reduce sediment resuspension.

Remarks: a. Built; working very well.
b. Implemented; working very well.

Project: Tillamook Bay, Oregon

Problem: Selection of jetty spacing for self-cleaning 18-ft deep channels.

Cause: N/A

Solution: A 1,200-ft-wide spacing between jetties was selected.

Remarks: Recommended by model studies and proven suitable in the prototype.

Project: Umpqua River, Oregon

1. Problem: Rapid shoaling of entrance channel.

Cause: a. Arrowhead jetty did not confine ebb flow enough to scour channel.
b. Movement of littoral drift through, over, and around north jetty.

Solution: a. Build a training jetty parallel to north jetty.
b. Rehabilitate north jetty.

Remarks: a. Constructed in 1979–1980; works well.
b. Constructed in 1977; works well.

2. Problem: Difficult navigation between arrowhead jetties.

Cause: Cross currents in arrowhead section.

Solution: Realign channel and build training jetty.

Remarks: Constructed in 1979–1980; no complaints about cross current now.

Project: Wells Harbor, Massachusetts

Problem: Rapid shoaling in entrance channel.

Cause: Arrowhead jetties did not confine ebb flow enough to scour channel, and littoral drift came around ends.

Solution: Extend jetties and make parallel.

Remarks: Jetty extension completed in 1967; works well.

C.3 SOURCE

This information was taken from McCartney, Hermann, and Simons (1991) "Estuary waterway projects—lessons learned." *Journal of Waterways*, Part 3, Coastal and Ocean Engineering, 117(4), July/August, and the Committee on Tidal Hydraulics, U.S. Army Corps of Engineers (1995) "Review of Problems in Tidal Waterways considered by the Committee on Tidal Hydraulics," June.

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