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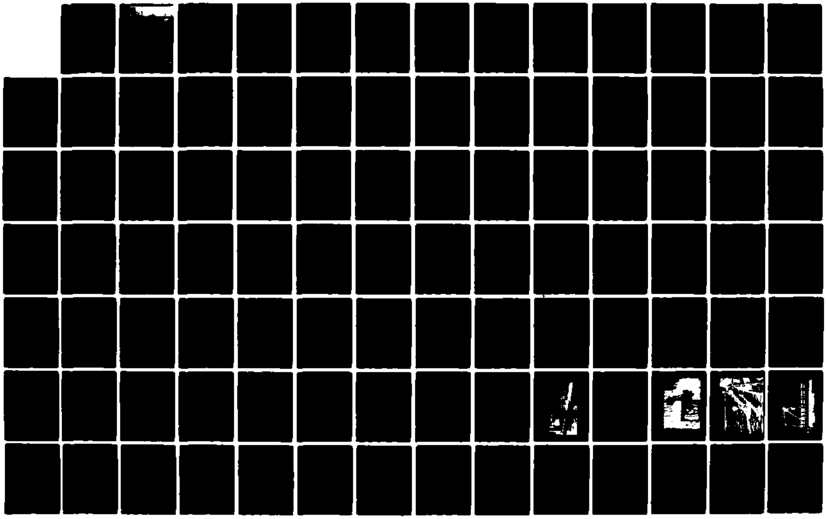

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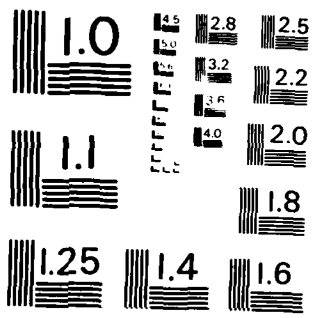

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Criteria for the Depths of Dredged Navigational Channels

Marine Board

Commission on Engineering and Technical Systems

National Research Council

CRITERIA FOR THE DEPTHS OF DREDGED NAVIGATIONAL CHANNELS

Panel on Criteria for Dredged Depths of Navigational Channels

Marine Board
Commission on Engineering and Technical Systems
National Research Council

National Academy Press
Washington, D.C. 1983

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PANEL ON CRITERIA FOR DREDGED DEPTHS
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Scope of the Study

The panel's evaluation encompassed review of the criteria used in the United States, as well as those used in foreign countries with highly developed port technology, and the consensus standards of international organizations; the analytical techniques used to determine depths and allowances; and the factors of greatest importance in channel design, such as the physical environment, ship characteristics, sedimentation, and interactive effects. The study addressed only the technical adequacy of depth criteria: the environmental implications of dredging and the disposal of dredged materials, as well as the economics of dredging and dredging cycles--although important to decisions about dredging--were specifically excluded.

Methods of the Study

In advance of undertaking its investigation, the panel searched the literature addressing the depths of navigational channels. The abstracts written and collected in the course of this search are reproduced in Appendix A.

With information provided by the U.S. Army Corps of Engineers about the dimensions of nine major channels of the United States, the panel tested the adequacy of existing channels for representative ships, using a simple computer model of ship behavior in restricted waters (a brief summary of the results is given in Chapter 4; the computer model is described in Appendix D).

To compare the criteria of the United States with those of other countries and international groups, the panel requested and received detailed information from the responsible ministries of Canada and Japan, from the Permanent International Association of Navigation Congresses (PIANC), and from the International Association of Ports and Harbors (IAPH).

The panel met three times--in Houston, Texas, Norfolk, Virginia, and San Diego, California--conducting site visits and hearing briefings in connection with its meetings from the U.S. Coast Guard, representatives of the district offices of the U.S. Army Corps of Engineers, ship pilots, and others with an interest in the design of navigational channels for oceangoing ships. In its meetings, the panel reviewed working papers prepared by members, the pertinent literature, the materials provided to the panel, and the results of the computer model. The conclusions and recommendations presented in Chapter 5 represent the panel's consensus.

Acknowledgments

The panel gratefully acknowledges the generous contributions of time and information of the Water Resources Support Center and Waterways Experiment Station of the U.S. Army Corps of Engineers, and the briefings and site visits provided by district offices of the U.S. Army Corps of Engineers, captains of the port of the U.S. Coast Guard, and representatives of local pilots associations. The cooperation of the Permanent International Association of Navigation Congresses and International Association of Ports and Harbors made the gathering of information from many countries expeditious, and their interest in the panel's work was of material assistance. Ronald K. Watanabe and Chih-Kang Lee of the Department of Ocean Engineering, Texas A&M University, assisted with the search of the literature and compilation of abstracts and with the computer simulation.

EXECUTIVE SUMMARY

At the request of the U.S. Army Corps of Engineers, the Panel on Criteria for Dredged Depths of Navigational Channels of the Marine Board appraised the criteria used in the United States to design the depths of dredged navigational channels and to specify overdredged depths.

Rules of Thumb

The criteria used by the U.S. Army Corps of Engineers are empirical--rules of thumb. For design depth, or underkeel clearance, the rule is to select the design ship, add its draft + squat* (3 ft) + rolling and pitching allowance (estimate) + clearance (2 ft for soft channel bottoms; 3 ft for rocky or hard bottoms). The Corps' criteria recommend model tests and site evaluations. Nevertheless, the references cited for assistance in determining squat and other characteristics of the design ship (aside from consultation with ship owners and local pilots) are at least 20 years old, some more than 30. Selection of the design ship is critical. While the regulations

*Sinkage of a ship in motion

indicate that the choice of design ship(s) should be made for safety of the largest expected ships, for economy, and for accommodation of projected trends, completing the process required for federal navigational projects takes 15 years to 25 years. So long a process does not allow for changes in ship design or technology.

The criteria for overdredged depths (for ensuring that specified dimensions are achieved and for advance maintenance dredging to reduce dredging intervals) have evolved from experience in the district offices of the Corps. Recently promulgated criteria update these historical rules of thumb or formulas and suggest more frequent surveys of channel dimensions. In most districts, surveys are no more frequent than semiannual.

Navigation

Data necessary for an adequate criterion of underkeel clearance are sparse, but model tests, full-scale trials, and computer simulations have increased understanding of ship behavior in open and confined channels and in the entrance channel to a port or harbor from the open ocean. Generally, vertical excursions may be large in the unprotected waters of a harbor entrance; squat is much increased by decreasing water depth and in maneuvers such as turning, passing, and overtaking. Squat in narrow channels is greater than that in open or wider channels. While channel width has been shown to be more important than depth in providing for ship controllability, the improvement depends on sufficient underkeel clearance. Although small depths of water under the keel tend to dampen ship movements, the possible effects of resonance among the complex variables preclude a general rule. As ship speed influences squat and maneuverability, the speed assumed for channel design is the minimum at which effective steering is possible.

The results of experiments and models, and the several relationships they suggest, offer useful means for evaluating the adequacy of existing channels. The panel used them in a simple computer analysis of nine major dredged channels* of the three coasts of the United States. The panel's choices of design ships and ship speeds for each channel were based on moderate assumptions, but the underkeel clearances in these channels were shown to be inadequate. Ships of greater draft are using the channels, and any increase in speed over those assumed will result in greater squat, further reducing underkeel clearances, and increasing the probability of grounding or striking bottom. The panel emphasizes that these results

*Calcasieu River (inner and outer channels), Lower Columbia River, Delaware River, Mobile Harbor, Norfolk Harbor, Oakland Harbor, San Francisco Bay, Thimble Shoal, and Galveston Channel are more indicative than definitive. A thorough, site-specific understanding of a channel and its environment is necessary for a complete assessment of a channel's adequacy.

Sedimentation

Data for control of sedimentation and shoaling by dredging are also site-specific. Essentially, two mechanisms of sediment movement may affect navigational channels in harbors and estuaries: interior and exterior. Interior mechanisms deliver sediment to a harbor from freshwater inland sources; exterior processes carry coastal sediment into a channel or harbor. Dredging may significantly alter existing relationships. While there are probably an optimum overdredged depth and an optimum dredging interval for the average conditions of channels, they may not be constant, owing to the flux of the variables. A major storm can undo all calculations. Examples studied by the panel indicate that the criteria for the dredged depths of harbor entrance channels (and perhaps for other channels as well) are dominated by the uncertainties of deposition and the irregular time constraints imposed by financial and institutional arrangements--not by the maneuvering requirements of ships.

"Nautical Depth" Concept

The results of research in the Netherlands preceding and following construction of the very deep draft channels and harbors of Europoort/Rotterdam could be applied to silty channels in the United States. Ascertaining the channel bottom is difficult when fine suspended sediments are in motion or settling. Dutch experience indicates that while the maneuvering characteristics of a ship change, it can navigate through suspended sediments to specific gravity of 1.2 ("fluid mud"). This "nautical depth" concept depends on frequent surveys for navigational safety. Density meters are used in weekly surveys in the Netherlands to determine the areas to be dredged (where specific gravity exceeds 1.2 above design depth), in connection with a conventional bottom-contouring echo sounder.

Overdredged Depths

Although the rules of thumb for overdredged depths to achieve the specified dimensions of a channel have evolved and become fixed, they are within the order of accuracy of various dredging processes. For some locations, they may need to be adjusted, and more accurate pre- and post-dredging surveys may need to be conducted.

Criteria of International Organizations, Other Maritime Countries, Shippers

Criteria for channel depths developed by international organizations and those used in other maritime countries have been established in concert with the evolving body of data, tests, and experience. Those of the Permanent International Association of Navigation Congresses (PIANC) have found application in the ports and harbors of many maritime nations and are included by reference in the standards of the International Association of Ports and Harbors (IAPH). PIANC criteria are for gross underkeel clearances in confined channels of approximately 15 percent of ship draft (the figure found to allow for vertical excursions), plus additional depths to allow for sounding accuracy, for sedimentation between two dredging intervals, and for dredging inaccuracies. This last figure varies from country to country: those making an allowance for dredging inaccuracies specify amounts close to the allowances used in the United States, but some countries allow none.

A statistical method has been developed by shipping interests that combines the values and uncertainties of all the factors known to be most important to the required underkeel clearance of ships to produce an acceptably small probability of grounding. Owing to the scarcity of data, the uncertainties for some factors are large, but these can be updated as information becomes available. This statistical method has been used to specify the design depths of at least one port (Zeebrugge, Belgium, under construction).

Conclusions and Recommendations

In light of its reviews and appraisals, the panel concludes that the physical environment and characteristics of each port are unique and that criteria for channel depth, as well as the specification of overdredged depths, must be site-specific. Nevertheless, general criteria provide a useful first approximation for design and practice, and basic standards of adequacy. The general criteria are old and need to be updated, but their inadequacy is determined more by institutional constraints than by their content. The very long time between initial studies and completion of the approval process in the United States for major navigational projects far exceeds the half-life of the world fleet. Channel improvements of the future will almost certainly be for the ships of the past. Immediate steps need to be taken to reduce the time between identification of physical and other constraints against major dredging projects and the time work can begin.

The panel recognizes that depth cannot be considered in isolation from other dimensions and features of channels, of ships, and of ships in the channel but notes that underkeel clearances in the channels of the United States are less than those of other countries, and much less than those recommended by international organizations. They may be as little as 2.5 percent of ship draft. Moreover, practices in the United States tend to rely on historical data to determine dredging frequency, rather than frequent channel surveys.

The panel suggests that

- The recommendations of PIANC be substituted for the general criteria now used in the United States for channel depths (and other dimensions)--these recommendations reflect the results of recent research and represent international consensus;
- Specific design criteria for particular channels be based on the results of comprehensive and detailed site studies;
- Frequent surveys be made in known, high-shoaling areas;
- The nautical depth concept be adopted for silty channels of the United States; and
- Better information about operational practices and the hydrodynamic behavior of ships be collected and incorporated in channel design.

1

INTRODUCTION

As elaborated in succeeding chapters of this report, several considerations affect decisions about the depths of dredged navigational channels. These can be separated into two general categories, the requirements of navigation (principally the underkeel clearance required in a variety of physical conditions) and those of achieving and maintaining dredged depths, but in actuality, they must be considered together. As noted by Kray (1973), "This is to provide for smooth operation and to avoid costly accidents for inadequately designed channels and maneuvering areas, and an excessive cost of constructing and maintaining the overdesigned navigational facilities."

Table 1 indicates the scope of concerns for navigation and maintenance in the channels of deep-draft ports and harbors--those 30 ft or more in depth.* The costs of dredging to maintain channel depths and the tonnages of trade accommodated by these channels are obviously considerable.

*The U.S. Army Corps of Engineers defines deep-draft navigational projects as those 14 ft or more in depth. The concern of this study is the navigational channels of the major coastal ports and harbors--the 85 ports and harbors reached by navigational channels 30 ft or more in depth.

Table 1 Costs to maintain channels and harbors of major ports in the United States by dredging, and 1978 trade, by tonnage*

Port	Depth (in feet)	Annual Average Maintenance Cost (in thousands)	1978 Tonnage[a]
Alaska			
Anchorage Harbor	35	$1,453.6	2,226,200
Alabama			
Mobile Harbor	40	5,303.2	17,336,800
California			
Humboldt Harbor & Bay	35	1,243.9	1,435,900
Stockton	30	979.8	2,277,600
Suisun Bay Channel	30	147.4	1,164,800
San Pablo Bay	35	503.1	7,082,600
Oakland Harbor	35	1,143.3	6,232,500
Richmond Harbor	35	1,182.1	15,902,900
San Francisco Harbor	40	39.1	50,401,500
Los Angeles-Long Beach Harbor	45	144.0	60,780,900
San Diego Harbor	35	0	2,360,200
Connecticut			
Bridgeport Harbor	35	224.8	3,732,600
New Haven Harbor	35	566.9	11,323,200
New London Harbor	33	7.8	2,550,600
Delaware			
IWW Delaware to	32	10,322.9	10,226,200
Wilmington Harbor	35	1,851.0	2,162,100
New Castle	35	1,202.2	8,278,200
Delaware City	35	516.5	3,556,400
Florida			
Charlotte Harbor	32	1,322.5	1,067,300
Canaveral Harbor	36	2,438.7	2,341,500
Panama City Harbor	32	210.0	282,900
Port St. Joe Harbor	35	167.8	326,200
Pensacola Harbor	33	633.6	1,538,600
Palm Beach Harbor	33	209.9	728,600
Jacksonville Harbor	38	3,098.7	13,119,400
Key West Harbor	30	25.7	202,600
Tampa Harbor	36	2,309.4	46,866,400
Miami Harbor	38	20.3	3,098,900
Port Everglades Harbor	42	83.7	11,929,300
Georgia			
Brunswick Harbor	30	3,490.5	1,259,000
Savannah Harbor	38	10,429.8	10,633,400

Port	Depth (in feet)	Annual Average Maintenance Cost (in thousands)	1978 Tonnage[a]
Hawaii			
Port Allen Harbor	35	63.7	89,300
Nawiliwili Harbor	35	535.3	765,900
Kahului Harbor	35	671.2	1,922,100
Hilo Harbor	35	352.2	1,272,700
Honolulu Harbor	45	167.7	7,740,500
Louisiana			
Calcasieu River & Pass	40	7,336.1	13,563,000
New Orleans	40	16,661.9	77,231,400
Baton Rouge	40	18,297.5	123,937,800
Maine			
Portland Harbor	35	613.4	21,984,800
Maryland			
Baltimore Harbor & Channel	42	2,477.6	37,074,600
Massachusetts			
Cape Cod Canal	32	4,096.6	12,226,600
Fall River Harbor	35	133.2	4,642,300
Boston Harbor	40	181.1	24,700
Mississippi			
Gulfport Harbor	30	1,899.2	950,000
Pascagoula Harbor	38	2,485.5	18,258,200
New Hampshire			
Portsmouth Harbor	35	140.7	3,293,300
New Jersey			
Camden	30	264.6	1,787,400
Gloucester	35	245.4	1,690,000
Paulsboro	40	2,522.9	17,372,800
New York			
Hudson River, Albany	32	1,907.5	10,440,500
New York-New Jersey	45	12,905.7	119,317,600
North Carolina			
Morehead City Harbor	40	1,969.6	2,069,400
Wilmington Harbor	38	3,041.6	7,422,800
Oregon			
Yaquina Bay & Harbor	32	1,379.2	668,500
Coos Bay	45	3,652.3	5,218,900
Portland	40	12,567.1	16,524,952
Astoria	40	881.7	1,159,300

Port	Depth (in feet)	Annual Average Maintenance Cost (in thousands)	1978 Tonnage[a]
Pennsylvania			
Penn Manor	40	1,376.6	4,041,200
Philadelphia	40	6,702.0	37,067,600
Chester	35	4.1	28,100
Marcus Hook	40	3,446.4	23,731,900
Puerto Rico			
Mayaguez Harbor	30	106.7	335,300
Ponce Harbor	30	77.7	911,400
San Juan Harbor	48	852.9	10,147,800
South Carolina			
Charleston Harbor	35	5,816.9	9,548,800
Texas			
Brazos Island Harbor	36	3,116.6	1,162,900
Matagorda Ship Channel	38	2,610.3	3,963,200
Freeport Harbor	36	3,590.8	18,657,400
Galveston Harbor & Channel	40	1,638.8	7,004,300
Corpus Christi	45	6,202.1	46,244,500
Sabine Ports	40	7,981.8	69,740,900
Houston	40	8,312.5	81,221,825
Texas City	40	1,954.1	23,627,800
Virginia			
Norfolk Harbor	45	2,801.7	25,286,900
Newport News	45	932.0	5,740,900
Washington			
Grays Harbor & Chehalis River	30	4,668.4	2,664,000
Vancouver	40	1,185.5	1,558,800
Kalama	40	199.6	262,500
Longview	40	4,645.5	6,108,500
Everett Harbor & Snohomish River	30	457.0	2,167,900
Bellingham Harbor	30	140.8	891,000
Seattle Harbor	34	376.5	11,357,500
Ediz Hook-Port Angeles	30	19.3	2,774,700
Tacoma Harbor	35	44.5	9,667,300

[a] Rounded to the nearest hundred tons

*SOURCE: From U.S. Senate Committee on Environment and Public Works (1981), Report to Accompany S. 1692, National Harbors Improvement and Maintenance Act of 1981, 97th Congress, 1st Session, pp. 29-32.

Thus, economic considerations (specifically excluded from the panel's analysis) dictate that the depth and other dimensions of a channel be minimal, but consistent with the safe passage of ships calling at the port or harbor. These ships, over the past decade and a half, have been increasingly larger. Some examples of common ship types and their design data are given in Table 2.

The hydrodynamic forces and effects experienced by these vessels in navigational channels differ markedly from those experienced in the open ocean. The draft and attitude of a vessel change continuously while it is under way in a navigational channel, owing to the combined effects of natural and ship-generated forces and the dimensions and layout of the channel. Vertical excursions present the danger that the vessel may ground or strike bottom. Ships are rarely reinforced in the areas most likely to be scratched or breached by grounding or striking bottom, nor is such reinforcement feasible, owing to the enormous forces that develop in such an accident. Thus, these casualties present risks from the leaking of hazardous or polluting cargoes. Damage to the ship, loss of cargo, and containment and cleanup operations can be expensive: the breaching of the tanker Tamano inbound to Portland, Maine, in 1972 cost more than $2 million in vessel damages and pollution mitigation.

The designed configuration of a navigational channel, according to the National Waterways Study (1980), "influences the probability of vessel casualties." In considering strategies to enhance the safety of domestic waterways, the report states: "the only single action which by itself could reduce accidents is the structural improvement of the waterways."

Depth is an important component of the designed configuration of a navigational channel. In the interest of providing the technical basis for design and maintenance of dredged navigational channels, the panel undertook an evaluation of the criteria used to determine channel depths in the United States. The panel reviewed

- Criteria used in the United States for channel depths;
- Considerations important to the evaluation of channel depths;
- Voluntary consensus standards developed by international organizations; and
- Criteria used in other maritime nations with highly developed port technology.

It also assessed the adequacy of the criteria used in the United States.

The results of the panel's review and appraisal are briefly summarized in succeeding chapters of this report: Chapter 2 discusses regulatory and institutional issues. Chapter 3 deals with considerations important to determining channel depth (ship movements and sedimentation). Chapter 4 addresses the adequacy of criteria for dredged depths of navigational channels and compares those of the United States and other countries, international organizations, and shippers. Chapter 5 sets out the panel's conclusions and recommendations. Abstracts compiled by the panel in a preliminary search of the literature constitute Appendix A.

Table 2 Common ship types and their design data

Type	Name	Cargo Capacity (dwt, unless noted)	Length (ft)	Beam (ft)	Draft (ft)
Ferry	STATEN ISLAND	2,721	310	70	12
Tugboat	JALBAR	1,010	126	36	17
Bulk	ALTNES	4,550	301	49	21
Tanker	MARINDUS	10,000	470	60	23
Submarine Tender	FRANK CABLE	23,000	643	85	25
Tanker	EXXON GALVESTON	27,240	552	95	29
Dry Cargo	AMFITRITI	16,952	468	69	31
Containership	EUROLINER	40,800	798	100	32
RO-RO	BOOGABELLA	31,500	749	105	35
Barge Carrier	YELIUS TUCHIK	36,382	874	115	36
Navy Tanker	HUDSON	37,276	672	89	36
LNG Carrier	EL PASO SOUTHERN	126,000m^3	846	135	37
Refined Product Tanker	BALDBUTTE	244bbl	665	84	37
Tanker	ESSO PORTLAND	50,084	645	120	37
Crane Ship	SARITA	42,000	677	121	37
Barge Carrier	ALMERIA LYKES	38,410	876	106	39
Dry Cargo	AMERICAN TRADER	29,749	820	100	41
Containership	KORRIGAN	57,200	947		43
Ore/Bulk/Oil	ULTRASEA	83,437	893	106	46
Bulk	WORLD DULCE	133,361	570	142	52
Bulk	SAMRAT ASHOK	72,600	856		58 [a]
Ore	SHINRYU MARU	88,800	959		59 [a]
Tanker	SAN DIEGO	188,500	952	166	59 [a]
Ore/Bulk/Oil	RHETORIC	77,000	996		60 [a]
Ore/Oil	BRAZILIAN WEALTH	141,800	1099		72 [a]
Bulk/Oil	LAUREL WREATH	72,300	940		72 [a]
Tanker	ESSO PACIFIC	508,000	1280	233	83

[a] Not accommodated by dredged channels of the United States

2

REGULATORY AND INSTITUTIONAL CONSIDERATIONS

Background

The legislative and regulatory structure governing dredged navigational channels reflects a lon history. A summary volume of regulations states that "since colonial times, harbors and channels have played an important role in the nation's settlement, commercial and industrial growth, and system of defense" (U.S. Army Corps of Engineers, 1981a). As the provision of dredged navigational channels has been taken to be a federal responsibility of both military and commercial importance, primary responsibility for the design and maintenance* of these works has been taken by the U.S. Army Corps of Engineers.

In recent decades, other national interests have increased in public importance, notably those of protecting the marine and coastal environment and preserving oceanic resources. (A summary of

*Until 1978, the U.S. Army Corps of Engineers also performed improvement and maintenance dredging with its own fleet of dredges, and by contract with private industry. In 1978, following the Industry Capability Program and a congressional act (P.L. 95-269), the Corps initiated a Minimum Dredge Fleet for purposes of national security or defense, preserving sufficient work to keep the fleet operational, and allowed private industry to bid on all other dredging work.

environmental protection laws requiring compliance in navigational projects is given in Appendix C.) Among the environmental questions raised about dredging are the immediate and long-term effects of the activity, the location of onshore or offshore disposal sites for dredged materials of different types, and the handling and disposal of dredged materials containing toxic or hazardous substances, such as Kepone, oil, and heavy metals.

A lengthy 20-step process for gaining approval and public funds for the construction of navigational projects has evolved in response to these and other interests and objectives, illustrated in Figure 1. Congress exercises control of the process at several stages, beginning with initiation (Congress must request a feasibility study), and including three to four separate congressional acts of authorization and appropriation of funds. The district office (in which a navigational project is located) of the U.S. Army Corps of Engineers examines several engineering options, as well as their costs and benefits, and prepares reports, including environmental impact statements, for various levels of internal and external approval. Public hearings are convened, and the review or concurrence (or both) of the affected organizations, units of government, and other federal agencies is sought. Progress to step 16, congressional authorization, takes about 6 years (and each year's activities depend on congressional appropriations), after which several years may elapse before the funds for advance engineering and design are appropriated. The median time to complete the process was 15.2 years in the mid-1970s. This was for 36 projects that were completed (many were not) and for which the initial survey reports were submitted in the late 1950s and early 1960s (Heiberg, 1981). The complexity of the process and the number of decision makers have since increased. It is estimated (no major improvements to navigational channels have been approved since 1976) that the process would take 20 years to 25 years to complete today.

The Corps recently proposed accelerating the pace of this process (but without reform or abbreviation, which requires congressional action) by assembling "fast-track teams" that would conduct concurrent studies and reviews, and (subject to congressional approval) by dropping work on projects that have not been recommended for further development (or have languished many years) and concentrating on those that have been recommended for pursual (U.S. Army Corps of Engineers, 1982a). The proposal aims to reduce the time spent by the Corps in completing required studies and reviews from 12 years to 7 years.

While it is possible for ports or private interests to undertake navigational projects that will be funded by sources other than the federal government, a permit is required from the district engineer of the Corps, who coordinates responses to the application from other agencies and affected groups. A period of public notice and comment is required. An environmental impact statement is also required, as well as a public hearing. Memoranda of understanding between the Corps and five other federal agencies state that decisions will be made on these applications within 90 days of the public notice. The Corps has also initiated a "pull" in place of "push" system for

Figure 1 Planning, approval, authorization, and funding process for major navigational projects.

1	2	3	4
Congress authorizes study	Congress appropriates funds	Following appropriation of funds, District Engineer conducts initial public meeting to review draft plan of study. This provides opportunity to identify and discuss local problems & alternatives emphasizing national economic efficiency and environmental quality	District Engineer o Investigates all alternatives o Performs limited - technical feasibility studies - environmental assessments o Proposes most feasible solutions in preliminary feasibility report

Survey Investigations

5	6	7	8
o Formulation Stage public meeting to discuss most feasible alternatives	District Engineer o Investigates formulation stage alternatives o Performs detailed - technical feasibility studies - Environmental assessments o Selects plan for proposal in detailed Feasibility Report (FR) o Distributes draft Environmental Impact Statement (EIS) & FR (15 days prior to late state public meeting) o Files draft EIS with EPA	Late stage public meeting Tentative plan proposed and discussed	States, agencies, interest groups, public respond to draft EIS and draft FR

9	10	11	12
District Engineer o Reviews comments to draft EIS & FR o Prepares recommended - Final EIS - Final FR	Division Engineer o Reviews o Modifies as Appropriate - Final FR as Appropriate - Final EIS o Issues public notice requesting public views be sent to Board of Engineers for Rivers & Harbors (BERH) o Forwards recommendations to BERH	BERH o Considers Views of - Public - States - Agencies o Reviews and provides recommendations - Final EIS - Final FR o Transmits to chief of engineers	Chief o Reviews Board report o Prepares his draft recommendations o Distributes for outside review o Files final EIS with EPA o Circulates to public for 30-day review period and to governors, federal departments 90-day review period

Survey Investigations — Review

13	14	15	16
Chief o Reviews received comments o Modifies report as appropriate o Prepares record of decision (ROD)	Chief o Forwards recommendations to Secretary of the Army for consideration - Final Report - Final EIS - ROD	Secretary of the Army o Reviews o Coordinates with OMB o Prepares his recommendations o Forwards final FR, final EIS. o ROD to Congress (6 mo.)	Project Authorization o Congress holds hearings o Congress includes in Water Resources Development Act or other legislation o President signs

Review — Project Authorization

17	18	19	20
OMB o Reviews Corps budget o Submits to Congress	Project Funding o Congress includes in Appropriations Act o President Signs	Local interests guarantee to fulfill obligations required by law (e.g., real estate, cost sharing, maintenance, operation, flood zoning)	CE o Formulates pre-construction planning general design memoranda (GDM) - Updates EIS as required for Sec. 404 compliance, obtains necessary Water Quality certificates - Issues public Notice and conducts at least one public meeting (36 mo.) o Obtains additional congressional authorization as appropriate (24 mo.) o Initiates and completes construction (60 mo.) o Operates and maintains

Awaiting Funds after Project Authorization by Congress — AE&D to Construction Funding — Construction internal decision making to allow as many decisions as possible to be made at lower levels, where local knowledge has been accumulated and more timely decisions can be made, and to allow higher levels of the Corps to "pull" up for consideration only the decisions that must be made at that level.

These recent changes are only now being exercised. As few major deepening projects have been undertaken in the United States since World War II, and only one planned for nonfederal funding,* the principal criteria used in this country to determine the depths of navigational channels are those of the U.S. Army Corps of Engineers. The criteria consist of guidelines published by the Corps for the use of district offices, and the practices of the districts established by research or experience. A brief summary is given in the succeeding section.

Criteria Used in the United States to Determine Channel Depth

The Engineer Regulation "Deep Draft Navigation Project Design" (U.S. Army Corps of Engineers, 1981b) states for determining the depths of channels:

> The channel depth must be adequate for the design vessel draft, squat, trim, sinkage due to fresh water conditions, location of salt water intakes on ship, wave action and appropriate under keel clearance. Minimum under keel clearance should be two feet for soft channel bottoms and three feet for hard channel bottoms. Squat is calculated for expected vessel speeds and passing conditions for two way traffic channels. Salt water intakes on vessels must be five feet or more above soft channel bottoms. This clearance is needed to prevent silt from being pulled into the vessel condenser. Additional channel depth may be provided by advanced maintenance dredging based on the economics of dredging intervals and the need to assure appropriate under keel clearance between dredging periods.

The references cited are the <u>Engineer Manual</u>, <u>Tidal Hydraulics</u>, published in 1965, "Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena," also published in 1965, and "Effects of Depth on Dredging Frequency," published in 1978 (U.S. Army Corps of Engineers, 1965a,b; Trawle and Boyd, 1978).

Turning to the cited <u>Engineer Manual</u>,** two sets of criteria are specified for determining channel depth: one for navigation, another for ease of maintenance. These are briefly summarized here. The factors considered by the panel in evaluating them are addressed in detail in succeeding sections.

*Galveston, Texas

**Pertinent sections are reproduced in Appendix B

Navigation

For navigation, channel depth is generally considered to be determined "by the in-motion draft of the design vessel, the density of water, wave characteristics, the tidal characteristics, the characteristics of the bottom, and the economics of greater depth as a factor to reducing power requirements for the propulsion of the design vessel."

Data for most of these factors are sparse and uncertain. The Engineer Manual recommends site-specific data gathering and consultation with ship owners and local pilots but acknowledges that for calculation of such factors as squat, for example, "dependence will have to be placed on estimates." The references cited for calculations and considerations in estimating squat and other important characteristics of the design ship are at least 20 years old, some more than 30. These have not been updated. The rules of thumb given by the Engineer Manual for underkeel clearance are draft + squat (3 ft) + rolling and pitching allowance (estimate) + clearance (2 ft or 3 ft).

While the criteria for underkeel clearance have not been updated, it is interesting to note that the more recent Engineer Regulation now requires consultations with pilots and the concurrence of the U.S. Coast Guard in channel dimensions and other aspects pertinent to the safe use of the proposed channel, both in the preliminary and in the final design stages. The Engineer Regulation also calls for site-specific evaluation of physical environmental factors, including gathering of baseline data and model studies, and recommends the use of "[p]ertinent textbooks, research reports, or expertise from other agencies."

The choice of the design ship(s), as pointed out in the Engineer Manual, is a crucial one, and this is clarified by the Engineer Regulation as "selected from comprehensive planning studies of the various types and sizes of vessels expected to transit the channel...over the economic life of the project...." Usually the largest vessel of the major commodity movers, it "is selected by evaluating tradeoffs of delay cost incurred by larger vessels and cost of increased channel dimensions. The maximum size vessel and least maneuverable vessel in the fleet must be able to make a safe transit [taking into account special conditions that may be imposed--for example, speed limits, use of high tides for additional water depth, one-way traffic, tug assistance]."

There are regulatory and institutional concerns beyond those of the U.S. Army Corps of Engineers: those of port authorities and the U.S. Coast Guard, for example, about the consequences of groundings. These may result in the "special conditions that may be imposed." While many vessels can strike a soft channel bottom or ground without harm, all groundings must be reported to the U.S. Coast Guard under the Port and Waterways Safety Act of 1972, and a fine may be levied against the master or pilot.

Maintenance

The Corps has expended considerable effort investigating, modeling, and adding to the understanding of the hydrology of channels, estuaries, and rivers. This understanding is essential to several missions of the Corps--for example, engineering design and construction of flood control and water-resources projects--and to the interactions of these works with navigational channels.

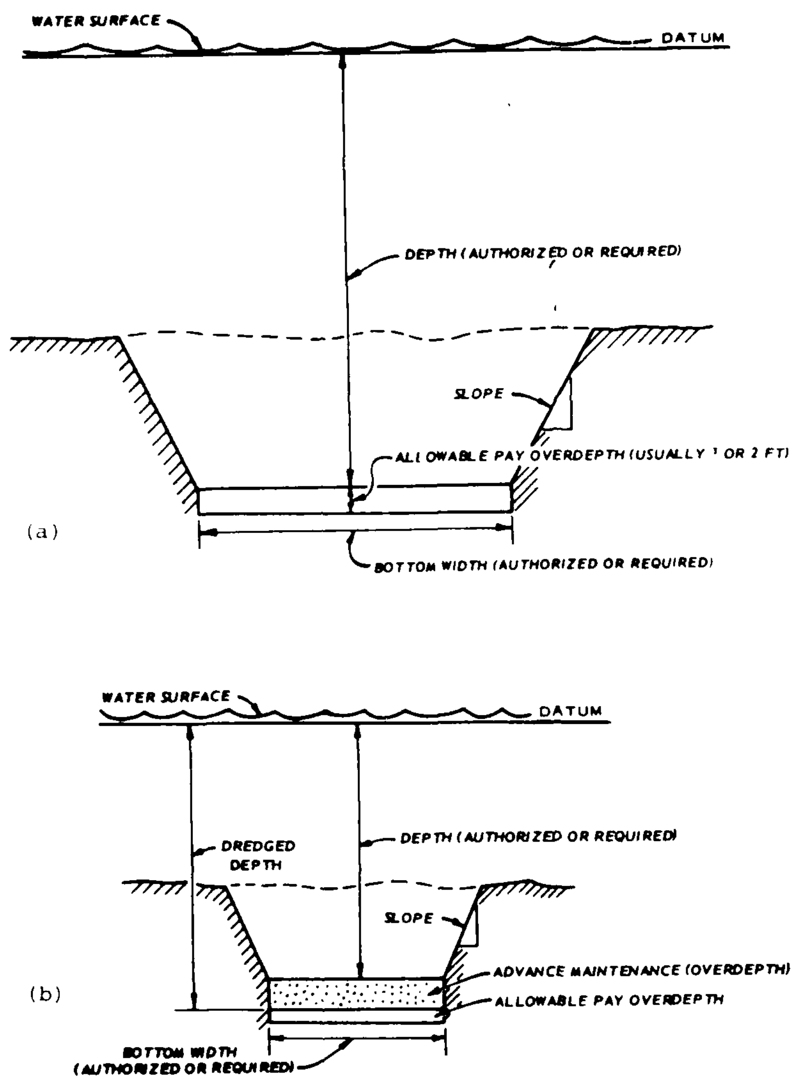
One updated reference in the Engineer Regulation is Trawle and Boyd (1978) and, by parity of reason, Trawle (1981b). Trawle and Boyd (1978) is the first and Trawle (1981b) the second report in the series Effects of Depth on Dredging Frequency. The first report discusses the evidence from questionnaire surveys of Corps districts respecting overdredged depths (or "overdepth dredging"). Overdredged depths are of two types (see Figure 2): One is the "allowable pay overdepth," an additional depth for which the Corps agrees to pay the dredger to ensure that the design depth is achieved--that is, allowing for the inaccuracies of dredging and surveying. The other is "advance maintenance overdepth" or "purposive overdepth" for (1) maintaining project depth in rapidly shoaling areas, (2) reducing the frequency of maintenance dredging, or (3) allowing more efficient dredging operations, if deeper cuts are more cost-effective, or for some combination of these reasons. The surveys indicated that in all coastal districts the allowable pay overdepth varies from 0 ft to 3 ft (0.9 m), most clustering at 2 ft (0.6 m), for channels from 30 ft to 47 ft (9.1 m to 14.2 m) deep. This "plus 2 ft" seems to be a rule of thumb that has evolved.

The surveys also revealed that past shoaling history seems to be the main determinant of advance maintenance dredging in the coastal districts (amounts varied from 1 ft to 8 ft (0.3 m to 2.4 m) but are 3 ft (0.9 m) or less in 84 percent of the projects) and that the method of assessing past shoaling varied from district to district. Specifically, Trawle (1981b) indicates that three techniques and formulas were being used to determine whether and where advance maintenance dredging was needed, all less than adequate, and that hydrographic surveys were generally infrequent (Table 3). The second report offers a formula for calculating shoaling rates as a function of the volumes dredged in the past (from annual records of dredging work) to maintain project depth in segments of a channel, and correcting with hydrographic surveys. One object of this technique and formula is more efficient scheduling of maintenance dredging, another is to encourage variable advance maintenance dredging (that is, by channel segment) for fast-shoaling areas. An implicit objective of the report seems to be to bring these practices into conformity with an adequate standard and encourage more frequent hydrographic surveys.

Implications

The glacial pace of the multistage process for approvals, congressional authorization, and other steps to be completed, and the number of years over which the process itself has evolved, have several implications for channel design. First, the validity of original assumptions and estimates attenuates with time, necessitating update studies and reexamination of needs, costs, and benefits. The

Figure 2 Two types of overdredged depths in navigational channels:* (a) typical dredged channel, showing allowable pay overdepth; (b) dredged channel with allowable pay overdepth and advance maintenance dredging overdepth



*SOURCE: M. J. Trawle and J. A. Boyd, Jr. (1978), Effects of Depth on Dredging Frequency, Report 1, Survey of District Offices, Technical Report H-78-5 (Vicksburg, Miss.: U.S. Army Engineer Waterways Experiment Station), May 1978, p. 6.

TABLE 3 Frequency of Channel Depth Surveys, by Coastal District Offices of the U. S. Army Corps of Engineers*

District Office	Frequency of Surveys	Areas
Alaska	Twice each ice-free season	Anchorage, Dillingham, Nome, Ninilchik, and Homer Harbors
	Monthly (1976 season)	Dillingham Harbor
Baltimore	Semiannually	All projects; backlog of requests for surveys
Charleston	Semiannually	Heavily shoaling areas
	Annually	All other areas
Galveston	Annually	All projects
Jacksonville	Twice yearly	Fernandina, Jacksonville and St. Augustine Harbors; Ponce de Leon Inlet; Canaveral, Ft. Pierce, Palm Beach, Port Everglades, Miami, Charlotte, and Tampa Harbors; St. Lucie Inlet
Los Angeles	Annually	All projects
Mobile	Annually	All projects
New Orleans	Semiannually	Bayous Lacombe, Bonfouca, Dupre, Lafourche, La Loutre, Segnette, Teche, Little Caillou, Petit Anse, Tigre, and Carlin; Bar and Inside Channels, Barataria Bay Waterway; Portions of Gulf Intracoastal Waterway; Calcasieu River, Pass and Pass Bar Channels; Houma Navigation Channel; Atchafalaya Basin; Berwick Harbor
	Monthly	Breton Sound, Bar Channel, Land Cut
	Weekly	Portion of Gulf Intracoastal Waterway; Mississippi River from Baton Rouge to New Orleans Harbor; Southwest Pass, Southwest Pass Bar, and Jetty Channels, Gulf of Mexico; Baton Rouge Harbor
New York	Semiannually	East Rockaway, Fire Island, and Jones Inlets; Hudson River Channel
Norfolk	Annually	All projects
Philadelphia	Semiannually	All portions of Delaware River, Philadelphia to Delaware Bay; Wilmington Harbor
Portland	at 3-6 week intervals	Portions of Columbia River; Vancouver, Washington; Coos Bay, Oregon
San Francisco	Semiannually	Mare Island Strait
Savannah	"Frequently"	Savannah Harbor
Seattle	Annually	All projects
Wilmington (N.C.)	Twice yearly	Wilmington Harbor
New England Div.[a]	Infrequently	
Pacific Ocean Div.[a,b]	----	----

a No districts in division

b No major navigational channels

*SOURCE: M. J. Trawle and J. A. Boyd, Jr. (1978), Effects of Depth on Dredging Frequency, Report 1, Survey of District Offices, Technical Report H-78-5 (Vicksburg, Miss.: U.S. Army Engineer Experiment Station), May 1978, pp. 14-16.

deepening of the major channel serving Tampa Bay, for example, was authorized in 1970. The final environmental impact statement was submitted in 1971, an updated statement was filed in 1975, the draft of a supplement in 1976, and the final supplement in 1977. The original estimated cost to deepen channel segments was $97.5 million. In 1981, the estimated cost was $178 million and this included reductions of more than $12 million owing to favorable bids, to work completed under bid, and to the savings represented in dredging to depths a foot less than those authorized (U.S. Army Corps of Engineers, 1982b).

While much may still remain valid from earlier studies, the time scale of the decision making process is far longer than the time scale of major changes in the world shipping fleet. Less than 5 percent of the ships in the world's merchant fleet are 25 years old or more: more than 59 percent are under 10 years old (Lloyd's, 1980). The design ship used to specify channel improvements may pass from drawing board to desuetude before channel improvements receive final approval and work begins.

Second, the nature of this process (and the time needed to complete it) discourages innovation. Approximately 1 percent of the total budget of the U.S. Army Corps of Engineers is for research, and this must be divided among several subjects of equally pressing importance to the missions of the Corps. As described in succeeding sections, the number and complexity of the factors that need to be understood to determine the depths (and other dimensions) of navigational channels demand considerable research. Some of this may be undertaken by the districts on passage of the legislation authorizing a navigational project--for example, model and simulation testing of the channel design for various vessels and unique features of the local environment--as their budgets allow. Model tests, simulations, and intensive local data collection are generally expensive. In their absence, design depth is usually based on empirical rules ("rules of thumb") set out in Corps publications, with additional depth(s) for achieving the design depth and advance maintenance dredging.

Furthermore, the design and engineering undertaken after authorization are bound by the terms of the authorizing act. Even in areas of a particular project's design and engineering that may allow some latitude, the nature of the decision making process and the number of decision makers involved ensure that changes will be addressed conservatively, and in terms that are readily understood or familiar. These considerations, together with the very long time needed to plan and secure approval of navigational projects, tend to fossilize the rules of thumb for channel depth.

3

CONSIDERATIONS IMPORTANT TO DETERMINING CHANNEL DEPTH

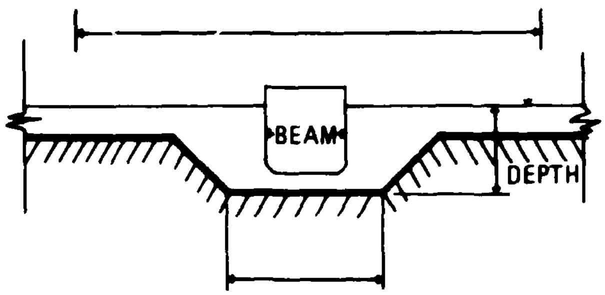
Channel Types

Dredged navigational channels may be open or confined (Figure 3). Open channels characterize entrances from the open sea to the port or harbor; confined channels may be canals, dredged estuaries or rivers, or excavated extensions of waterway systems.

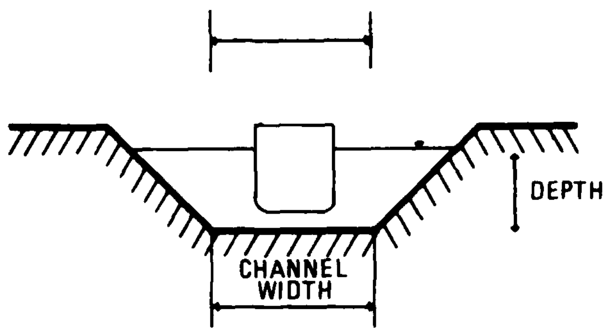
Definition of Water Level

Depths of navigational channels must be specified relative to the water surface and channel bottom (special problems of defining the bottom in silty channels are addressed in a separate section). The water surface is defined by reference to a datum, mean low water (MLW) or mean lower low water (MLLW) on the Pacific Coast. These are averages of low (or lower low) waters for 19 years. The actual water surface in the channel is often difficult to specify. The main tides produced by the relative motions and positions of the earth, moon, and sun are not experienced instantaneously. The tide is a gravity water wave with a very long wavelength and, owing to coastal bathymetric and hydrodynamic effects (such as losses to friction and reflections from the seabottom and boundaries), may have significantly different elevations at different locations in a bay or estuary at the same time. The mean surface itself is an irregularly warped plane that is sensitive to changes in the shoreline and the depths of channels

Figure 3 Types of dredged navigational channels



Open



Confined

(Johnson, 1929). Few tide gauges are located in the open waters of major coastal channels.

Dramatic (and sometimes rapid) vertical changes may occur with the impoundment of river outflow owing to constricted harbor entrances, or with strong prevailing winds in one direction. Wind stress at the water surface may induce a surface current in the direction of the wind that forces more water to the leeward side and lowers the windward side (with a resulting return flow below the surface). This wind setup, or setdown, depending on the point of measurement, can be considerable in confined or estuarine channels; in open channels located in coastal areas, the phenomenon is called storm surge. If the storm surge is caused by hurricane winds, the lowering of atmospheric pressure will cause water levels to rise well above those induced by wind stress alone.

A few channels and harbors are subject to seiches, or standing waves of relatively long period, induced by an intermittent or periodic series of changes in local atmospheric pressure and winds, or by oscillations communicated through a harbor entrance from the open sea (resulting, for example, from wave groups, offshore earthquakes or landslides, or changes in atmospheric pressure and winds). These standing waves may achieve large amplitude if the causative force or forces are periodic, and their period is close to that of the resonance frequency of the waterway system, harbor, or bay.

The measurement and prediction of these changes in water level present formidable challenges to designing channel depths and to evaluating the effect of changes. These are carefully addressed in the Engineer Manual. As the manual states, "The determination of these effects may be accomplished by means of difficult computations, hydraulic models, or electric analogs....For investigations of problems within a waterway, where it is not contemplated that significant modifications in the geometry of the waterway will be made, it is necessary that tidal data be available at a sufficient number of stations along its course to define the tidal establishment throughout."

With the exception of some sites, tide, current, and channel depth information is provided by an annual prediction of daily tides and currents, published by the National Ocean Survey (NOS), tide-gauge readings, nautical charts, and the surveys conducted by the U.S. Army Corps of Engineers. At the request of ship pilots or the U.S. Coast Guard, NOS or the Corps will sound the channel bottom or check shoaling areas, but as indicated in Chapter 2, surveys are typically conducted annually or semiannually, and nautical charts are typically updated annually (National Ocean Survey, 1982). Information is rarely available in real time on water levels at points of interest in the channel, and the difference between predicted and actual high or low tide may be as great as 1 ft.

Ship Behavior and Channel Depth

Ships moving in navigational channels are subject to forces that have no counterpart in the open ocean, such as bank and bottom suction. They also experience significant changes in the effects of hydrodynamic phenomena associated with forward motion and maneuvers, forces of the physical environment, and the forces generated between ships in passing and overtaking. The effects of channel depth can be considerable, particularly when underkeel clearance is small, and may be significantly amplified or dampened by interactive forces. A vessel's six degrees of freedom in motion are illustrated in Figure 4.

The interactive effects experienced by a ship vary with the type of channel: if confined, the channel's sides and bottom will increase the longitudinal flow of water under and around the ship, improving dynamic course stability and consequently reducing maneuverability (Eda, 1971). If the channel is in open water, the restricted flow of water under the ship increases water resistance, but less sinkage, or squat, is experienced in such a channel than in a confined channel of equal depth (Kray, 1973).

Frequently critical for ship controllability is the harbor entrance. Ships may experience extraordinary vertical (and horizontal) excursions owing to the characteristics of the ship--its speed and trim, for example, or length and natural frequency in heave and pitch--and its interactions with waves and swells, currents, winds, and salinity and temperature gradients.

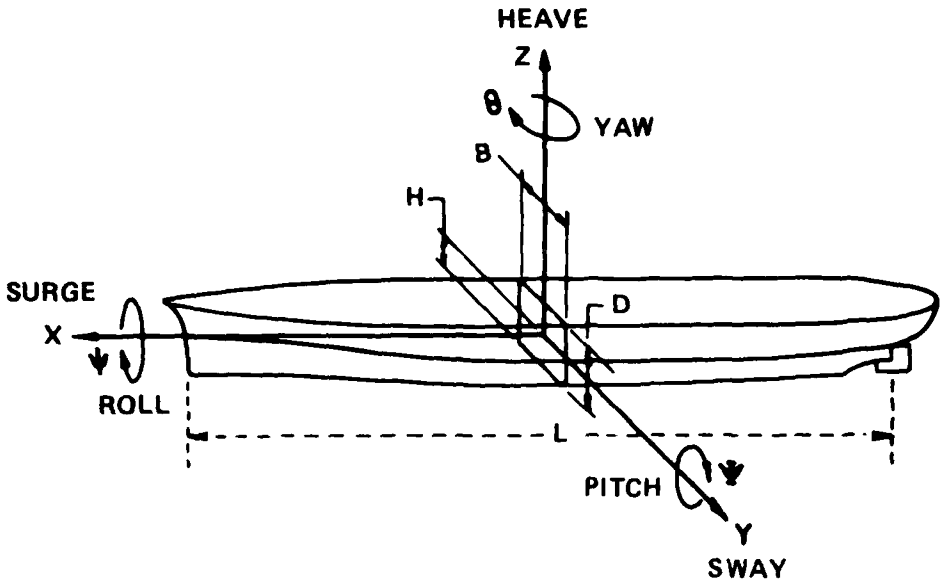
Squat

A ship in motion depresses water levels around it, and its draft increases. The difference in a ship's dynamic draft and static draft, or squat, depends primarily on speed and water depth, becoming more pronounced at higher speeds and shallower depths. The panel's preliminary calculations of the squat of typical ships in nine major channels in the United States are set out in a section of Chapter 4 ("Evaluating the Adequacy of Criteria...").

Squat increases in passing or overtaking. This case is not so well understood as that of a ship in motion in a confined channel, but some research and modeling has been undertaken in recent years (Eda, 1973; Eda et al., 1979; Dand, 1980). Combining the curves and tables developed by Dand (1980) from model tests and data for shallow and confined water given by Sjostrum (1965), Kimon (1982) developed a set of guidelines (Table 4) for the squat of the slower vessel in passing situations. (The complex hydrodynamic forces generated in overtaking are essentially the same as those for passing, with the critical difference that the duration of the encounter is longer in overtaking.)

Other factors may influence the amount of squat: Kimon (1982) indicates that squat can double in executing turns, reversing the propeller, and experiencing sudden changes in water depth.

Figure 4   Ship's six degrees of freedom in motion



X, Y, Z = System of coordinates, related to ship's principal axes
x, y, z = Linear displacements
Ψ, φ, θ = Angular displacements

Table 4 Multipliers for additional squat, ships passing*

$$\frac{\text{Own Ship Speed}}{\text{Passing Ship Speed}} = 0.5$$

Lateral Separation of Ship Center Lines ÷ Larger Ship's Beam	Passing Ship Multiplier - Bow, Nominal Depth/Draft 1.10	1.20	1.50	Passing Ship Multiplier - Stern, Nominal Depth/Draft 1.10	1.20	1.50
1.1	3.4	5.0	6.0	5.4	3.2	5.0
1.3	3.1	3.2	3.9	5.0	4.0	4.6
1.6	3.2	3.6	4.8	4.7	3.8	4.5
2.2	2.0	3.2	4.3	3.1	3.5	3.8
3.65	2.0	2.0	2.5	2.5	2.0	2.0
4.0	1.0	1.0	1.0	1.0	1.0	1.0

$$\frac{\text{Own Ship Speed}}{\text{Passing Ship Speed}} = 0.6$$

Lateral Separation of Ship Center Lines ÷ Larger Ship's Beam	Passing Ship Multiplier - Bow, Nominal Depth/Draft 1.10	1.20	1.50	Passing Ship Multiplier - Stern, Nominal Depth/Draft 1.10	1.20	1.50
1.1	2.7	2.5	4.1	4.5	2.3	3.6
1.3	2.6	2.6	3.1	4.0	3.4	3.6
1.6	2.4	2.8	3.4	3.8	2.8	3.0
2.2	1.8	2.6	2.9	2.8	2.8	2.6
3.65	1.6	1.6	2.0	2.1	1.4	1.7
4.0	1.0	1.0	1.0	1.0	1.0	1.0

$$\frac{\text{Own Ship Speed}}{\text{Passing Ship Speed}} = 0.7$$

Lateral Separation of Ships Center Lines ÷ Larger Ship's Beam	Passing Ship Multiplier - Bow, Nominal Depth/Draft 1.10	1.20	1.50	Passing Ship Multiplier - Stern, Nominal Depth/Draft 1.10	1.20	1.50
1.1	2.3	2.5	3.0	3.9	1.8	2.9
1.3	2.1	2.1	2.6	3.5	2.9	3.0
1.6	2.1	2.2	2.6	3.3	2.2	2.3
2.2	1.7	2.1	2.2	2.7	2.4	2.0
3.65	1.4	1.4	1.7	1.9	1.4	1.5
4.0	1.0	1.0	1.0	1.0	1.0	1.0

$$\frac{\text{Own Ship Speed}}{\text{Passing Ship Speed}} = 0.8$$

Lateral Separation of Ships Center Lines ÷ Larger Ship's Beam	Passing Ship Multiplier - Bow: Nominal Depth/Draft 1.10	1.20	1.50	Passing Ship Multiplier - Stern: Nominal Depth/Draft 1.10	1.20	1.30
1.1	2.1	2.0	2.5	3.6	1.6	2.6
1.3	2.0	2.0	2.2	3.1	2.7	2.6
1.6	1.8	2.0	2.0	2.9	2.0	1.9
2.2	1.6	2.0	1.8	2.5	2.3	1.7
3.65	1.3	1.3	1.5	1.6	1.3	1.3
4.0	1.0	1.0	1.0	1.0	1.0	1.0

$$\frac{\text{Own Ship Speed}}{\text{Passing Ship Speed}} = 0.9$$

Lateral Separtion of Ships Center Line ÷ Larger Shi's Beam	Passing Ship Multiplier - Bow: Nominal Depth/Draft 1.10	1.20	1.50	Passing Ship Multiplier - Stern: Nominal Depth/Draft 1.10	1.20	1.30
1.1	1.7	1.7	2.2	3.0	1.6	2.2
1.3	1.7	1.7	2.1	2.8	2.6	2.2
1.6	1.7	1.7	1.8	2.7	2.1	1.6
2.2	1.6	1.7	1.6	2.5	1.8	1.5
3.65	1.3	1.1	1.4	1.4	1.2	1.2
4.0	1.0	1.0	1.0	1.0	1.0	1.0

*SOURCE: P. M. Kimon (1982), "Underkeel Clearance in Ports," Paper presented at SHIP-TRANS-PORT Symposium, September 8-10, 1982, Rotterdam.

Trim

The difference in a ship's draft over its length, or trim, also changes with varying conditions. Changes in squat are generally accompanied by changes in trim. Theories and experiments have shown that the change in trim (from bow down to bow up) occurs at the critical speed, $V/(gL)^{1/2} = 1$, where V is the ship's speed, g is the gravitational acceleration, and L is the ship length. At the critical speed, the vessel's bow will be at its lowest point relative to the channel bottom.

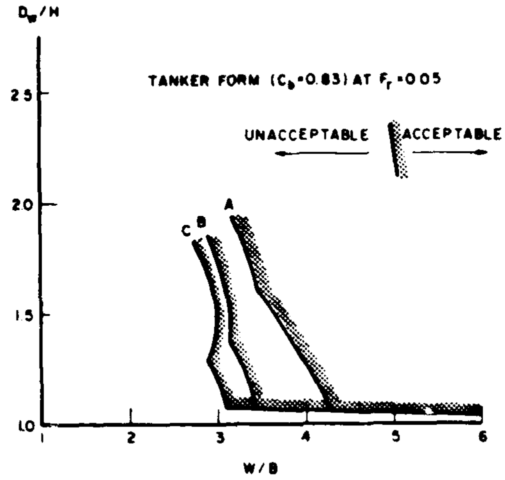
Ratio of Channel Depth to Ship Draft: Confined Channels

Curves for acceptable ratios of channel depth to ship draft (and channel width to ship beam), based on digital simulations, observed performance of pilot-controlled ships in small and large model tests, and full-scale ship trials in deep and shallow water, are shown in Figure 5 (Eda, 1971). Contours A, B, and C represent differences among pilots steering straight channel segments in the degree of their sensitivity to small changes in heading angle and in their response with changes in rudder angle, A being least and C being most sensitive and responsive. (Actually, the pilots of contours A, B, and C are simple mathematical models suggested and validated by observation of the complex human activity of ship handling.) While any channel configuration within the acceptable contour offers equal ship controllability by the selected criteria (maximum rudder angle, directional stability, and underkeel clearance), one or another of the three factors dominates the limits of acceptable ship control for various channel cross-sections, as indicated in Figure 6. The experiments and analysis were directed to determine the relationship between channel dimensions and acceptable ship size, with a particular view to the proposed interoceanic canal across the Central American Isthmus, and thus assume calm water and tanker traffic.

The results indicate that canal width is far more important than depth in ship controllability. "When canal width is increased at any water depth," the report concludes, "there is a significant improvement in ship controllability" (Eda, 1971). Shallow channel depths need not affect ship control, but only "if sufficient bottom clearance exists for sinkage at a given speed" (emphasis added). Figure 7 dramatically illustrates the underlined statement with the turning trajectories of various tankers in deep and shallow water. Figures 7a and 7b are computer simulations; Figure 7c shows the results of marine trials.

In all sets of curves, the limits of acceptable channel depth to ship draft ratios are reached at channel depth = 1.1 x ship draft. Pilots indicate a preference for channel depths 20 percent deeper than ship draft (Knierim, 1981). As an approximate check, Table 5 indicates the controlling depth ("shoalest," or shallowest, point) in

Figure 5 Composite limiting contours of relationships between canal dimensions (confined channel, calm water, tanker-form ships)*

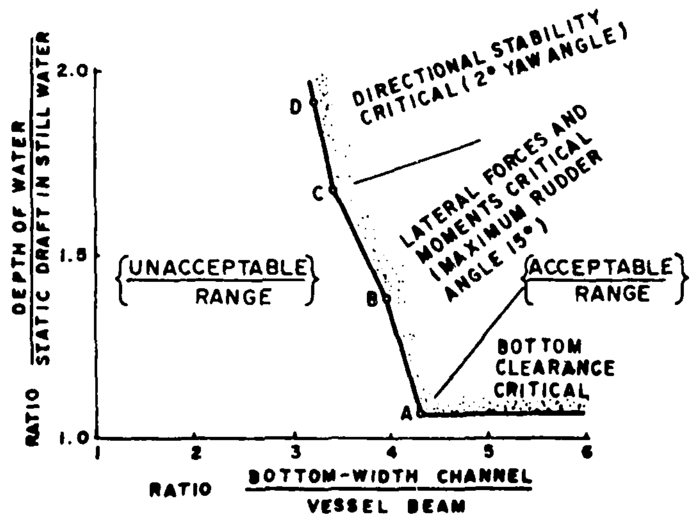


D_w/H = water depth/ship draft

W/B = channel width/ship beam

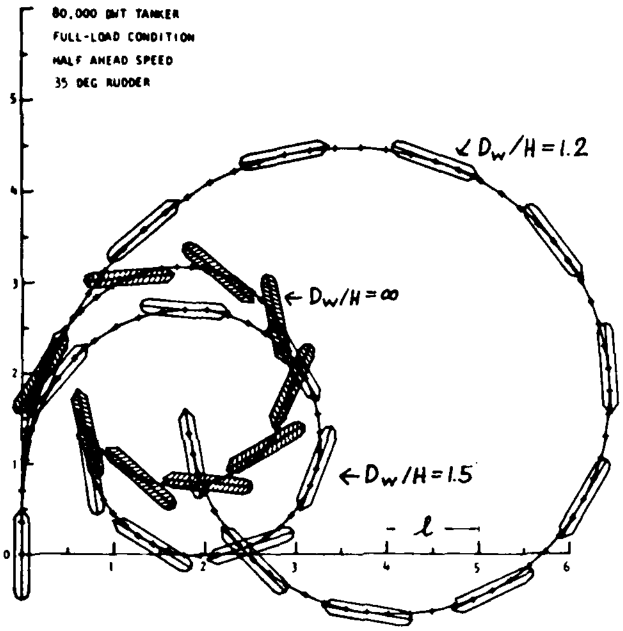
*SOURCE: Haruzo Eda (1971), "Directional Stability and Control of Ships in Restricted Channels," Trans. SNAME, 79: 88.

Figure 6 Ranges of influence of directional stability, turning moments, and bottom clearance on ship controllability for various channel cross-sections (dimensionless ratios)*

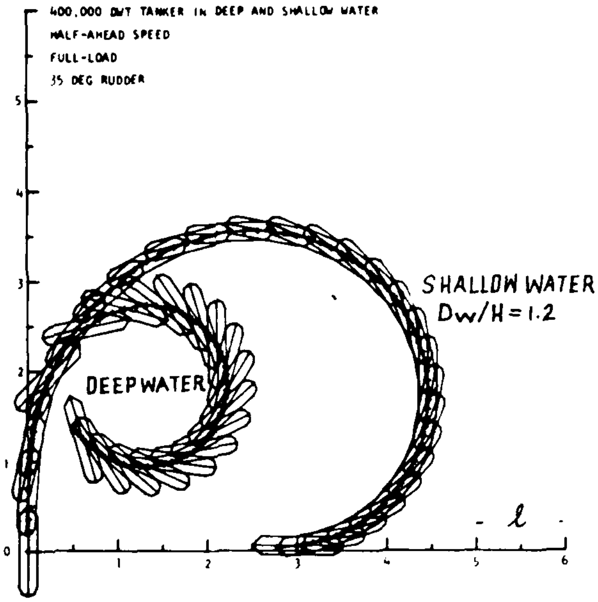


*SOURCE: Edwin W. Eden, Jr. (1971), "Vessel Controllability in Restricted Waters," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 97(WW3): 486.

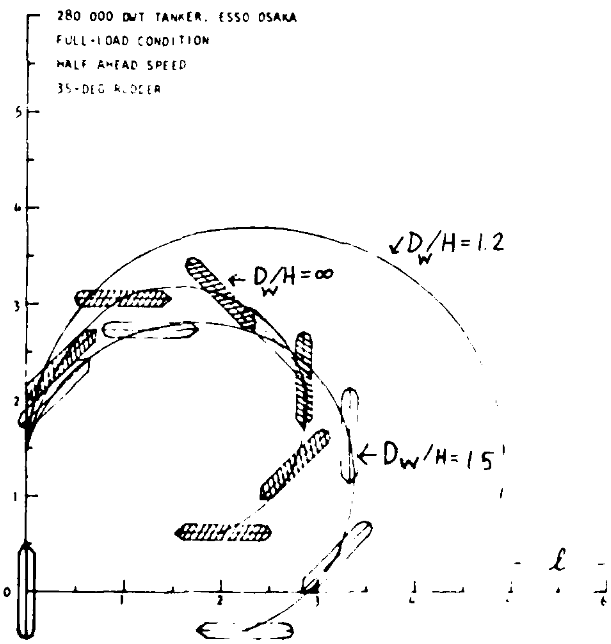
Figure 7 Turning trajectories for various ships with changing water depth*



a) Effect of water depth on turning performance



b) Turning trajectory



c) Effect of water depth on turning performance (*Esso Osaka* trial results in deep and shallow water)

*SOURCE: Haruzo Eda, Robert Falls, and David A. Walden (1979), "Ship Maneuvering Safety Studies," Trans. SNAME, 87: 231.

the channels of four major ports of the United States, the tidal range, drafts of the larger ships using the channels, and their number. The implication of the table is that the tidal range is being used to assure minimum underkeel clearance over the shoaling points. Assuming maximum high water, clearance of the shallowest points of the channels of Baltimore and Hampton Roads is below the acceptable minimum for calm water given by Eda (1971) and Eda et al. (1979), and at Galveston and Philadelphia it is near the minimum.

Moreover, the predicted values may differ from those observed (predicted and observed high-water levels differed by more than a foot 79 times in Baltimore in 1981).

Several uncertainties and compensating or aggravating factors affect the interpretation of Table 5 (these are discussed in succeeding sections), and while caution must therefore be exercised in drawing conclusions from the table, it does indicate clearly that a significant number of ships using the channels of these ports have less than rule-of-thumb underkeel clearance. The information presented agrees with the reports of ship pilots to the panel during its site visits that underkeel clearances are less than 2.5 percent for many ships in the navigational channels of major domestic ports and harbors.

Ships in Harbor Entrance Channels

As noted by Kray (1973), vessels in an entrance channel are subjected to many external forces, such as crosswinds, turbulent waters, breaking waves, tides, and currents. Some of these physical phenomena are strongly interactive; for example, extreme standing waves may be caused by the opposing oscillatory forces of waves and tides in the face of a strong opposing current. Wang (1980) notes that for swells occurring in the predominant direction at the entrance channel of the Columbia River, an ebb tide tends to steepen the wave front and may cause it to break, whereas a flood tide tends to lengthen the swell and reduce the likelihood of breaking. The range of motion experienced by a ship in this transition between the open ocean and the sheltered waters of a port or harbor is a function of the outward current from river flow; of wave and swell heights, directions, and celerity; of the ship's length and natural frequency in heave and pitch, and the ship's speed and trim; and of salinity and temperature gradients (Waugh, 1971), and it may be considerable. Entrance channels must therefore be deeper "to allow a safe vessel's entrance and provide for some reasonable reserve of depth...to compensate for harmful effects of elements acting on vessel, and for the storage of sediments" (Kray, 1981, p. 100), but relatively few data have been collected for the variables of interest. Participants in an interdisciplinary meeting on the design of entrances to ports and harbors gave the highest priority for research to the prediction of ship motions (Marine Board, 1981). Specifically,

> Improved and validated models are needed for the prediction of ship motions, vertical and horizontal, in the environmental and operational situations found in harbor entrances. These models are needed in the development of channel design geometry (depth, cross-section, shape, and planform), in the assessment of operating limits and traffic capacity, and to support the training of operators (simulators).

An attempt to measure the continuously varying draft and trim of ships under way in a port approach channel was undertaken in the United Kingdom using specially adapted and calibrated cameras at selected observation points (National Ports Council, 1976).

Wang (1980), Wang et al. (1980), Wang and Noble (1982) report the results of an extensive program to validate design widths and depths for proposed improvement of the entrance channel of the Columbia River. Instrumentation developed to measure and record heave, pitch, roll, and vessel position was carried on 53 voyages of ships in the channel, and information was collected or calculated for each voyage about weather, wave and swell height and direction, and other factors. Tables 6 and 7 give the draft and loading conditions of the ships, and their maximum vertical penetration of the channel during each voyage. The statistical distribution of motion amplitudes for a particular voyage was found to follow a Rayleigh distribution. The long-term statistical pattern of vertical vessel excursion was found to follow a log-normal distribution. The extreme-value analysis indicates that for any given transit, the vessel may experience a vertical excursion to as much as 23 ft (7 m), or that on the average, one of every ten transits will experience so great an excursion (Wang and Noble, 1982).

As the project depth of the entrance channel varies from 48 ft (14.5 m) in the initial segment to 40 ft (12.1 m), Wang and Noble conclude that "a deeper channel will improve the movement of the existing vessel fleet and will be required for the consistent movement of larger vessels." An interesting result of the program is that "the magnitude of vertical motion [is] a function of position along the channel axis."

Ship Speed

The speed of the ship is a factor of considerable importance in both confined channels and harbor entrances. Model tests, verified by full-scale experience in the Panama Canal, indicate that for confined channels, the suction-moment rate coefficient increases with increasing speed: the coefficient remains fairly constant at low speeds but rises abruptly above certain speeds in shallow channels (water depth to ship draft ratio = 1.18). Ship controllability could be expected to decline above these speeds, but rudder effectiveness would be increased owing to greater propeller slip. Thus, for shallow underkeel clearance, a critical speed can be projected at which a ship

Table 5 Controlling depths, tidal range, drafts and number of ships in channels of four ports of the United States*

Port	Controlling Depth[a]	Tidal Range[b]	Vessel Traffic[c] Draft	Vessel Traffic[c] Number
	feet (meters)			
Baltimore	42.5 (12.9)	1.1 (0.3)	41 (12.4)	9
			40 (12.1)	145
			39 (11.8)	67
			38 (11.5)	82
Philadelphia	40 (12.1)	6.7 (2.0)	41 (12.4)	230
			40 (12.1)	112
			39 (11.8)	223
			38 (11.5)	244
			37 (11.2)	197
			36 (10.9)	177
			35 (10.6)	267
Hampton Roads, Virginia	45 (13.6)	2.5 (0.8)	47 (14.2)	39
			46 (13.9)	30
			45 (13.6)	69
			44 (13.3)	25
			43 (13.0)	48
			42 (12.7)	71
Galveston	42 (12.7)	1.4 (0.4)	40 (12.1)	162
	43 (13.0)		39 (11.8)	453
			38 (11.5)	413
			37 (11 2)	301
			36 (10.9)	308

[a]"Shoalest," or shallowest, point at mean low water.

[b]Maximum, from National Ocean Survey (1982) Tide Tables 1982: High and Low Water Predictions (Washington, D.C.: National Oceanic and Atmospheric Administration).

[c]From U.S. Army Corps of Engineers (1979) Waterborne Commerce of the United States Calendar Year 1979 (Ft. Belvoir, Va.: Water Resources Support Center).

*SOURCE: "Real-Time Digitized Marine Navigation Data," National Ocean Survey, National Oceanic and Atmospheric Administration, October, 1982, p. 121.

will be most difficult to control. The abrupt change is not noticed in wider, deeper channels (Eda, 1971).

Yamaguchi et al. (1966, 1967; also cited in Eda (1971)) give the equation below for determining the limiting Froude number from the required underkeel clearance for tankers:

$$F_{rL} = \left(\frac{2pq(m-1)}{\left[\frac{m}{q(1+me)-n}\right]^2 - 1} \right)^{\frac{1}{2}}$$

where F_{rL} = limiting Froude number based on ship length
p = draft/ship length H/L
q = 1/(1 + e), e determined from model tests to be 0.24
m = water depth/ship draft D_w/H
n = ship beam/canal width, B/W

Contours of limiting speed are shown in Figure 8 for various channel cross-sections.

Wang (1980) notes that damping of heave and pitch decreases with increasing ship speed and that it is common practice for masters to reduce speed in rough seas to control ship motions. He observed in 53 instrumented voyages in the entrance to the Columbia River that reduction of speeds below the average (12 kn, tankers; 14 kn bulk carriers; 16 kn, containerships) directly followed increased ship motions in swells, tides, and waves.

Ship speed is also a compensating factor pilots can use to reduce squat, particularly in passing, overtaking, or maneuvering turns. As one pilot states, "If a vessel will float, we will move it safely at a slow rate" (Knierim, 1981). On the other hand, Bertsche and Atkins (1981) point out that while the "findings of several port-related studies have indicated that safety may be inversely dependent on ship's speed over a limited range...with reduced speed comes a reduction of maneuverability and an increase in crosstrack variability. Increased speed not only increases maneuverability, but also significantly reduces the required drift angle for adverse wind and current conditions" (p. 33). Speed, therefore, cannot be reduced below certain minima for given ships in given channels. In some cases, tug assistance will be required.

Few speed limits are stated for the major channels of the United States. Some are given as guidelines by the U.S. Coast Guard or local pilots associations.

Other Factors

The extensive studies reported by Wang (1980), Wang et al. (1980), and Wang and Noble (1982) indicate the dominance of swell as the environmental factor of concern in navigating the entrance channel of

Table 6 Summary of vessel condition at transit of Columbia River entrance channel, full-scale measurement program*

VOYAGE NO.	DATE	VESSEL NAME	VESSEL TYPE	TRANSIT DIRECTION	VESSEL SPEED (KTS.)	PRINCIPAL DIMENSIONS: LOA (FT)	LBP (FT)	BREADTH (FT)	DESIGN DRAFT (FT)	DWT (LT)	LOADING CONDITIONS: DRAFT FWD (FT)	DRAFT AFT (FT)	DRAFT MEAN (FT)	DISPLACEMENT (LT)	LCG (FT)	VCG (FT)
1	5/20/78	CHEVRON LOUISIANA	OIL CARRIER	IN	9-11	651.3	625.0	96.0	34.0	35,000	32.5	33.5	33.0	43,022	322.9	25.4
2	5/29/78	CHEVRON ARIZONA	OIL CARRIER	IN	11-14	651.3	625.0	96.0	34.0	35,000	33.4	33.9	33.7	44,100	319.6	29.4
3	6/05/78	HOEGH MALLARD	BULK CARRIER	IN	12-14	657.8	623.4	101.1	33.0	36,000	21.4	27.6	24.5	35,544	311.8	27.5
4	6/07/78	HOEGH MALLARD	BULK CARRIER	OUT	14	657.8	623.4	101.1	33.0	36,000	23.2	27.8	25.5	37,071	319.3	27.9
5	6/21/78	CHEVRON OREGON	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	34.5	35.5	35.0	46,120	319.5	27.3
6	6/23/78	HOEGH MARLIN	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	26.3	28.8	27.6	40,394	325.2	28.7
7	6/24/78	HOEGH MARLIN	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	27.8	28.3	28.0	41,125	329.1	30.6
8	11/01/78	CHEVRON WASHINGTON	OIL CARRIER	IN	9-13	651.3	625.0	96.0	34.0	35,000	32.8	34.2	33.5	43,840	318.8	29.2
9	11/04/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	12-15	651.3	625.0	96.0	34.0	35,000	27.0	30.0	28.5	36,385	318.9	22.6
10	11/09/78	CHEVRON WASHINGTON	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	33.2	34.7	33.9	44,519	318.4	29.2
11	11/10/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	14-16	651.3	625.0	96.0	34.0	35,000	22.5	24.5	23.5	29,256	325.5	23.4
12	11/28/78	ALASKA MARU	CONTAINER CARRIER	IN	10-19	685.7	639.8	98.4	34.4	23,000	26.5	30.9	28.7	28,288	302.4	35.5
13	12/03/78	CHEVRON COLORADO	OIL CARRIER	IN	12-14	651.3	625.0	96.0	34.0	35,000	33.4	34.1	33.8	44,240	319.3	29.1
14	12/04/78	CHEVRON COLORADO	OIL CARRIER	OUT	10-13	651.3	625.0	96.0	34.0	35,000	24.3	19.3	21.8	26,733	317.7	23.2
15	12/15/78	HILLYER BROWN	OIL CARRIER	IN	8	523.5	503.0	68.0	32.1	18,000	24.4	29.3	26.8	19,205	248.7	20.9
16	12/17/78	HILLYER BROWN	OIL CARRIER	OUT	6	523.5	503.0	68.0	32.1	18,000	25.1	28.2	26.6	19,028	252.9	22.2
17	12/29-30/78	ALASKA MARU	CONTAINER CARRIER	IN	17	685.7	639.8	98.4	34.4	23,000	28.3	29.1	28.8	27,778	307.5	35.9
18	1/16/79	MAUNA LEI	CONTAINER CARRIER	IN	13	630.3	606.0	71.5	32.9	18,000	21.8	30.0	25.9	22,296	299.3	23.2
19	1/19/79	MAUNA LEI	CONTAINER CARRIER	OUT	9	630.3	606.0	71.5	32.9	18,000	22.8	31.5	27.2	23,670	295.4	24.1
20	1/21/79	HIKAWA MARU	CONTAINER CARRIER	IN	14	700.3	656.0	101.7	34.4	23,000	26.8	30.9	28.9	28,926	308.8	37.6
21	1/24/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	25.7	33.7	29.7	22,483	268.8	29.0
22	1/28/79	ALASKA MARU	CONTAINER CARRIER	IN	17	685.7	639.8	98.4	34.4	23,000	28.5	30.6	29.6	29,176	302.3	34.6
23	2/07/79	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	16-21	718.5	669.3	102.4	36.8	27,000	32.6	32.6	32.6	35,101	320.0	37.6
24	2/11/79	BEISHU MARU	CONTAINER CARRIER	IN	16	697.2	656.2	98.4	34.5	24,000	28.1	30.5	29.3	29,544	318.3	31.4
25	2/22/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	28.5	34.6	31.6	24,722	266.6	31.0
26	2/27/79	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	34.4	23,000	30.0	30.9	30.4	30,280	306.0	35.9
27	3/14/79	BEISHU MARU	CONTAINER CARRIER	IN	15	697.2	656.2	98.4	34.5	24,000	27.7	32.4	30.1	30,714	316.7	34.5
28	3/22/79	CHEVRON WASHINGTON	OIL CARRIER	IN	13	651.3	625.0	96.0	34.0	35,000	26.3	28.0	27.2	34,430	320.9	23.4
29	3/23/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	7-14	651.3	625.0	96.0	34.0	35,000	23.3	26.9	25.1	31,520	320.0	23.9

Table 6, continued*

VOYAGE NO.	DATE	VESSEL NAME	VESSEL TYPE	TRANSIT DIRECTION	VESSEL SPEED (KTS.)	PRINCIPAL DIMENSIONS: LOA (FT)	LBP (FT)	BREADTH (FT)	DESIGN DRAFT (FT)	DWT (LT)	LOADING CONDITIONS: DRAFT FWD (FT)	DRAFT AFT (FT)	DRAFT MEAN (FT)	DISPLACEMENT (LT)	LCG (FT)	VCG (FT)
30	10/16/79	CHEVRON ARIZONA	OIL CARRIER	IN	11-14	651.3	625.0	96.0	34.0	35,000	32.8	33.5	33.2	43,300	320.4	29.2
31	10/17/79	CHEVRON ARIZONA	OIL CARRIER	OUT	11-14	651.3	625.0	96.0	34.0	35,000	21.9	23.4	22.7	28,000	321.5	24.0
32	10/28/79	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	34.4	23,000	30.9	31.6	31.3	31,108	329.3	36.1
33	11/14/79	HOEGH MUSKETEER	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	25.7	29.3	27.5	40,774	324.0	28.8
34	11/17/79	HOEGH MUSKETEER	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	27.0	31.2	29.1	43,286	322.6	30.0
35	11/21/79	MAUNA LEI	CONTAINER CARRIER	OUT	13	630.3	606.0	71.5	32.9	18,000	19.0	29.0	24.0	20,600	294.4	24.8
36	11/26/79	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	31.2	34.2	32.7	25,775	275.8	31.9
37	11/28/79	HOEGH MASCOT	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	21.8	25.5	23.7	34,252	318.6	32.5
38	12/03/79	HOEGH MASCOT	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	25.3	28.2	26.8	39,070	318.7	26.8
39	12/16/79	CHEVRON WASHINGTON	OIL CARRIER	IN	11-14	651.3	625.0	96.0	34.0	35,000	33.4	33.9	33.7	44,100	320.7	29.3
40	12/18/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	11-14	651.3	625.0	96.0	34.0	35,000	21.5	25.5	23.5	29,200	319.7	24.2
41	1/20/80	HIKAWA MARU	CONTAINER CARRIER	IN	14	700.3	656.0	101.7	34.4	23,000	28.3	30.6	29.5	29,049	310.3	36.6
42	1/24/80	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	29.5	32.1	30.8	23,960	277.6	30.8
43	2/04/80	WORLD WING	AUTO CARRIER	IN	16-21	566.7	557.7	90.6	29.0	23,000	22.5	24.3	23.4	26,305	296.3	31.6
44	2/06/80	WORLD WING	AUTO CARRIER	OUT	16-21	566.7	557.7	90.6	29.0	23,000	22.3	21.8	22.3	25,686	300.8	31.6
45	2/10/80	HOEGH MUSKETEER	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	27.3	31.5	29.3	43,665	[illegible]	[illegible]
46	2/14/80	HOEGH MUSKETEER	BULK CARRIER	OUT	~14	657.8	621.4	101.1	33.0	36,000	28.2	31.3	29.8	44,351	330.3	31.2
47	3/04/80	MAUNA LEI	CONTAINER CARRIER	IN	13	630.3	606.0	71.5	32.9	18,000	25.5	25.5	25.5	22,070	[illegible]	24.8
48	3/10/80	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	16-21	718.5	669.3	102.4	36.8	27,000	30.4	32.6	31.5	33,637	318.4	37.9
49	3/18/80	HOEGH MERCHANT	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	28.5	33.0	30.8	46,094	•	•
50	3/22/80	HOEGH MERCHANT	BULK CARRIER	OUT	~14	657.8	623.4	101.1	33.0	36,000	30.7	33.7	32.2	48,260	322.4	27.0
51	3/26/80	GOLDEN ARROW	CONTAINER CARRIER	IN	17	616.8	574.1	82.7	35.2	19,000	28.8	32.8	30.8	23,960	298.0	31.7
52	4/01/80	ALASKA MARU	CONTAINER CARRIER	IN	16	685.7	639.8	98.4	34.4	23,000	31.7	33.5	32.6	33,175	335.7	37.2
53	4/03/80	HOEGH MALLARD	BULK CARRIER	IN	~14	657.8	623.4	101.1	33.0	36,000	35.0	30.0	27.5	40,261	311.7	25.8

*SOURCE: S. Wang, C. Butcher, M. Kimble, and G. Cox (1980), "Columbia River Entrance Channel Deep-Draft Vessel Motion Study," Tetra Tech Report No. TC-3925, Final Report to U.S. Army Corps of Engineers, Pasadena, Calif., September 1980.

Table 7 Summary of vertical motions, vessels transiting Columbia River entrance channel*

VOYAGE NO	DATE	VESSEL NAME	VESSEL TYPE	TRANSIT DIRECTION	PITCH (DEG) MAX	PITCH (DEG) AVERAGE	ROLL (DEG) MAX	ROLL (DEG) AVERAGE	HEAVE (FT) MAX	HEAVE (FT) AVERAGE	BOW (FT) MAX UP	BOW (FT) MAX DOWN	BOW (FT) AVERAGE	STERN (FT) MAX UP	STERN (FT) MAX DOWN	STERN (FT) AVERAGE	SIDE (FT) MAX	SIDE (FT) AVERAGE	AMPLITUDE (FT)	PORTION OF SHIP	LOCATION IN CHANNEL (BETWEEN BUOYS)	PILOT'S RATING OF TRANSIT
1	5/20/78	CHEVRON LOUISIANA	OIL CARRIER	IN	2.5	0.9	6.4	2.7	7.0	2.6	20.2	17.0	7.3	7.4	7.6	3.2	9.0	3.7	49.5	BOW	6-8	EASY
2	5/29/78	CHEVRON ARIZONA	OIL CARRIER	IN	1.3	0.6	2.9	1.1	3.6	1.6	8.9	10.4	4.2	3.8	3.1	1.5	4.3	1.8	43.8	BOW	2-4	EASY
3	6/05/78	HOEGH MALLARD	BULK CARRIER	IN	0.7	0.3	1.4	0.6	2.8	1.1	6.3	5.7	2.6	2.1	1.7	0.9	2.5	1.0	29.3	STERN	*	EASY
4	6/07/78	HOEGH MALLARD	BULK CARRIER	OUT	1.0	0.4	1.3	0.4	4.1	1.5	9.5	8.1	2.8	1.7	1.8	0.8	4.1	1.4	31.3	BOW	2-4	EASY
5	6/21/78	CHEVRON OREGON	OIL CARRIER	IN	1.5	0.7	3.8	1.6	4.7	2.0	12.6	11.8	4.6	4.9	4.8	2.0	5.7	2.3	46.3	BOW	4-6	EASY
6	6/23/78	HOEGH MARLIN	BULK CARRIER	IN	0.9	0.4	2.8	1.3	3.3	1.3	7.8	7.0	2.0	2.6	2.4	1.0	4.4	1.9	33.3	BOW	4-6	EASY
7	6/24/78	HOEGH MARLIN	BULK CARRIER	OUT	0.9	0.4	1.5	0.4	3.5	1.8	7.7	8.1	3.4	2.4	2.5	1.4	3.4	1.8	35.9	BOW	2-4	EASY
8	11/01/78	CHEVRON WASHINGTON	OIL CARRIER	IN	2.3	0.7	4.8	1.4	8.0	2.0	16.4	20.3	5.3	6.4	5.4	1.8	8.5	2.8	53.1	BOW	6-8	MODERATE
9	11/04/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.7	0.8	6.2	2.3	6.6	2.7	11.6	13.9	5.9	10.1	9.7	3.6	7.3	2.7	40.9	BOW	4-6	EASY
10	11/09/78	CHEVRON WASHINGTON	OIL CARRIER	IN	1.8	0.7	3.8	1.3	5.5	2.0	13.1	15.0	5.3	5.0	4.6	2.0	5.9	2.3	48.2	BOW	6-8	EASY
11	11/10/78	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.2	0.5	2.1	0.7	4.5	2.2	9.3	10.6	4.4	3.6	3.1	2.0	4.3	2.2	33.1	BOW	6-8	EASY
12	11/28/78	ALASKA MARU	CONTAINER CARRIER	IN	0.8	0.4	4.0	1.3	1.8	0.8	5.5	6.2	2.4	3.2	2.8	1.3	3.5	1.2	33.7	STERN	6-8	EASY
13	12/03/78	CHEVRON COLORADO	OIL CARRIER	IN	0.8	0.4	2.3	0.8	2.9	1.3	6.6	6.9	2.4	2.7	2.7	1.0	3.9	1.5	40.3	BOW	6-8	EASY
14	12/04/78	CHEVRON COLORADO	OIL CARRIER	OUT	2.9	1.2	13.4	3.7	8.4	3.1	22.6	22.0	8.5	12.1	12.1	4.5	10.1	3.2	46.3	BOW	2-4	MODERATE
15	12/15/78	HILLYER BROWN	OIL CARRIER	IN	6.0	1.9	17.5	4.4	9.7	2.7	16.1	16.7	6.0	12.6	21.9	9.8	16.1	4.9	51.2	STERN	4-6	DIFFICULT
16	12/17/78	HILLYER BROWN	OIL CARRIER	OUT	4.9	2.2	13.0	5.1	8.3	2.5	21.6	19.8	9.5	27.9	25.7	10.7	12.7	4.0	53.9	STERN	4-6	DIFFICULT
17	12/29-30/78	ALASKA MARU	CONTAINER CARRIER	IN	0.7	0.3	2.3	0.8	2.5	0.8	4.6	4.2	1.5	2.7	2.4	1.1	3.0	1.0	32.5	BOW	4-6	EASY
18	1/16/79	MAUNA LEI	CONTAINER CARRIER	IN	1.7	0.4	2.6	1.1	3.8	1.2	3.6	5.1	1.3	12.5	7.7	2.6	4.3	1.5	37.7	STERN	4-6	EASY
19	1/19/79	MAUNA LEI	CONTAINER CARRIER	OUT	5.2	1.7	14.5	4.4	12.4	3.7	17.0	19.4	6.9	38.3	24.8	10.8	15.5	4.4	56.3	STERN	6-8	MODERATE
20	1/21/79	HIKAWA MARU	CONTAINER CARRIER	IN	1.2	0.4	5.7	2.7	2.5	0.8	8.0	7.6	2.5	4.2	5.7	1.5	5.9	2.6	36.6	STERN	6-8	MODERATE
21	1/24/79	GOLDEN ARROW	CONTAINER CARRIER	IN	1.8	0.8	11.7	5.1	4.0	1.6	12.0	12.3	4.4	6.8	7.4	2.7	10.4	3.8	41.1	STERN	6-8	MODERATE
22	1/28/79	ALASKA MARU	CONTAINER CARRIER	IN	1.5	0.6	8.1	3.1	3.8	1.2	11.7	11.7	4.2	6.9	5.4	2.3	7.0	2.9	40.2	BOW	6-8	EASY
23	2/07/79	LION'S GATE BRIDGE	CONTAINER CARRIER	IN	1.1	0.4	5.6	1.7	2.3	0.9	9.0	8.1	2.9	3.2	4.5	1.7	6.0	1.8	40.7	BOW	4-6	MODERATE
24	2/11/79	BEISHU MARU	CONTAINER CARRIER	IN	0.8	0.3	4.3	1.7	1.4	0.6	5.8	4.3	1.8	3.1	3.3	1.2	3.7	1.7	33.8	STERN	6-8	EASY
25	2/22/79	GOLDEN ARROW	CONTAINER CARRIER	IN	0.9	0.4	6.0	2.7	1.8	0.7	5.9	4.4	2.1	2.4	3.0	1.3	5.1	2.1	37.6	STERN	2-4	EASY
26	2/27/79	ALASKA MARU	CONTAINER CARRIER	IN	0.6	0.3	3.2	1.3	1.4	0.6	4.8	3.9	1.6	2.3	2.2	0.9	3.6	1.3	34.0	SIDE	8-10	EASY
27	3/14/79	BEISHU MARU	CONTAINER CARRIER	IN	0.9	0.5	5.4	2.2	1.9	0.9	7.2	6.9	3.0	3.5	3.7	1.6	5.8	2.0	36.1	STERN	6-8	EASY
28	3/22/79	CHEVRON WASHINGTON	OIL CARRIER	IN	1.6	0.6	3.6	1.4	6.1	1.8	14.6	12.0	4.3	5.6	4.5	1.9	7.1	2.1	38.3	BOW	6-8	EASY
29	3/23/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	1.8	0.7	3.7	1.0	5.5	1.9	13.0	15.2	5.1	6.3	6.5	2.1	4.8	2.0	38.5	BOW	2-4	EASY

* Data not available due to Mini-Ranger failure and no log to retrieve location in channel.

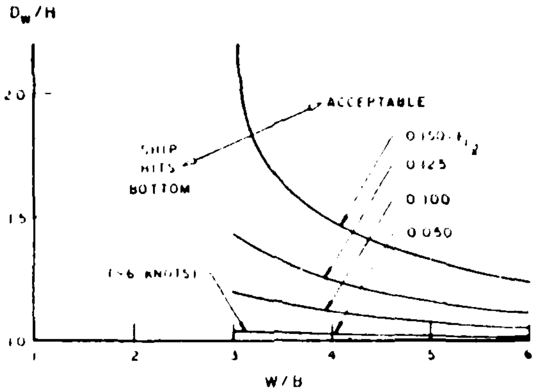
Table 7, continued

VOYAGE NO.	DATE	VESSEL NAME	VESSEL TYPE	TRANSIT DIRECTION	PITCH (DEG) MAX	PITCH (DEG) AVERAGE	ROLL (DEG) MAX	ROLL (DEG) AVERAGE	HEAVE (FT) MAX	HEAVE (FT) AVERAGE	BOW (FT) MAX UP	BOW (FT) MAX DOWN	BOW (FT) AVERAGE	STERN (FT) MAX UP	STERN (FT) MAX DOWN	STERN (FT) AVERAGE	SIDE (FT) MAX	SIDE (FT) AVERAGE	AMPLITUDE (FT)	PORTION OF SHIP	LOCATION IN CHANNEL (BETWEEN BUOYS)	PILOT'S RATING OF TRANSIT
					VESSEL MOTIONS (Amplitude)						**VERTICAL MOVEMENT AT VARIOUS PORTIONS OF SHIP**								**MAXIMUM VESSEL PENETRATION**			
30	10/16/79	CHEVRON ARIZONA	OIL CARRIER	IN	0.4	0.3	1.2	0.5	1.4	0.8	3.3	3.5	1.3	1.4	1.25	0.7	2.1	0.9	36.3	BOW	6-8	EASY
31	10/17/79	CHEVRON ARIZONA	OIL CARRIER	OUT	2.8	1.5	8.6	2.8	9.7	4.1	23.3	22.9	11.2	12.0	9.1	4.4	7.9	3.1	44.8	BOW	4-6	EASY
32	10/28/79	ALASKA MARU	CONTAINER CARRIER	IN	1.4	0.5	3.9	1.8	3.2	1.0	6.4	10.1	2.9	4.6	4.1	1.6	4.5	2.1	32.0	BOW	6-8	EASY
33	11/14/79	HÖEGH MUSKETEER	BULK CARRIER	IN	0.4	0.15	1.5	0.47	1.5	.58	3.6	2.4	1.18	0.66	0.8	0.38	2.4	0.74	30.10	STERN	4-6	EASY
34	11/17/79	HÖEGH MUSKETEER	BULK CARRIER	OUT	1.4	0.6	2.8	1.1	5.9	2.3	10.2	13.5	5.0	5.6	4.6	2.3	5.5	2.4	40.5	BOW	2-4	EASY
35	11/21/79	MAUNA LEI	CONTAINER CARRIER	OUT	2.9	1.1	2.9	1.1	5.2	2.1	12.6	12.7	4.6	17.4	14.0	6.7	4.8	1.4	43.0	STERN	6-8	EASY
36	11/26/79	GOLDEN ARROW	CONTAINER CARRIER	IN	0.7	0.3	5.6	1.9	2.4	0.9	5.7	4.7	1.7	3.0	3.1	1.2	4.7	1.7	37.4	SIDE	6-8	EASY
37	11/28/79	HÖEGH MASCOT	BULK CARRIER	IN	0.6	0.3	1.5	0.4	2.3	0.7	5.3	3.9	1.2	1.1	1.0	0.5	1.1	0.5	26.5	STERN	2-4	EASY
Δ38	12/03/79	HÖEGH MASCOT	BULK CARRIER	OUT	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	MODERATE
39	12/16/79	CHEVRON WASHINGTON	OIL CARRIER	IN	0.4	0.2	1.3	0.4	0.4	0.3	2.0	1.7	0.7	1.8	2.1	0.8	0.8	0.4	36.0	STERN	6-8	EASY
40	12/18/79	CHEVRON WASHINGTON	OIL CARRIER	OUT	2.1	1.0	2.0	0.8	6.0	2.8	15.2	15.8	7.9	7.4	7.5	3.2	5.7	2.6	37.3	BOW	2-4	EASY
41	1/20/80	HIKAWA MARU	CONTAINER CARRIER	IN	0.5	0.2	2.4	1.2	0.9	0.5	3.6	4.1	1.0	2.2	1.8	0.7	2.2	1.2	32.4	BOW	6-8	EASY
42	1/24/80	GOLDEN ARROW	CONTAINER CARRIER	IN	1.0	0.3	5.5	2.2	1.0	0.4	3.0	4.8	1.3	5.1	3.5	1.3	3.7	1.5	35.6	STERN	4-6	EASY
43	2/04/80	WORLD WING	AUTO CARRIER	IN	1.0	0.4	2.7	1.0	2.0	0.7	2.5	3.6	1.6	5.9	4.3	1.6	2.4	1.0	28.6	STERN	4-6	EASY
44	2/06/80	WORLD WING	AUTO CARRIER	OUT	3.0	1.0	3.2	1.1	6.2	2.6	15.0	16.6	9.5	8.0	8.6	3.2	8.6	3.2	38.9	BOW	6-8	MODERATE
45	2/10/80	HÖEGH MUSKETEER	BULK CARRIER	IN	0.9	0.3	1.9	0.9	1.4	0.6	3.7	3.0	1.4	3.7	4.8	1.7	2.2	0.9	36.3	STERN	6-8	EASY
46	2/14/80	HÖEGH MUSKETEER	BULK CARRIER	OUT	2.8	0.7	1.3	0.5	6.0	2.8	19.2	14.4	6.8	4.0	3.7	1.9	8.1	2.4	42.6	BOW	4-2	EASY
47	3/04/80	MAUNA LEI	CONTAINER CARRIER	IN	1.1	0.4	5.6	1.6	1.9	0.7	5.5	6.3	2.0	5.5	3.6	1.5	2.9	0.9	31.8	BOW	6-8	EASY
48	3/10/80	LIONS GATE BRIDGE	CONTAINER CARRIER	IN	1.7	0.5	5.0	2.0	3.3	0.9	12.9	9.6	2.9	5.7	5.9	1.8	5.2	1.8	40.0	BOW	6-8	EASY
Δ49	3/18/80	HÖEGH MERCHANT	BULK CARRIER	IN	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	EASY
50	3/22/80	HÖEGH MERCHANT	BULK CARRIER	OUT	2.2	0.8	3.9	1.4	8.5	2.5	16.8	18.5	5.9	7.6	6.8	2.8	6.5	2.3	49.7	BOW	6-4	MODERATE
51	3/26/80	GOLDEN ARROW	CONTAINER CARRIER	IN	1.6	0.5	13.3	5.5	3.6	0.9	10.2	9.0	2.4	6.0	6.1	2.0	11.4	4.0	44.2	SIDE	4-6	EASY
52	4/01/80	ALASKA MARU	CONTAINER CARRIER	IN	2.4	0.7	7.1	2.6	5.8	1.4	15.7	18.1	3.8	8.7	8.2	2.2	6.9	2.0	49.8	BOW	4-6	MODERATE
53	4/03/80	HÖEGH MALLARD	BULK CARRIER	IN	0.5	0.3	1.7	0.6	0.9	0.4	2.7	2.8	0.8	3.1	3.0	1.0	1.7	0.7	33.1	STERN	6-8	EASY

Δ No data due to equipment failure

*SOURCE: S. Wang, C. Butcher, M. Kimble, and G. Cox (1980), "Columbia River Entrance Channel Deep-Draft Vessel Motion Study," Tetra Tech Report No. TC-3925, Final Report to U.S. Army Corps of Engineers, Pasadena, Calif., September 1980.

Figure 8 Contours of limiting speed for ships in confined channels*



D_W/H = water depth/ship draft

W/B = channel width/ship beam

*SOURCE: Haruzo Eda (1971), "Directional Stability and Control of Ships in Restricted Channels," Trans. SNAME, 79: 87.

the Columbia River. The environmental factor(s) of greatest concern in other channels may be wind setup and setdown or storm surges, waves, currents, or ice. Intensive study of the physical environment and of ship interactions with environmental factors and the navigational channel is essential for design and maintenance.

Practices have evolved in the channels of the United States to accommodate the increased traffic of larger ships--for example, loading and lightering at sea, agreements among pilots against passing or overtaking in certain areas or between certain sizes of ships, and the use of high water for underkeel clearance. Many vessels--notably tankers, but other vessels as well--sail at considerably less than full load to maintain adequate underkeel clearance. A report to the U.S. Coast Guard acknowledges that (among other reasons) a systematic plan for aids to navigation must compensate for the navigational deficiencies of channels and indicates that in congested or particularly difficult areas "the Coast Guard might limit the transit speed for user vessels or limit operations to one-way traffic" (Eclectech Associates, Inc., 1982).

Thus, while aids to navigation and local practices may adjust for the deficiencies of navigational channels, the accumulation of such compensations eventually contradicts the basis of the original channel design, which was to provide for existing and projected ship traffic or to reduce delays (and the propulsion requirements of ships, although it is doubtful if this can be demonstrated) at an economical price. Compensating factors also reach a limit. In an analysis of casualties in the Houston-Galveston area, the U.S. Coast Guard found that over the period 1969-1977, cargo tonnage increased 100 percent, but transits only 15 percent, owing to larger and more heavily laden ships. Over this period, the number of ship casualties rose steadily, then accelerated with 22 accidents in a 6 month period. The report suggests that the Houston-Galveston system has reached saturation and that safety can be expected to continue to decline (Thompson et al., 1981).

Bertsche and Atkins (1981), Kray (1973), Waugh (1971), and Eden (1971) note that studies of ship characteristics in navigational channels undertaken for one purpose often yield insights for another (the value of training pilots on simulators, the implications for ship design of channel dimension validations, placement of navigational aids to reduce crosstrack variances in maneuvering bends and turns, the need for additional ship controllability at low speeds), and all note that as yet there are few mechanisms for communication of these insights among the community of interests. "It would appear," Eden concludes, "that there has been little or no effort made to consider the design of vessels, canals, and controllability facilities as a system...an interdisciplinary system approach could indicate that transportation costs could be reduced without increase in risk, or even that both hazard and costs could be reduced to the end that projects could be constructed for less money and in less time."

Sediment Transport and Deposition

Two mechanisms of sediment movement may affect navigational channels in harbors and estuaries, denoted here as interior and exterior processes. The interior process is the transport of material delivered to a harbor from freshwater inland sources. Exterior processes refer to the transport of sediment into a harbor from the ocean, i.e., the sediment carried by longshore processes, or suspended sediment carried into the harbor by tides or storms. Johnson (1981) discusses several modes of deposition at harbor entrances and summarizes the problem of transport by littoral currents.

Interior and exterior processes are associated with different types of material as well as transport mechanisms; thus, they may represent different dredging problems.

Exterior Processes

In most cases, the sediment carried by longshore transport processes is composed of sand with a median diameter varying from about 0.1 mm to 0.4 mm. This material has usually been transported along the beaches outside the harbor by waves that refract as they propagate from deeper water toward the coast, breaking at an angle to the nearshore contours. This creates a component of momentum flux parallel to the beach, which (once material is put into suspension by wave-breaking) can move the suspended material along the beach. In addition, sand is moved onshore and offshore by wave activity. Komar and Inman (1970) give a brief summary:

> [The] movement takes place in two manners--in suspension, and by rolling in a zigzag motion along the beach face. For a beach with an equilibrium profile formed by waves of relatively large steepness, which is characteristic of storm conditions, the sediment movement is mainly in suspension. In the case of an equilibrium beach profile formed by waves of low steepness, which is typical of calm summer conditions, the transport appears to be the result of rolling or skipping along the beach face. It is believed that as much as 80 percent of the material moved by wave action is moved in the area shoreward of the breaking point.

Sand moved along the coast can become the material that must be dredged from harbor entrances and shipping channels. By its very nature, the material usually forms relatively firm deposits (or shoals), with a well-defined boundary between the sea and the bottom.

Numerous measurements of rates of transport along natural shorelines have been estimated--for example, from the amount of material trapped by man-made shoreline structures. A summary of such measured rates along U.S. coasts, compiled by the Coastal Engineering Research Center, is presented in Table 8. The Shore Protection Manual

Table 6 Longshore transport rates for U.S. coasts*

Location	Predominant Direction of Transport	Longshore[a] Transport (cu. yd./yr.)	Date of Record
	Atlantic Coast		
Suffolk County, NY	W	200,000	1946-55
Sandy Hook, N.J.	N	493,000	1885-1933
Sandy Hook, N.J.	N	436,000	1933-51
Asbury Park, N.J.	N	200,000	1922-25
Shark River, N.J.	N	300,000	1947-53
Manasquan, N.J.	N	360,000	1930-31
Barnegat Inlet, N.J.	S	250,000	1939-41
Absecon Inlet, N.J.[b]	S	400,000	1935-46
Ocean City, N.J.[b]	S	400,000	1935-46
Cold Spring Inlet, N.J.	S	200,000	-------
Ocean City, Md.	S	150,000	1934-36
Atlantic Beach, N.C.	E	29,500	1850-1908
Hillsboro Inlet, Fla.	S	75,000	1850-1908
Palm Beach, Fla.	S	150,000 to 225,000	1925-30
	Gulf of Mexico		
Pinellas County, Fla.	S	50,000	1922-50
Perdido Pass, Ala.	W	200,000	1934-53
	Pacific Coast		
Santa Barbara, Calif.	E	280,000	1932-51
Oxnard Plain Shore, Calif.	S	1,000,000	1938-48
Port Hueneme, Calif.	S	500,000	-------
Santa Monica, Calif.	S	270,000	1936-40
El Segundo, Calif.	S	162,000	1936-40
Redondo Beach, Calif.	S	30,000	-------
Anaheim Bay, Calif.	E	150,000	1937-48
Camp Pendleton, Calif.	S	100,000	1950-52
	Great Lakes		
Milwaukee County, Wis.	S	8,000	1894-1912
Racine County, Wis.	S	40,000	1912-49
Kenosha, Wis.	S	15,000	1872-1909
Ill. State Line to Waukegan	S	90,000	---------
Waukegan to Evanston, Ill.	S	57,000	---------
South of Evanston, Ill.	S	40,000	---------
	Hawaii		
Waikiki Beach[b]	-	10,000	---------

[a]Transport rates are estimated net transport rates. In some cases, these approximate the gross transport rates.

[b]Method of measurement is by accretion except for Absecon Inlet, and Ocean City, New Jersey, and Anaheim Bay, California, which is by erosion, and Waikiki Beach, Hawaii, which is by suspended load samples.

*SOURCE: U.S. Army Corps of Engineers (1977), Shore Protection Manual (Washington, D.C.: Government Printing Office).

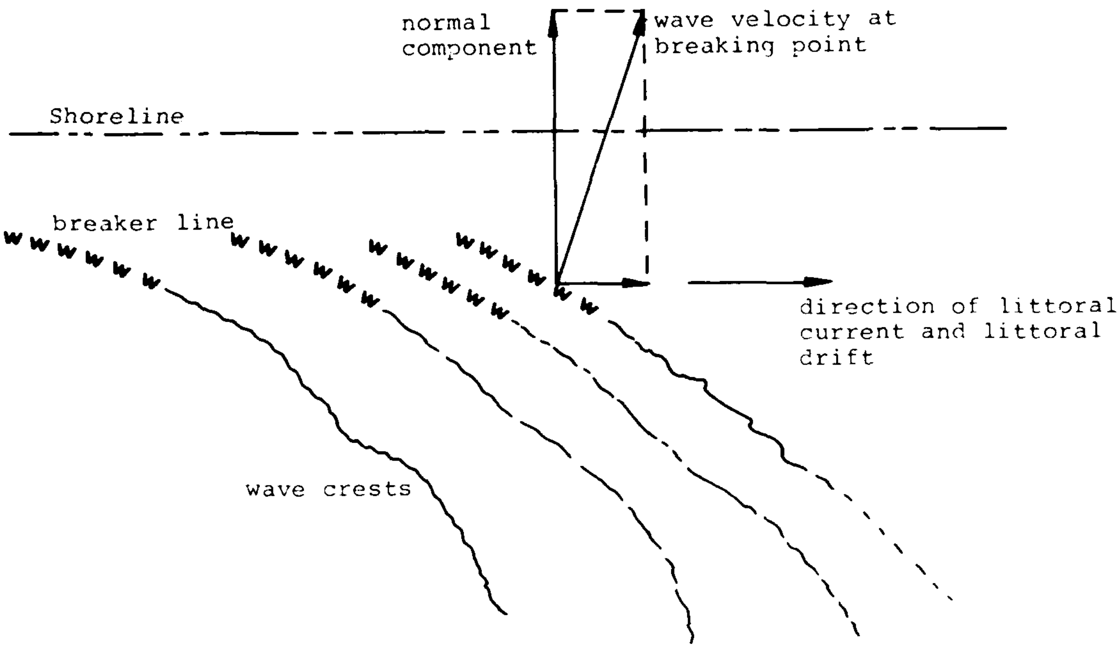
(U.S. Army Corps of Engineers, 1977) gives procedures for estimating rates of drift for particular localities, but as Komar and Inman note, "no general relationship between wave and sediment characteristics is available for estimating the rate of littoral transport that occurs along a given shoreline."

Predominant Direction of Littoral Transport The direction of littoral transport at a particular time is dictated by the direction of the alongshore component of the wave velocity at the breaking point (Figure 9). On many coastlines, important reversals in the direction of littoral drift occur because of the seasonal or long-term variation in the direction of the wave attack. Usually, however, the intensity of wave attack predominates in one direction, resulting in a net or predominant direction of drift. For the locations for which rates of transport are given in Table 8, the predominant direction is also given. Undoubtedly, the drift occurs in one direction along the various coastlines at certain times of the year, and in the opposite direction during the remainder of the year; nevertheless, a net drift occurs in the direction and at the rate indicated. For example, along the south Atlantic coast of the United States, the littoral drift is northward during the summer season, when light winds from the south and southeast prevail, but during the fall and winter, strong northeasterly storms, accompanied by relatively high seas, drive the sand southward. These winter storms are more severe than the summer storms, with the result that the predominant drift is southward along the south Atlantic coast (Johnson, 1981).

Sand Waves A factor that may affect channel entrances and navigational channels is the generation of sand waves. Sand waves of considerable height and length can occur at locations where water velocities are high: examples cited in the literature include Brazil, Tampa Bay, Florida; and San Francisco, California (Gibson, 1951; Johnson, 1973). Sand waves observed at several locations along the coast of northern Brazil, for example, are generated by the high velocities resulting from large tidal ranges and large inland tidal basins. At the easterly approach to the Golden Gate in San Francisco, the velocity of the tidal current increases with the constriction of the seaway, and sand waves occur in depths between 48 ft and 51 ft, having average lengths from crest to crest of 240 ft and heights varying from 6 ft to 17 ft. These waves do not now appear to present a problem, because the channel depths where sand waves occur are less than the 50 ft depths maintained in the balance of the dredged channel across the San Francisco Bar.

Nevertheless, if ships are transiting navigational channels with little underkeel clearance, the accuracy of nautical charts may present problems, as it will not be clear whether the soundings shown represent the crest, bottom, or face of sand waves. Because sand waves develop with relatively high currents, they will constantly be moving, and the soundings will be unreliable unless frequent surveys are made.

Figure 9 Direction of littoral current and littoral drift determined by direction of alongshore component of wave velocity at breaking point*



*SOURCE: J. W. Johnson (1981), "Sedimentation in Harbors," Problems and Opportunities in the Design of Entrances to Ports and Harbors (Washington, D.C.: National Academy Press), p. 104.

Interior Processes

The material delivered to a harbor from inland sources presents a more serious problem with regard to the required dredged depth of shipping channels because, in general, the material is of a type that does not allow the boundary between the bottom and the fluid to be well defined. Indeed, the density in shoals created from material delivered from inland sources may vary from 1050 g/l and less to 1300 g/l; this corresponds to 20 percent to 30 percent of dry solids (Ippen, 1966). Generally, this material is classified as silt, but it consists of clay and minerals. Particle sizes are less than 100 microns and may consist of material less than 1 micron in diameter. The material in suspension, which may comprise the shoals, could be colloidal. (The special problems of silty channels for dredging and navigation are taken up in a separate section.)

Very little is understood about the transport of fine material--even for noncohesive sediments--in unsteady flows. Thus, in harbors and estuaries with tidal flows, the mechanics of sediment transport are not firmly known, and considering that the transported sediment may behave as a cohesive material, the development and movement of shoals and shoallike material does not appear to be easily predicted.

The process of wave-induced transport of noncohesive material is understood in a general way but is not easily or reliably quantified. This understanding permits description of certain aspects of the process of sedimentation and shoaling owing to the fine sediments delivered by freshwater inland sources to harbors (discussed in some detail by Ippen (1966).

The flow within the harbor where sediment is being delivered from inland sources is complex and relates to aspects of freshwater flow into a saline body. An important aspect of the flow is the currents induced by the tide, together with the lag between currents and tides from friction effects. The estuary may be well mixed or stratified; the degree of stratification strongly influences the shoaling characteristics of the harbor or estuary (Herrmann, 1981).

A simplified case can be described where a well-defined density stratification occurs. In this case, the more dense seawater travels up into an estuary or harbor and freshwater travels seaward over the top of the intruding saline wedge. Since flow velocities are present within the wedge due to tides and because continuity conditions must be satisfied, at the furthest upstream penetration of the wedge (within the wedge, near the toe) the direction of velocity must reverse. In this region of flow reversal, fine material transported toward the ocean entrance of the estuary by the freshwater flow may be deposited by sedimentation processes. Thus, the region of maximum intrusion of the saline wedge originating from the ocean entrance into an estuary may be a region of excessive shoaling. In the case of an estuary which is well mixed by turbulence, such large density differences are not observed, nor will the extremes of velocities characteristic of a highly stratified system be seen; however, similar features are evidenced.

A simplified description of the velocity and salinity distributions in a fully stratified estuary and a well-mixed estuary is presented in Figure 10. The upper part of the figure shows the velocity distribution in a stratified estuary, demonstrating the general seaward flow of fresh water near the surface, with velocities being upstream near the bottom within the saline wedge and seaward near the top of the wedge to satisfy continuity conditions. Similar characteristics of a well-mixed estuary are presented in the lower part of Figure 10.

Fine material transported in estuaries and harbors is generally in suspension. Ippen (1966) gives an excellent description of the shoaling process in a turbulent flow:

> Turbulence near the bottom boundary is increasingly damped by the presence of silt which settles downward continuously as long as only moderate currents exist. Diffusion is hindered locally and with increasing consistency the material will gradually be able to resist the shear exerted, and damp the turbulence, for longer and longer periods of the tidal cycle. A shoal will grow. Occasionally, with application of exceptionally large shear due to variations in tides or flow, the shoal may be failing again. It can be eroded from the top downward as the turbulence and shear forces overcome the resistance to deformation inherent at that level of consistency of the mixture. On the other hand, large portions of the shoal may fail along shear planes where local shear and consistency combine to produce an optimum condition for rupture. Large masses of mud may then be displaced in bulk and slide to new positions or may be broken down and dispersed to be redeposited elsewhere.

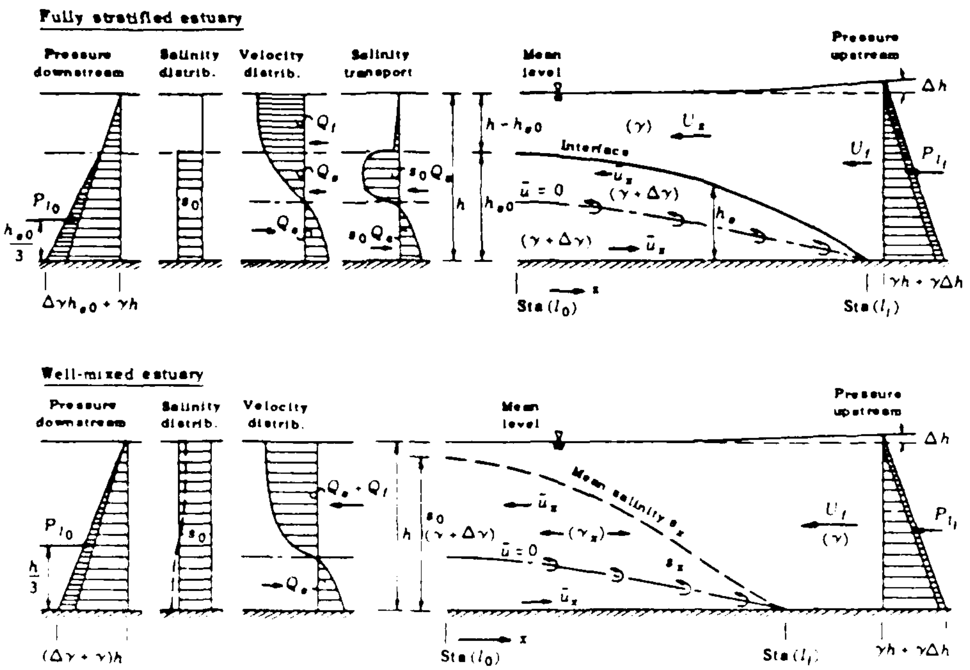
The establishment of shoals in estuaries and harbors and the breakdown of these shoals may take place over a long period during which an averaging process takes place in terms of saline intrusion or fresh-saline mixtures in a well-mixed estuary.

Changes in the saline intrusion brought about by dredging can have significant effects in terms of the location of shoals as well as the amount of shoaling after dredging. For example, channel deepening can allow the salt wedge to travel deeper into an estuary, creating shoaling in regions where shoaling has never before occurred.

In addition, these tidal-induced bottom currents transport material within a harbor. If dredged materials are disposed of within the harbor, it is quite possible they will migrate to the position from which they were removed.

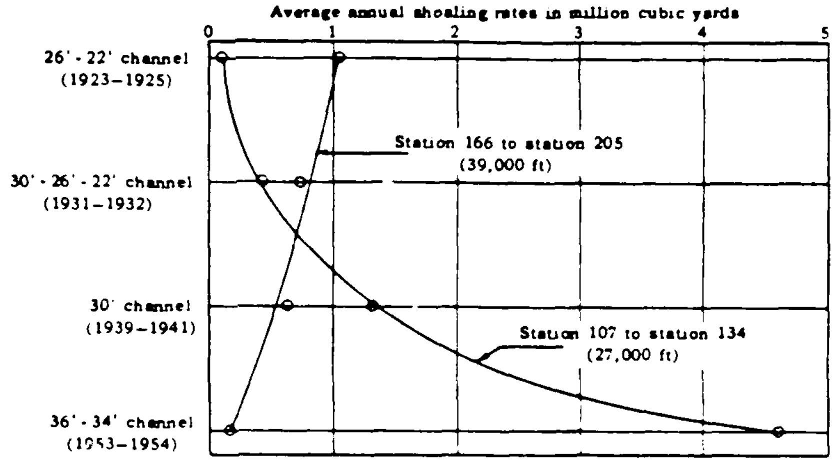
An excellent example of some of the problems that arise with dredging is presented in Figure 11, which shows the shoaling characteristics of Savannah Harbor. Two curves are shown in this figure, one for a 39,000 ft (11,818 m) section of the estuary in the lower harbor, and the other for a 27,000 ft (8,181 m) reach of the estuary in the upper harbor. The average annual shoaling rates in million cubic yards (cy) of material are plotted as a function of

Figure 10 Schematic representation of salinity intrusions in estuaries*



*SOURCE: A. T. Ippen, ed. (1966), Estuary and Coastline Hydrodynamics (New York: McGraw-Hill)

Figure 11 Shoaling characteristics of Savannah Harbor*



(Stations numbered from mouth of Savannah River upward)

*SOURCE: A. T. Ippen, ed. (1966), Estuary and Coastline Hydrodynamics (New York: McGraw-Hill).

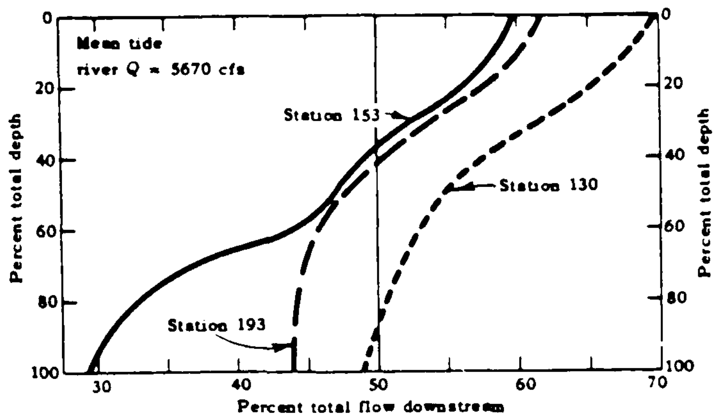
changes in channel configuration. From 1923 to 1925--when nearly 3 miles (4.8 km) of channel were dredged to depths of 22 ft to 26 ft (7 m to 8 m)--the amount of shoaling in the lower reach of the estuary was nearly 10 times that in the upper reach. However, as the channel that was dredged was both deepened and lengthened, the situation changed. In the early 1950s, a 7-1/2 mile (12 km) section of the channel was deepened to 34 ft to 36 ft (10 m to 11 m), resulting in nearly 40 times more shoaling at the upstream station than at the downstream station. Thus, the material brought into the estuary from inland sources was deposited farther and farther upstream each time the channel was dredged.

The vertical distribution of velocity at several sections in Savannah Harbor can be seen in Figure 12. Station 193 is located near the harbor entrance, and Station 130 is near the upstream limit of salt-water intrusion. The agreement with the simplified description of Figure 10 is evident.

Considering the complex hydrodynamic aspects of the flows in the interior of a harbor or estuary due to the hydrography of the fresh-water inflows and the nature of tidal-induced currents, and the importance of the details of these flows on the effects of changes of depth (by dredging, for example) on shoaling, it appears that numerical modeling can, at best, reveal only very approximate ideas about dredging criteria. This review suggests that more or less a case-by-case investigation may be necessary to indicate the problems likely to accompany overdredging. On the other hand, it is possible that the overdredging is not nearly so important as the initial dredging decision in modifying shoaling characteristics in an estuary.

Some coastal inlets are believed to have reached a state of equilibrium; some have not and will continue to be unstable. O'Brien (1969) found that the equilibrium minimum flow area of a tidal inlet, with or without jetties, is controlled by the tidal prism. A reduction of the tidal area by sedimentation will reduce the flow area. Figure 13 shows a typical tidal inlet which has approximately ideal proportions: a crescent-shaped bar seaward having a center of curvature near the throat section, a swash channel at each end of the bar, and a controlling depth over the bar much smaller than at the throat section. The flood currents are shown in Figure 13a and ebb currents in Figure 13b. Tidal currents through the inlet must sweep the littoral sediment drift out of the inlet, moving the sediment into the bay, or seaward to the offshore bar. Along the Pacific coast, the ebb currents predominate, owing to diurnal inequality, and move the sediment seaward. Along the Gulf of Mexico, the opposite is true, and the littoral drift tends to accumulate inside the bay. This accounts for the instability of many Gulf of Mexico inlets prior to stabilization by jetties and dredging.

Figure 12 Normal distribution of flow (in vertical) in Savannah Harbor*



*SOURCE: A. T. Ippen, ed. (1966), Estuary and Coastline Hydrodynamics (New York: McGraw-Hill)

Figure 13 Tidal inlet, showing (a) flood currents; (b) ebb currents*

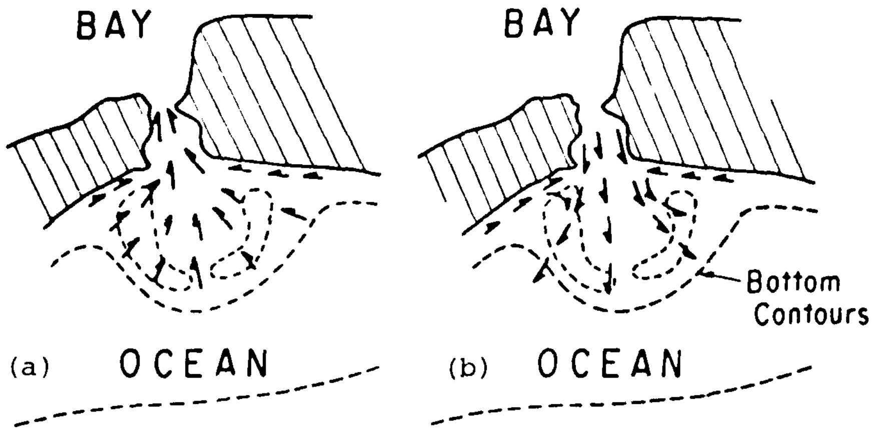
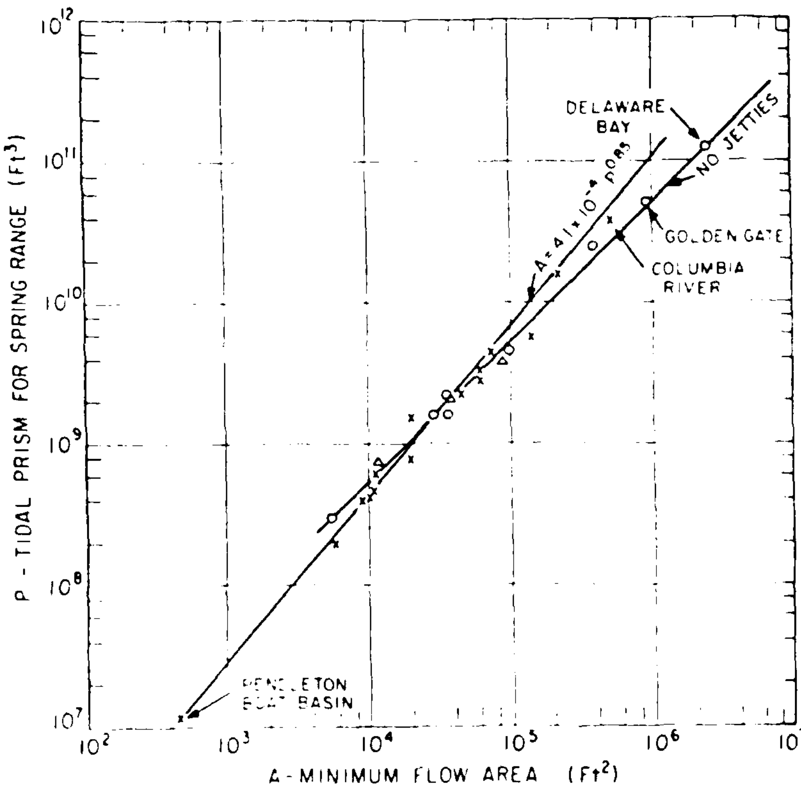


Figure 14 Relationship between minimum flow cross-section of entrance channel (ft^2) and tidal prism (ft^3) for diurnal range of tide*



SOURCE: M. P. O'Brien (1969), "Equilibrium Flow Areas of Tidal Inlets on Sandy Coasts," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 95(WW1): 43-52.

The relationship between entrance area and tidal prism (based on available data) is given by

$$A = 4.69(10)^{-4} P^{0.85}$$

where A = area (in ft^2), the minimum flow cross-section of the entrance channel (throat) measured below mean sea level, and

P = the tidal prism (in ft^3) corresponding to the diurnal range of tide.

Figure 14 shows the relationship between A and P for several inlets.

Harbor Entrances

Sedimentation by Type of Harbor, and Mitigation Strategies

Sediments tend to collect at different types of harbor entrances for different reasons. These harbors (Figure 15) have been classified (Caldwell, 1950; Komar and Inman, 1970) as:

River-Channel Harbors Fresh river waters keep the clays moving; consequently, the principal sedimentation problem becomes one of sand. Dredging, training walls, and diversion of the river are the usual corrective measures in such harbors.

Off-River Harbors These harbors have little difficulty with sand and gravel but do often have problems with silts and clays. The solution to shoaling is dredging, training walls and dikes, and the use of locks or floodgates.

Fall-Line Harbors Sedimentation problems generally result from sand and gravel deposits. Solutions usually consist of dredging, training walls, or the creation of an off-channel harbor.

Off-Channel Harbors in Tidal Estuaries Shoaling is usually due to suspended silt and clay. Improvement is the same as for off-channel river harbors--namely, dredging, training dikes, and use of locks.

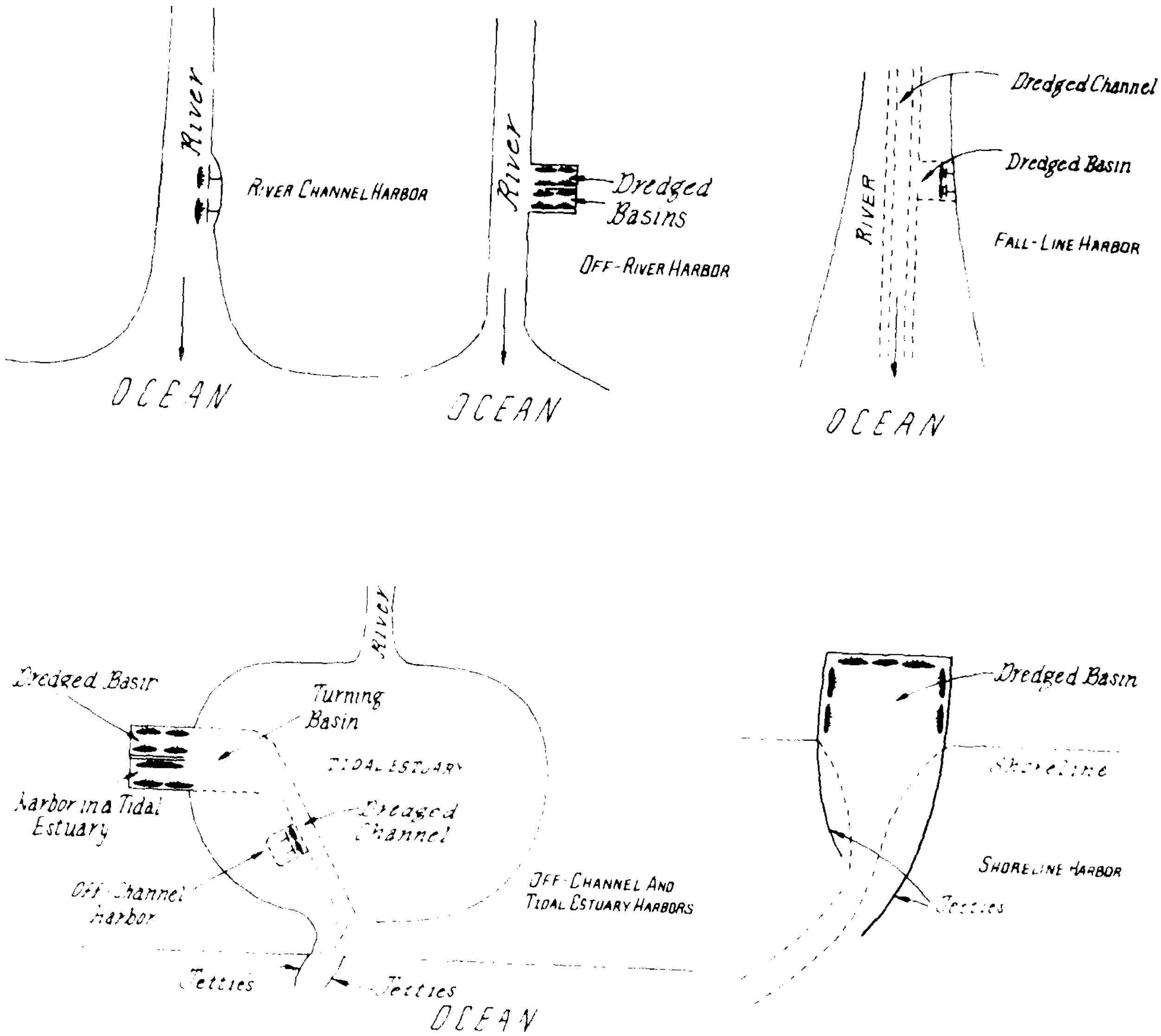
Shoreline Harbors The problem at such localities is the deposition of sand moved into the harbor by littoral currents (discussed in the preceding section). Maintenance of such harbors usually involves a sand-bypassing operation.

Thus, mitigation strategies may encompass efforts to control sedimentation as well as dredging.

Minimizing Sedimentation

Sedimentation can be minimized in several ways. These were studied in the MKO project in the Netherlands (van Oostrum, 1979). The balance of particle transport with current velocity, with variations in deposition density, and with possible silt traps was researched, as well as recirculation from offshore dumping. Studies of the orientation of harbor approaches can lead to designs for partial self-cleaning of the dredged channel. River, tidal, or littoral currents can sometimes be directed to help scour the navigational channel, carrying sediments into deeper water outside the dredged area.

Figure 15 Types of harbors



Sedimentation can be minimized by increasing the channel velocity in a number of ways, such as

- o Groins, to reduce the width of flow;
- o Training walls to direct flow;
- o Closing of side channels;
- o Straightening channels;
- o Increasing the tidal prism;
- o Increasing flushing by reservoirs, releasing at ebb tide;
- o Reducing flocculation by diversion of freshwater flow;
- o Avoiding river sediments passing through the navigable channel; and
- o Creating turbulence artifically. Ships' propellers do this very well in some busy channels.

Model tests are helpful in observing the comparative velocities of water in different areas of a harbor entrance. Extensive model studies are routinely conducted at many laboratories in the world, including the Waterways Experiment Station of the U.S. Army Corps of Engineers.

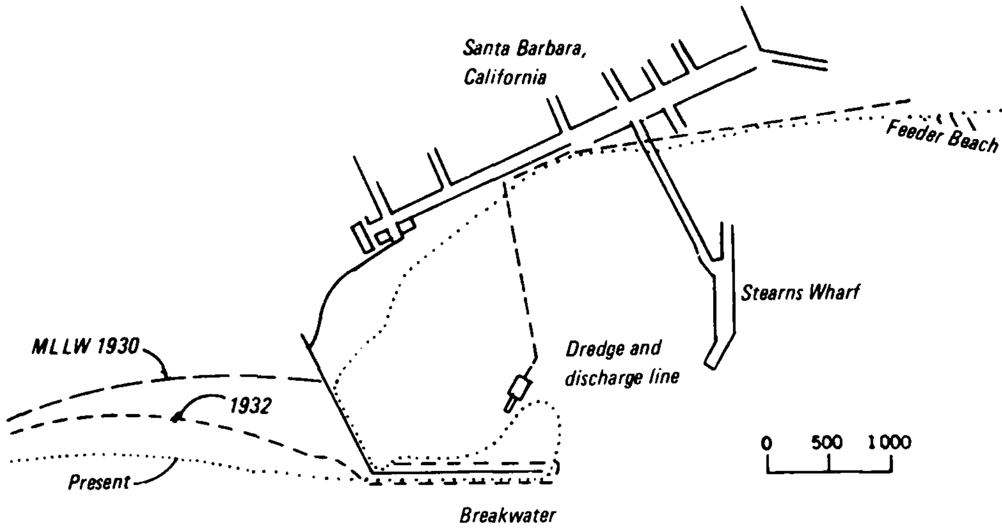
Fixed bypassing plants for moving sediments from one side of the channel to the other have been employed, working steadily or intermittently. These may be land-based or floating. Since major sediment movements generally occur during major periods of wave action, or storms, the rate of bypassing becomes variable. Because of the standby plant costs, the procedure may evolve into periodic dredging, as in normal channel maintenance with floating mobile equipment.

Examples of Mitigation Strategies and Effects

One example (Figure 16) is the sand transfer arrangement at the entrance to Santa Barbara Harbor, California, which was constructed in 1930. Here the dominant direction of littoral drift is from west to east. Five years after the west shore-connected breakwater was built, sand had filled up the area to the west. The sand then moved along and around the seaward end and settled in the protected harbor in the form of a bulb. The rate of drift was about 270,000 cy (205,200 m^3) per year. Severe erosion prevailed downcoast until the first bypassing arrangement in the country was initiated in the late 1930s.

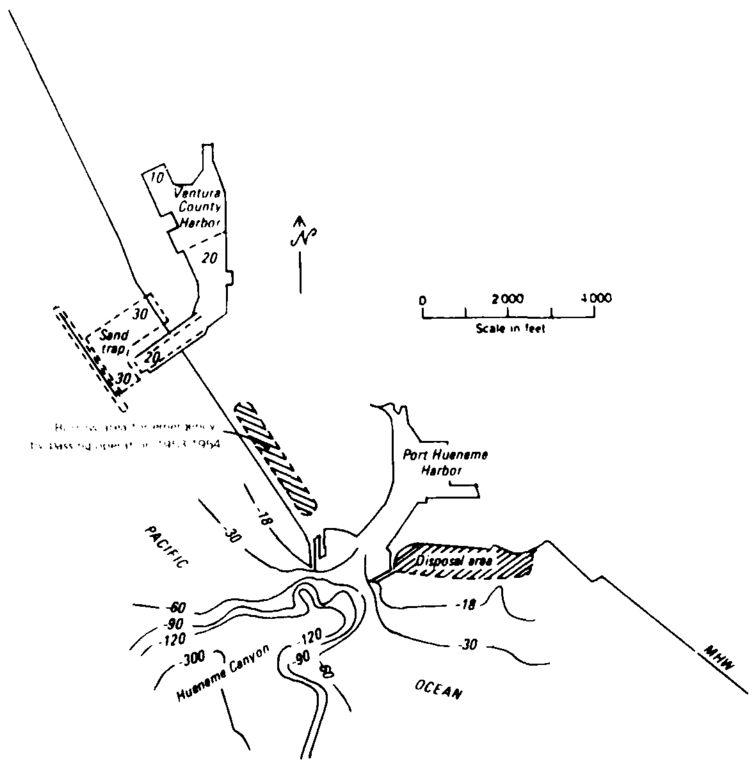
Another bypassing operation designed to handle all the littoral drift moving to an inlet was put into service at Ventura, California (Figure 17). The plan involved an offshore rubble breakwater, 2500 ft (758 m) long and parallel to the shore, to minimize wave action at the channel entrance and create a trap for the easterly moving littoral drift. The trapped material is then transferred to the shores downdrift of the Port Hueneme east jetty. The purpose was both to minimize maintenance of the entrance channel to the Ventura County Harbor and to stabilize the shores downdrift of Port Hueneme, whose harbor was acquired by the Navy in 1942.

From 1938 when the west jetty was completed, littoral drift was diverted into the Hueneme Submarine Canyon, thus removing from 800,000 cy to 1,600,000 cy (608,000 m^3 to 1,216,000 m^3) of drift and practically eliminating all maintenance in the 35 ft (11 m) channel. However, erosion began southeast of Port Hueneme at a rate about equal to the average annual drift.



SANTA BARBARA BYPASSING SYSTEM

Figure 16



VENTURA COUNTY HARBOR, CALIF

Figure 17

In 1953-1954 an emergency bypassing operation was conducted moving about 2 million cy (1.5 million m^3) from the impounding trap to the shores east of the harbor, and from there by conventional floating dredge to points below Hueneme.

Decisions and results are site-specific. Ediz Hook, Washington, is a low, bare sand and gravel spit extending easterly from the mainland some 3-1/2 miles (5.6 km) into the Strait of Juan de Fuca (Figure 18). The protective arm of Ediz Hook acts as a natural breakwater and protects the city of Port Angeles and its harbor from the direct wave attack of swells from the west.

The development of the present spit began when the sea had worn away the cliffs to the west and carried detritus from the Elwna River east and southeast. A dam was built on the Elwha River, however, and erosion of the cliffs was reduced by works constructed to protect the water-supply pipeline to Port Angeles (O'Brien and Johnson, 1980). The more westerly portions of the spit then began to migrate southward by a process of breaching and overtopping. This movement into the deeper water of Port Angeles Harbor thinned the spit progressively so that now it is in danger of becoming a mere shoal. In 1974, extensive studies were started to determine the details of a nourishment program at 5 year intervals of feeding, based on unsupported theories about the nature and behavior of the coarse materials involved here in overfilling to anticipate erosion. About 100,000 cy (76,000 m^3) of selected gravel were planned each cycle.

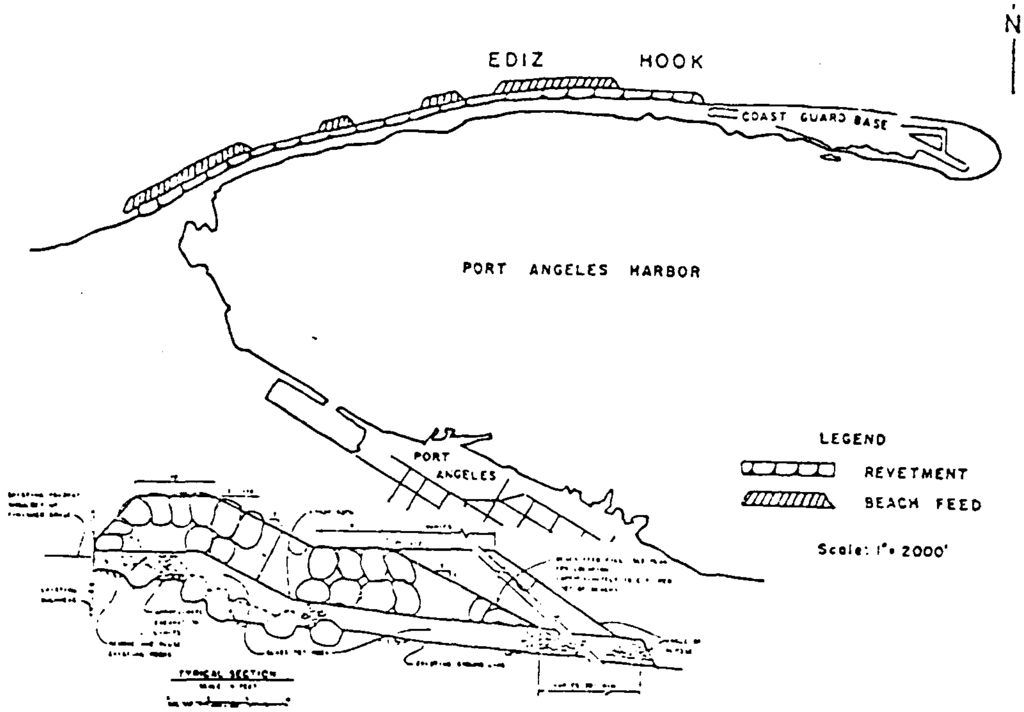
Some harbor entrances, because they are subjected to both tidal and storm wave attack from the open ocean and because the shoreline is composed of sandy soil, are so amorphous that they defy economical methods for providing safe navigation. In Chatham Harbor (Cape Cod), for example, flood and ebb deltas shift with almost every change in tide. Attempts at stabilization have so far not been economic, because the harbor is mostly for fishing and pleasure boating. However, as an example of the problems of harbor entrances in the United States, this is one of the oldest: the first recorded shipwreck in the New World was in this vicinity in 1626.

Perhaps a classic case of a migrating harbor entrance, fed by littoral drift predominantly from one direction, is that of Fire Island, New York, which serves a series of small ports and pleasure boat centers in Great South Bay. It is a tidal estuary with a large tidal prism and a mean tide range of 4.1 ft (1.2 m). Maximum is from -6.0 ft to +9.4 ft (-1.8 m to +2.8 m).

Figure 19 shows historical shoreline changes (Survey Report, N.D.). Note the radical alteration in the shape of the elongating tip between 1939, when the jetty was built (1939-1941), and 1955, when sand had fully impounded behind the jetty and was spilling over into the navigable inlet.

Figure 20 shows dredging and shoaling between 1955 and 1962, as sand continued to spill around the jetty. A major problem of erosion to the west had threatened to destroy the newly built Ocean Parkway. Sand was imported from Great South Bay to make up the deficit. The

Figure 18


EDIZ HOOK
COAST GUARD BASE
N
PORT ANGELES HARBOR
PORT ANGELES
LEGEND
REVETMENT
BEACH FEED
Scale: 1" = 2000'
TYPICAL SECTION

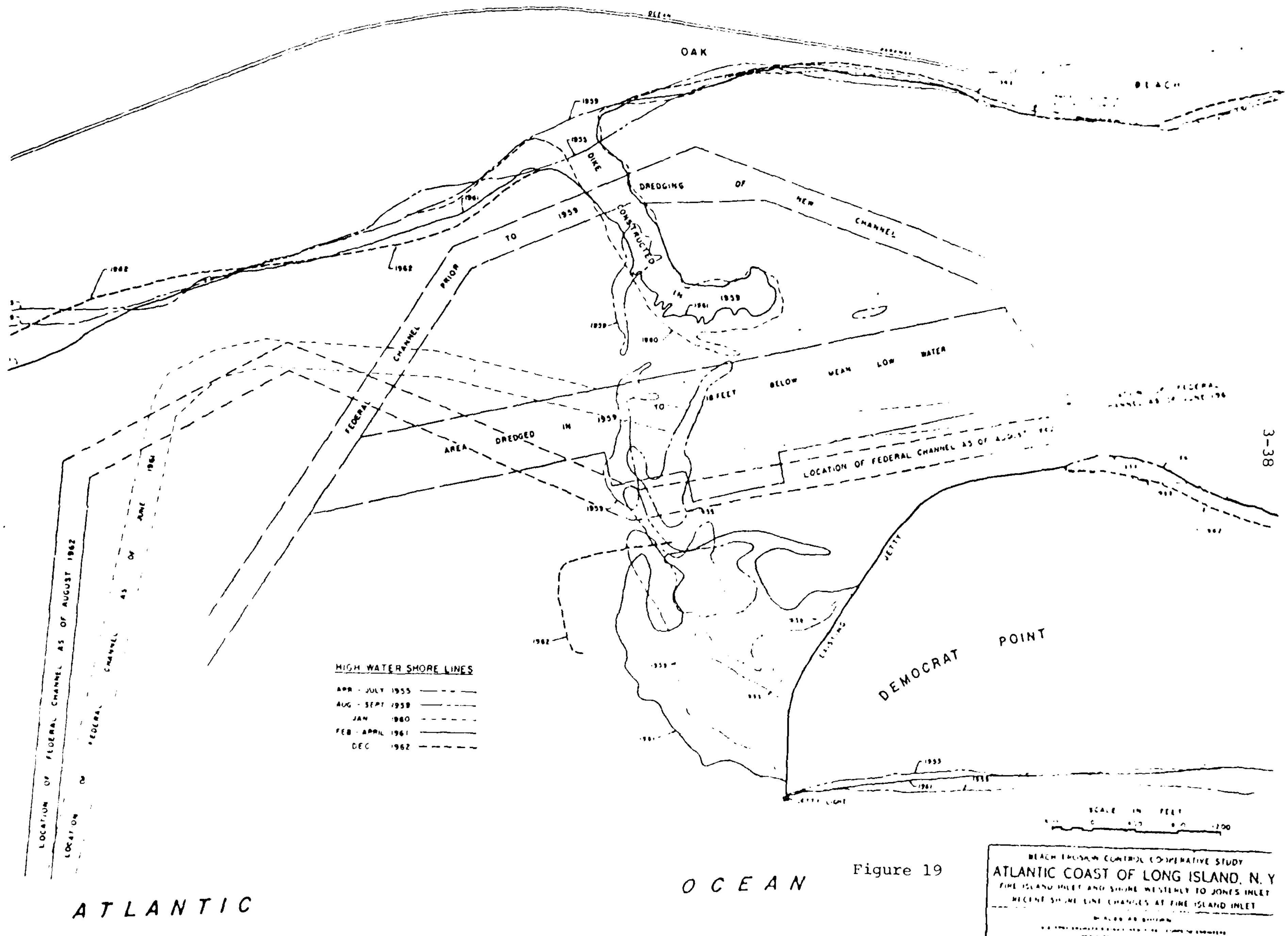

OAK
BEACH
DIKE
DREDGING OF NEW CHANNEL
CONSTRUCTED IN 1959
PRIOR TO 1959
FEDERAL CHANNEL
AREA DREDGED IN 1959 TO 18 FEET BELOW MEAN LOW WATER
LOCATION OF FEDERAL CHANNEL AS OF AUGUST 1962
LOCATION OF FEDERAL CHANNEL AS OF JUNE 1961
DEMOCRAT POINT
JETTY
JETTY LIGHT
HIGH WATER SHORE LINES
APR - JULY 1955
AUG - SEPT 1959
JAN 1960
FEB - APRIL 1961
DEC 1962
SCALE IN FEET
ATLANTIC
OCEAN
BEACH EROSION CONTROL COOPERATIVE STUDY
ATLANTIC COAST OF LONG ISLAND, N. Y
FIRE ISLAND INLET AND SHORE WESTERLY TO JONES INLET
RECENT SHORE LINE CHANGES AT FIRE ISLAND INLET

Figure 19

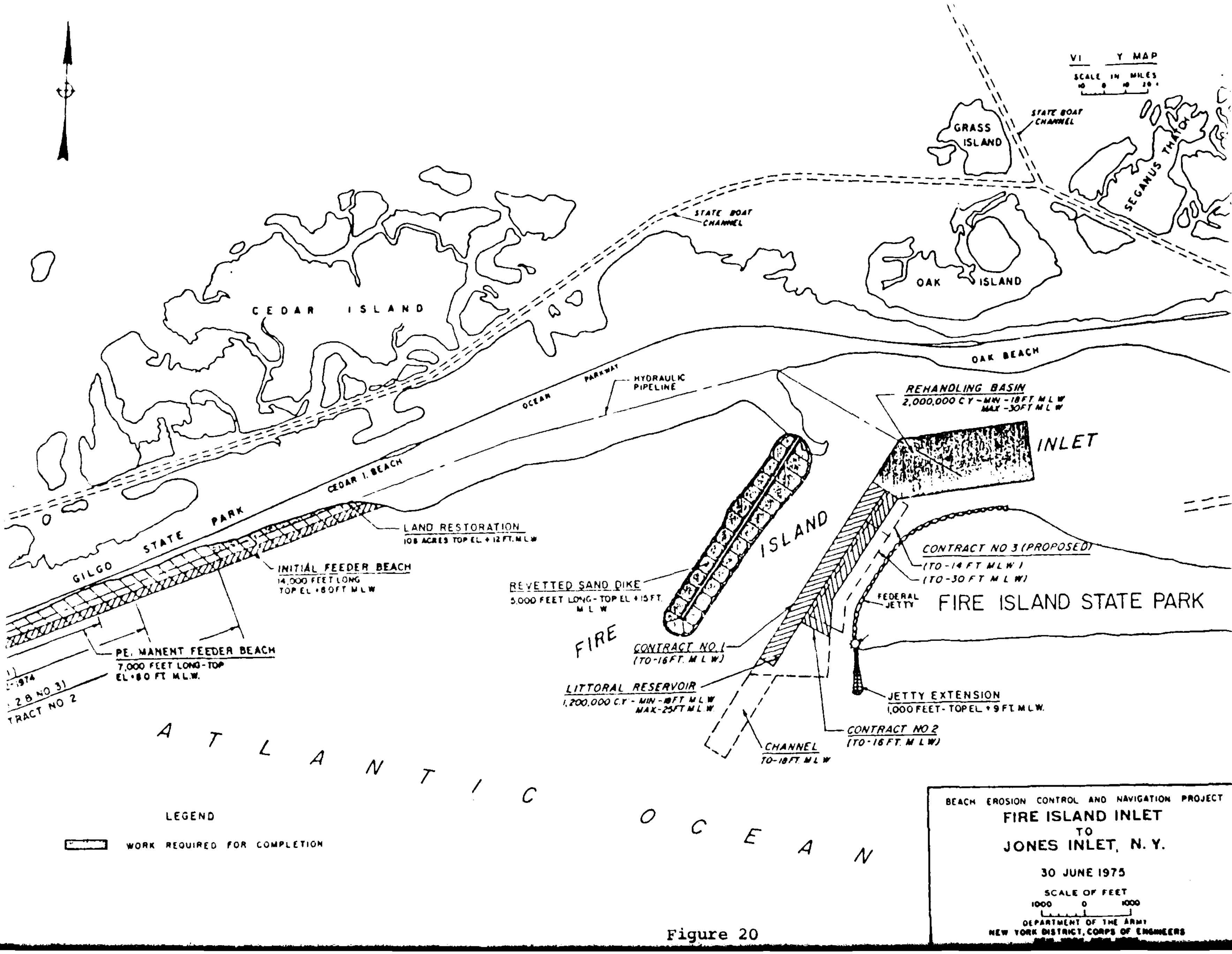

VI Y MAP
SCALE IN MILES
GRASS ISLAND
STATE BOAT CHANNEL
SEGANUS THATCH
OAK ISLAND
CEDAR ISLAND
STATE BOAT CHANNEL
OAK BEACH
OCEAN PARKWAY
HYDRAULIC PIPELINE
REHANDLING BASIN
2,000,000 C.Y. - MIN -18 FT M L W
MAX -30 FT M L W
INLET
CEDAR I. BEACH
GILGO STATE PARK
LAND RESTORATION
108 ACRES TOP EL + 12 FT. M.L.W.
INITIAL FEEDER BEACH
14,000 FEET LONG
TOP EL + 8.0 FT M.L.W.
REVETTED SAND DIKE
5,000 FEET LONG - TOP EL + 15 FT. M.L.W.
ISLAND
FIRE
CONTRACT NO 3 (PROPOSED)
(TO -14 FT M L W)
(TO -30 FT M L W)
FEDERAL JETTY
FIRE ISLAND STATE PARK
CONTRACT NO. 1
(TO -16 FT. M.L.W.)
PE. MANENT FEEDER BEACH
7,000 FEET LONG - TOP EL + 8.0 FT. M.L.W.
LITTORAL RESERVOIR
1,200,000 C.Y. - MIN -18 FT M L W
MAX -25 FT M L W
JETTY EXTENSION
1,000 FEET - TOP EL + 9 FT. M.L.W.
CONTRACT NO 2
(TO -16 FT. M.L.W.)
CHANNEL
TO -18 FT M L W
TRACT NO 2
ATLANTIC OCEAN
LEGEND
WORK REQUIRED FOR COMPLETION
BEACH EROSION CONTROL AND NAVIGATION PROJECT
FIRE ISLAND INLET
TO
JONES INLET, N.Y.
30 JUNE 1975
SCALE OF FEET
1000 0 1000
DEPARTMENT OF THE ARMY
NEW YORK DISTRICT, CORPS OF ENGINEERS

Figure 20

dike within the Fire Island entrance channel had been built in 1959 to train tidal flows through the shoaling area. Various plans for fixed sand-bypassing plants were then considered. An extensive model study was carried out at the Waterways Experiment Station of the U.S. Army Corps of Engineers in Vicksburg, Mississippi, in which 14 different basic plans, along with many alternatives, were modeled using both fixed- and movable-bed models. Twelve agencies and subcontractors made contributions. Figure 21 shows the recommended plan (3A), which required dredging a littoral trap (1.2 million cy, or 912,000 m^3) to El. -18, and a rehandling basin (2 million cy, or 1.5 million m^3) to El. -30, as well as land reclamation to the west (3,370,000 cy, or 561,200 m^3) and a feeder beach to supply it (2 million cy, or 1.5 million m^3) initially, with biennial nourishment of 1.2 million cy (900,000 m^3). The estimated volume of littoral drift was 600,000 cy (456,000 m^3) per year (U.S. Army Corps of Engineers, 1970).

The design studies continued until April 1971, alternative methods of dredging were studied in 1972, and the first dredging contract in 1973 and 1974 placed 1 million cy (760,000 m^3) along 9000 ft (2727.2 m) of feeder beach. A second contract placed 930,000 cy (706,800 m^3) in 1975 but ran short of funds. A third contract, begun in June 1976 and completed May 1977, placed 2,272,000 cy (1,726,700 m^3) directly on the beach to the west, and the rehandling basin was eliminated, as was the revetted sand dike.

The 1977 report on construction states that "the configuration of the inlet shoal experiences such significant changes over short periods of time that dredging operations are often times hampered and delayed." This statement came 22 years after shoaling and erosion had reached a critical stage, endangering both navigation and highway transportation.

From these examples, the criteria for dredged depths at harbor entrances appear to be dominated more by the uncertainties of deposition and the irregular time constraints imposed by financial and institutional arrangements than by the maneuverability of ships.

Special Considerations of Silty Channels

In many ship channels, the interface between the sediment and overlying water is clearly defined and the sediment-water interface is easily seen on depth sounders. In many other channels and coastal inlets with active circulation systems carrying suspended sediment, siltation of the channel occurs through the deposition of silt or the presence of fluid mud (static suspension).

Research work on cohesive sediment suspensions in coastal areas (Parker and Kirby, 1977) has revealed the behavioral link between sediment suspended in the water column and dense cohesive sediment suspensions on the seabed (Figure 22). This work shows that high-energy events (tidal currents or storms) erode cohesive sediments and transport them into navigational channels. When first eroded, the sediments are mixed throughout the water column as a homogeneous mobile suspension. As energy levels decline, the mobile suspensions begin to differentiate by settling, forming marked steps that continue

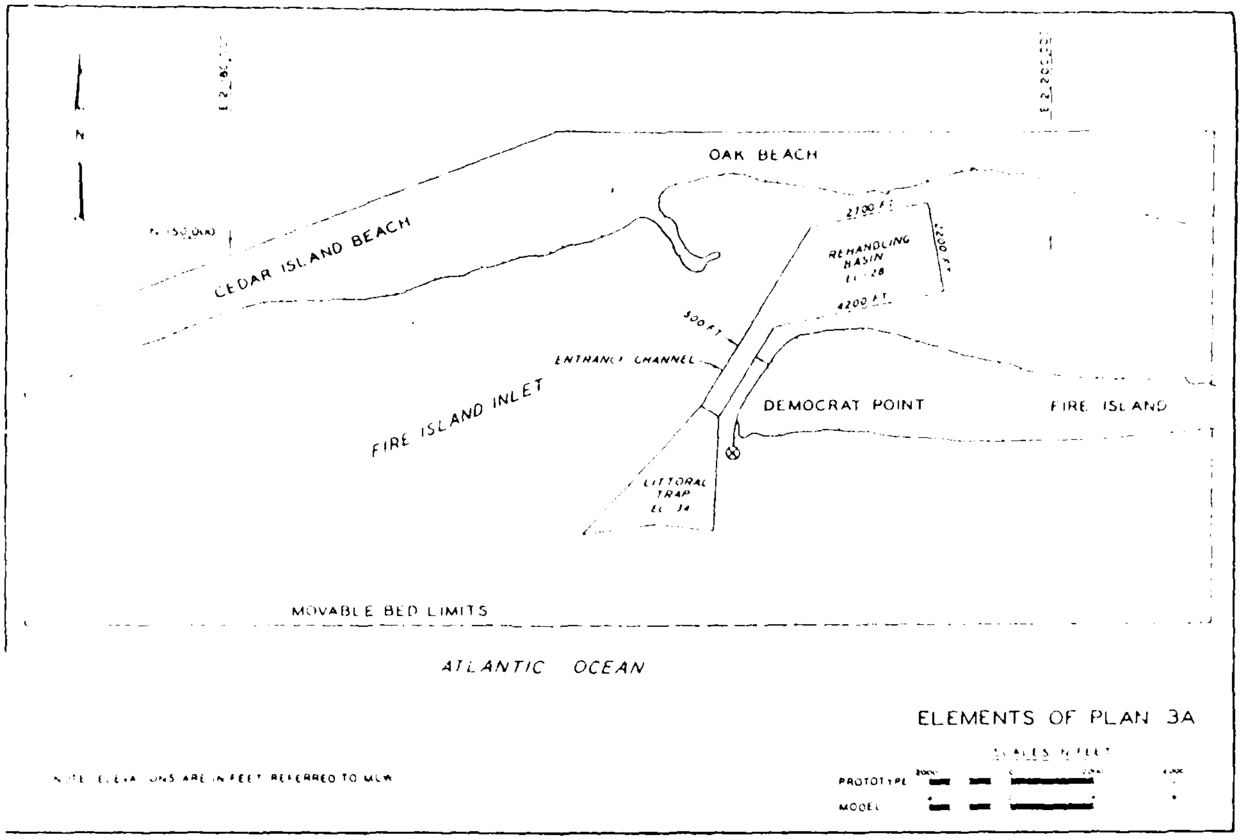

OAK BEACH
CEDAR ISLAND BEACH
REHANDLING BASIN
4200 FT
ENTRANCE CHANNEL
FIRE ISLAND INLET
DEMOCRAT POINT
FIRE ISLAND
LITTORAL TRAP
MOVABLE BED LIMITS
ATLANTIC OCEAN
ELEMENTS OF PLAN 3A
PROTOTYPE
MODEL

Figure .1

Figure 22 Relationships between mobile and static suspensions and settled mud*

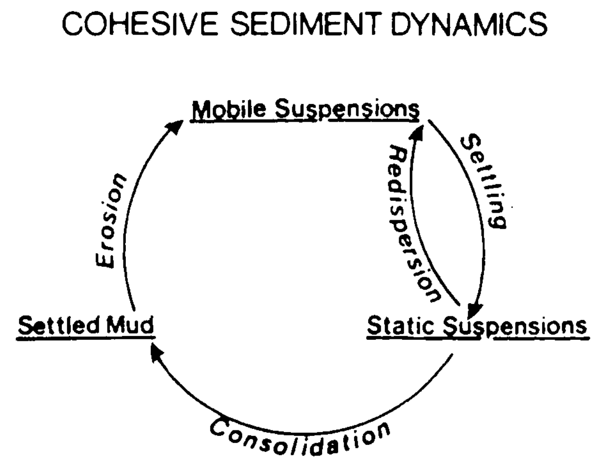
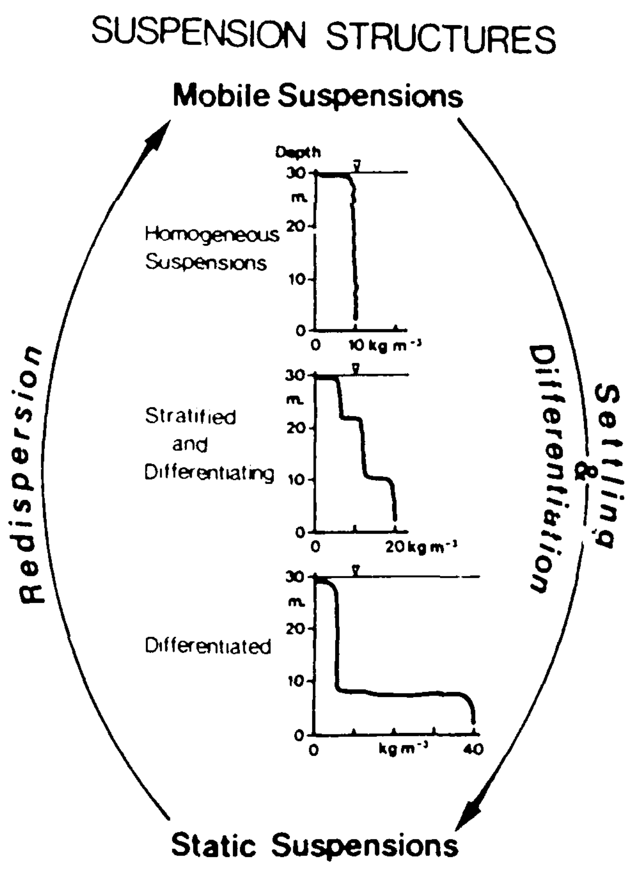


Figure 23 Structures developed in mobile suspensions during spring to neap cycle*



*SOURCE: W. R. Parker and R. Kirby (1977), "Fine Sediment Studies Relevant to Dredging Practice and Control," BHRA Fluid Engineering/Texas A&M University, 2nd Int. Symp. on Dredging Tech., Vol B.2, pp. 15-26.

to settle through the water column until dense layers several meters thick of specific gravity equal to about 1.15 are observed flowing along the bed. Eventually, these mobile layers stagnate to form dense static suspensions (mud flow). It is patent, therefore, that where static suspensions occur, deposition has been rapid. Mobile suspensions commonly show multiple stratification, and although layering within the static suspensions is also common, there is as yet no unequivocal explanation of the cause.

Following stagnation, the static suspensions continue to settle, and within a few hours they consolidate to a stage at which they can be detected by normal hydrographic survey echo sounders.

Once they become detectable, these suspensions--"fluid mud" or "silty bottom"--present a survey problem, since no evidence is presented on the echo sounder record that allows confident selection of the layer to be regarded as the seabed. Such static suspensions appear very suddenly after storms, commonly have two or more layers, and may reach 2 m or 3 m (7 ft or 10 ft) in thickness--a significant height above the channel bottom.

Field studies in the United Kingdom and the Netherlands indicate that cohesive fine sediments occur in estuaries in three forms (Figure 23):

1. Mobile suspensions, which are common in estuaries with high tidal exchange and significant turbidity. These may also occur during major storms, such as hurricanes in the Gulf of Mexico or along the eastern seaboard, or may be caused (on a smaller, local scale) by engineering operations.

2. Static suspensions, which may be referred to as "fluid mud," or "fluff." These suspensions develop during neap tides and may be dispersed by spring tides. If not dispersed, they will settle at the bottom of the channel and eventually consolidate.

3. Settled mud, formed by consolidation of static suspensions.

Implications

The consequences of arbitrarily choosing one layer or another on the echo sounder record in the absence of supporting information were considered by Parker and Kirby (1977). Among these are the evident hazard to navigation of uncertain information about channel depths and the location of the bottom, and the expense of dredging "false" bottoms that may actually be navigable, as described in a succeeding section, "Nautical Depth Concept." Mobile and static suspensions also create problems for dredging operations. The mobile phase may pass undetected by the usual survey techniques (particularly where surveys are infrequent). In the static phase, suspended sediments may be detected by an echo sounder, but the time-dependent properties of the suspensions control the actual readings. These readings, in turn, affect the evaluation of navigable depths, the determination of the maintenance dredging required, and the measurement of new depths following dredging. They may also influence the timing of maintenance dredging operations.

Measurement Technology

The suspensions described here have long been recognized by hydrographic surveyors. In the early days of lead-line techniques, a special "mud lead" was devised for static suspensions. Echo sounders have largely replaced lead lines; however, the acoustic detection of dense suspensions is difficult to achieve. In the simplest case, particles settle from a sharp-surface concentration zone onto the bottom material, which may be loosely defined as the channel "bed" (Figure 24).

The simplest case is not the usual case. Echo sounders respond to both the density and the acoustic velocity gradients of the medium, and these acoustic properties cannot readily be converted into information about the altitude within the suspension at which its mechanical properties may significantly affect ship handling.

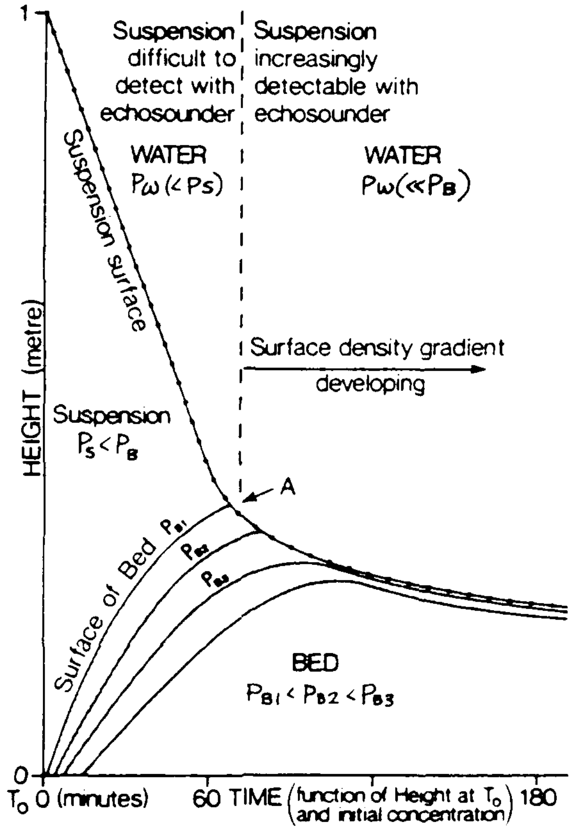
As pointed out by Kirby et al. (1980), information was needed about the behavior of vessels sailing through such areas (see the section "Nautical Depth Concept") and in situ measurements. Two radioactive probes were tested for measurement of specific gravity in situ: the transmission type and the backscatter type (Figure 25). The transmission probe is an H-shaped instrument with a radioactive source in one leg and a detector in the other. The source radiates directly to the detector. The transmission probe is able to average the specific gravity with a resolution of 3 cm in depth (which is the height of the detection crystal). Since the instrument must sink into the silt by its own weight, the H-shape is a disadvantage.

The sturdier backscatter probe carries source and detector in a single pencil-shaped tube. The source radiates in all directions; the detector, placed above the source and screened from it by a shield, receives only part of this radiation. The backscatter probe registers densities with a resolution of 15 cm (i.e., the distance between the source and the detector). Because of its shape, this probe penetrates the bottom more readily than the transmission probe.

The probes and associated equipment were developed by the Atomic Energy Research Establishment (United Kingdom) and tested for field use by the hydrographic survey department of the Rijkswaterstaat. The method, now in regular use in Europoort, is essentially a modern mud lead and shares with the older technology the disadvantage of providing only point-by-point information. A towed, continuously measuring probe is under development in the Netherlands. Present practice is to superimpose the point-by-point measurements of specific gravity on the continuous bottom profile of the echo sounder.

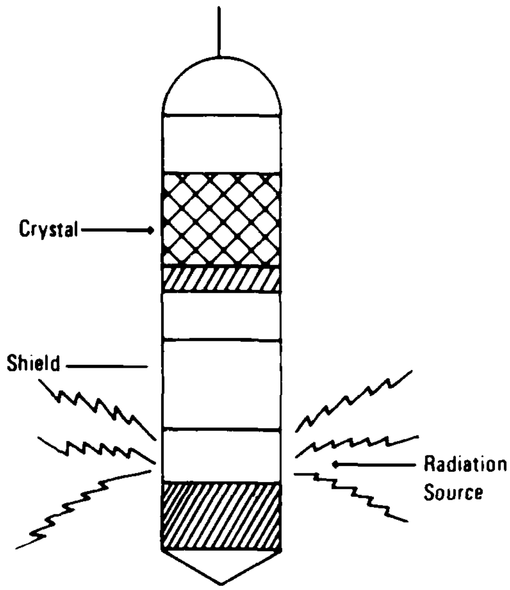
Although far from ideal or convenient, the combination of these two techniques offers considerable advantages in establishing "true" channel depths, and in pre- and post-dredging surveys in silty channels, as fluid muds dewater slowly and may be subject to considerable tide-created movement.

Figure 24 Diagrammatic illustration of the settling of a stati suspension showing bed and density structure development*

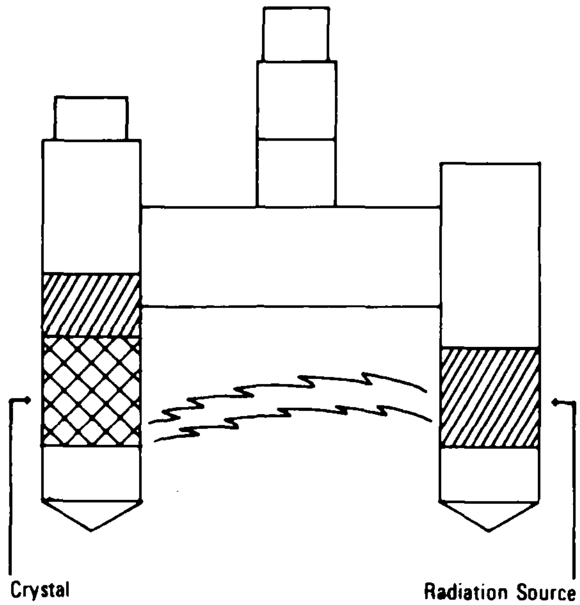


*SOURCE: Based on data from A. J. Mehta and E. Partheniades (1973), "Depositional Behavior of Cohesive Sediments," Technical Report 16, Coastal and Oceanographic Engineering Laboratory, University of Florida, p. 274.

Figure 25   Radioactive density probes: (a) backscatter, (b) transmission



(a)



(b)

Nautical Depth Concept

The "nautical depth" concept evolved from studies of the behavior of vessels in Europoort and Rotterdam harbors as part of an effort to minimize the maintenance dredging costs. The normal design depth of ship channels in sheltered waters includes a 10 percent underkeel clearance to provide safe navigation and maneuverability (Figure 26).

The behavior of vessels sailing close to the surface and in the upper layers of dense suspensions was investigated, and extensive model tests were conducted in the Netherlands Ship Model Basin with a two-layer system to study the sailing and maneuvering characteristics of supertankers in a channel with a soft bed. Prototype field tests were made with the 240,000 DWT supertanker Lepton sailing in the Eurooport channels. Extensive investigations were also made in the Chao Phraya River, Bangkok, and along the coast of Surinam where ships sail in mud with a negative underkeel clearance. On the basis of these investigations and a search of the literature, it was found that fluids of specific gravity to 1.2 had only a slight influence on maneuverability (van Oostrum, 1979; van Oostrum et al., 1981; Kirby et al., 1980).

Thus, channel depth can be increased if the upper layers of static suspensions are included in the underkeel clearance.

Based on the results of the investigations and studies, the concept of nautical depth was developed (Nederlof, 1980): "a density within the suspension above whose altitude vessels can safely sail" (Figure 27), and the density was defined as 1.2 g/cm^3, or having specific gravity of 1.2.

Use of the nautical depth concept to define channel depths depends critically on frequent (weekly) and accurate density measurements.

Dredging

Among the considerations important to judging criteria for the depths of dredged navigational channels is the accuracy of the dredging process. As indicated in a preceding section, the two types of overdepths specified in channel design and (more usually) maintenance are intended to (1) achieve and preserve the design depth (an allowance for inaccuracies of dredging and surveys) and (2) provide advance maintenance dredging, i.e., to reduce dredging frequency.

Neither decision is simple; neither can be characterized by a general formula. By tradition and contract specification, the Corps pays only for the material removed within the overdepth specified. Because dredging is a highly competitive activity worldwide, technological advances that enable greater accuracy to be achieved are regarded as proprietary industrial information. Thus, the leading edge of technology in dredging is hidden within the industry, with a lag time of several years between the development and use of innovations and their description in the literature.

Figure 26 Required minimum water depth over a firm sandy bed: draft of vessel + 10%*

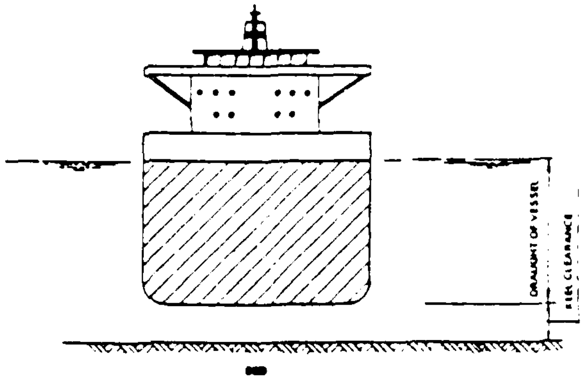
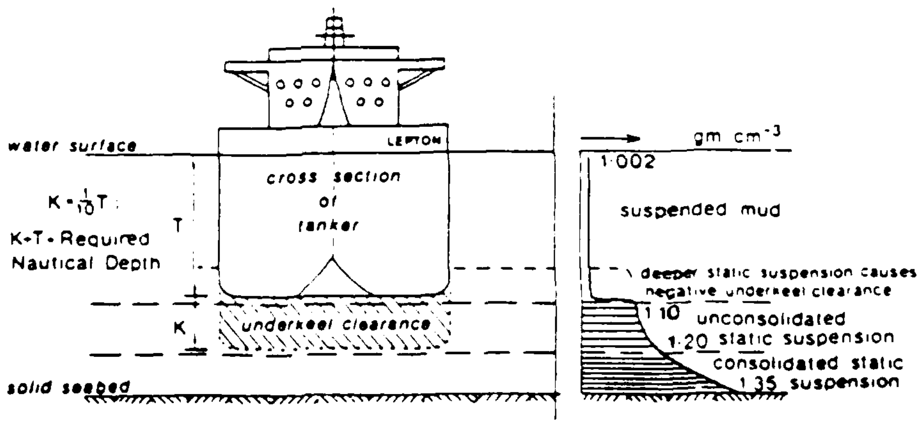


Figure 27 Comparison of density profile and tanker cross-section to illustrate concept of nautical depth*



*SOURCE: L. Nederlof (1980), "Sailing through Water Rich in Floating Silt: A Vessel Behaves Differently, but Remains Manageable," Rotterdam Europoort Delta, p. 20.

For advance maintenance dredging, several countervailing consequences must be weighed: a deeper cut may reduce the velocity of water in the channel and increase the rate of sedimentation (as evidenced in a preceding section for Savannah Harbor). Unit dredging costs, on the other hand, are likely to be less for larger than for smaller contracts.

Some of the considerations most important to decisions about overdredged depths and (especially) dredging cycles are beyond the scope of this study. Among the most important are those pertaining to the disposal of dredged materials--the nature and distance of disposal sites from the channel to be dredged, the requirements to be met in the handling of dredged materials, and the time needed to secure permits and access to new disposal sites.

Accuracy of Dredging Processes

Accuracy depends on the type of equipment used, the sediments encountered, control of the dredge's position, whether the work to be performed is new or maintenance dredging, and, if the latter, the previous dredging work. It can be influenced strongly by such local conditions as tides and currents and by the accuracy of pre- and post-dredging surveys.

Type of Equipment Dredging plant is diverse: types used in the United States for dredging major navigational channels can be categorized as fixed relative to the channel bottom or independent.

Fixed Equipment Fixed equipment includes cutter suction dredges (Figure 28) with a spud pole (pilelike leg) firmly implanted in the channel bottom and the dredge itself rotating about this axis. The distance from the cutterhead to the spud pole is fixed mechanically, as is the depth of the cutter beneath the surface. In theory, the only variable is the angular motion of the dredge itself as it pivots about the fixed spud pole. This motion is usually controlled by cables attached to anchors.

It is imperative that the dredge operator know the exact location of the spud pole and the relative position of the cutterhead to the spud pole as well as the transverse position of the cutterhead to the channel centerline at all times. The position of the spud pole can be assumed to be known within an accuracy of less than 5 ft. Spud placement has little effect on the dredging operation, except in terms of the horizontal cut. Therefore, the position of the spud pole in normal maintenance dredging is not of prime concern. Electronic positioning equipment or gyrocompasses are used to measure the deflection of the dredge from the channel heading. With the use of these two control methods, the accuracy of the channel width can be controlled within 5 ft to 10 ft.

Other fixed-spud plants are grab dredges and dipper dredges. They differ from the cutter suction dredge in that their hulls do not move relative to the spud pole. The bucket used for the excavation is moved relative to the hull. The movement of the excavating bucket can be controlled more precisely than that of the cutterhead.

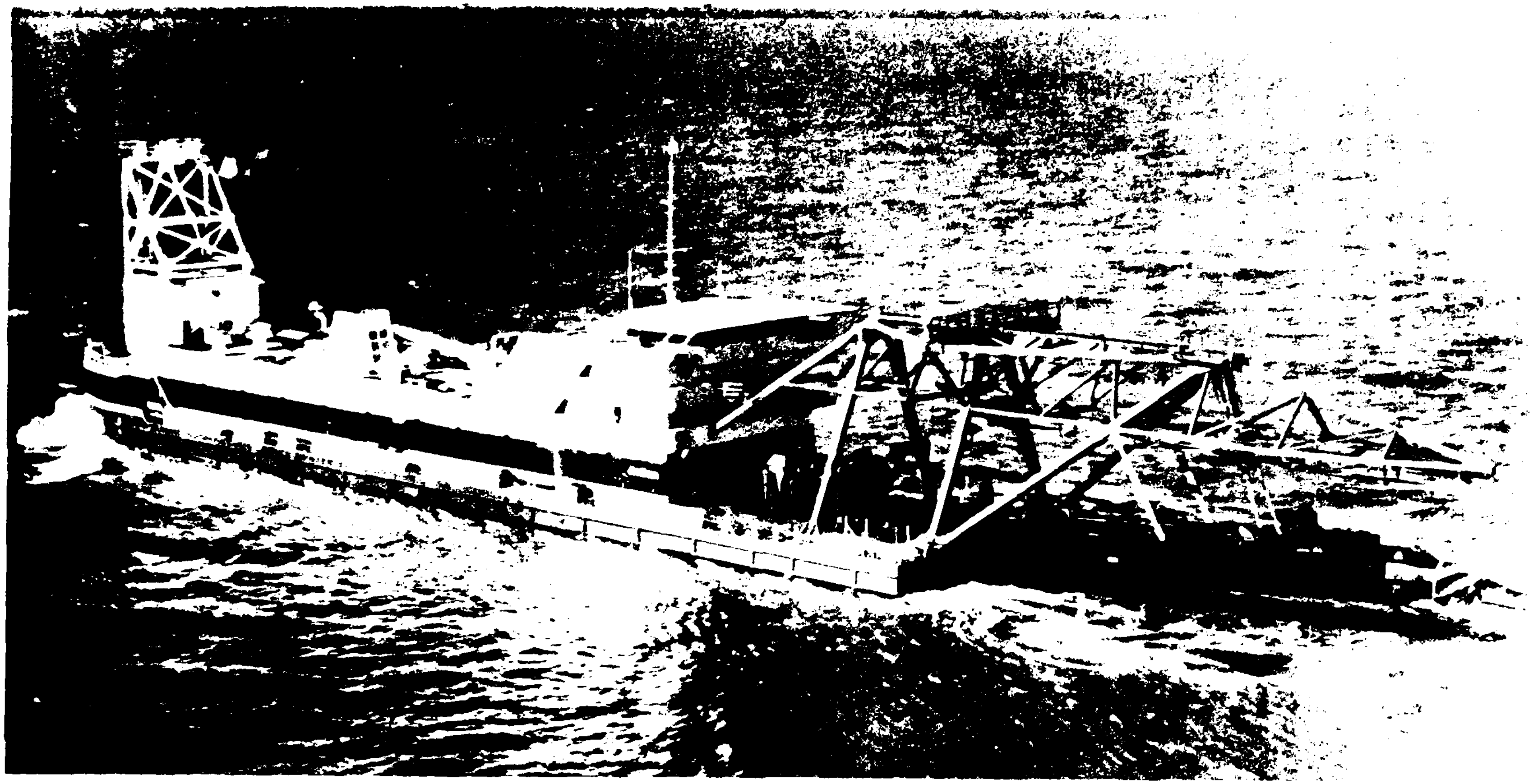


Figure 28   Cutterhead dredge

<u>Independent Equipment</u> Hopper dredges (Figure 29) are the most common among independent equipment. As they are not fixed relative to the channel bottom, they have no fixed point of reference for determining the accuracy of operations. The head attached to the suction pipe (Figure 30) acts very much like the household vacuum cleaner, with the exception that the hopper dredge drags its suction head ("draghead") while the cutterhead is pushed forward in dredging operations. Unlike the cutter suction dredge, the hopper dredge removes a very thin layer of the bottom material as it dredges. It must therefore traverse the area to be dredged many times before the channel is substantially deepened. Electronic positioning and track plotters are used to indicate those areas that have been traversed. Continued surveys are required to assist the operator in controlling the dredging operation. Occasional passes outside the dredging area or in areas that have already been dredged entail very little damage or lost effort because only 2 or 3 vertical inches of material are removed.

The accuracy of hopper dredges is much more dependent on the physical shape and dimension of the area to be dredged than that of the fixed dredges, which can more precisely control their location. The accuracy that can be achieved also depends on the type of soil encountered.

Another example of independent dredges is the dustpan dredge (Figure 31), which propels itself by cables attached to anchors, using propulsion devices to aid steering. This dredge, like a cutter suction dredge, excavates a substantial depth of material at one time. It therefore moves much more slowly, and because of the anchoring system, has much better control of its horizontal position. It relies very heavily on electronic positioning. The vertical control of the dustpan is such that accuracy within 1 ft (0.3 m) can be achieved and horizontal control within 3 ft (0.9 m).

<u>Type of Bottom</u> The accuracy of the dredging process is affected by a change in the material encountered. Cohesive or hard soils lead to the development of trenches. Different materials may dictate the dredging method. Certain hard materials such as sandstone or limestone cannot be dredged with hopper dredges or dustpan dredges, since these types of dredges generally require the material to be loose and free-flowing. Such hard materials can be dredged with a cutterhead dredge.

<u>To Achieve Design Prism</u> Again, the accuracy of the equipment remains unchanged, but the quantity of no-pay material dredged to ensure achieving the design prism can vary significantly. Dredging narrow shoals adjacent to the slope with a hopper may result in dredging 200 to 300 percent of the pay quantity. Rock often must be cut 3 ft to 4 ft (0.9 m to 1.2 m) below grade to preclude strikes during a bar survey.

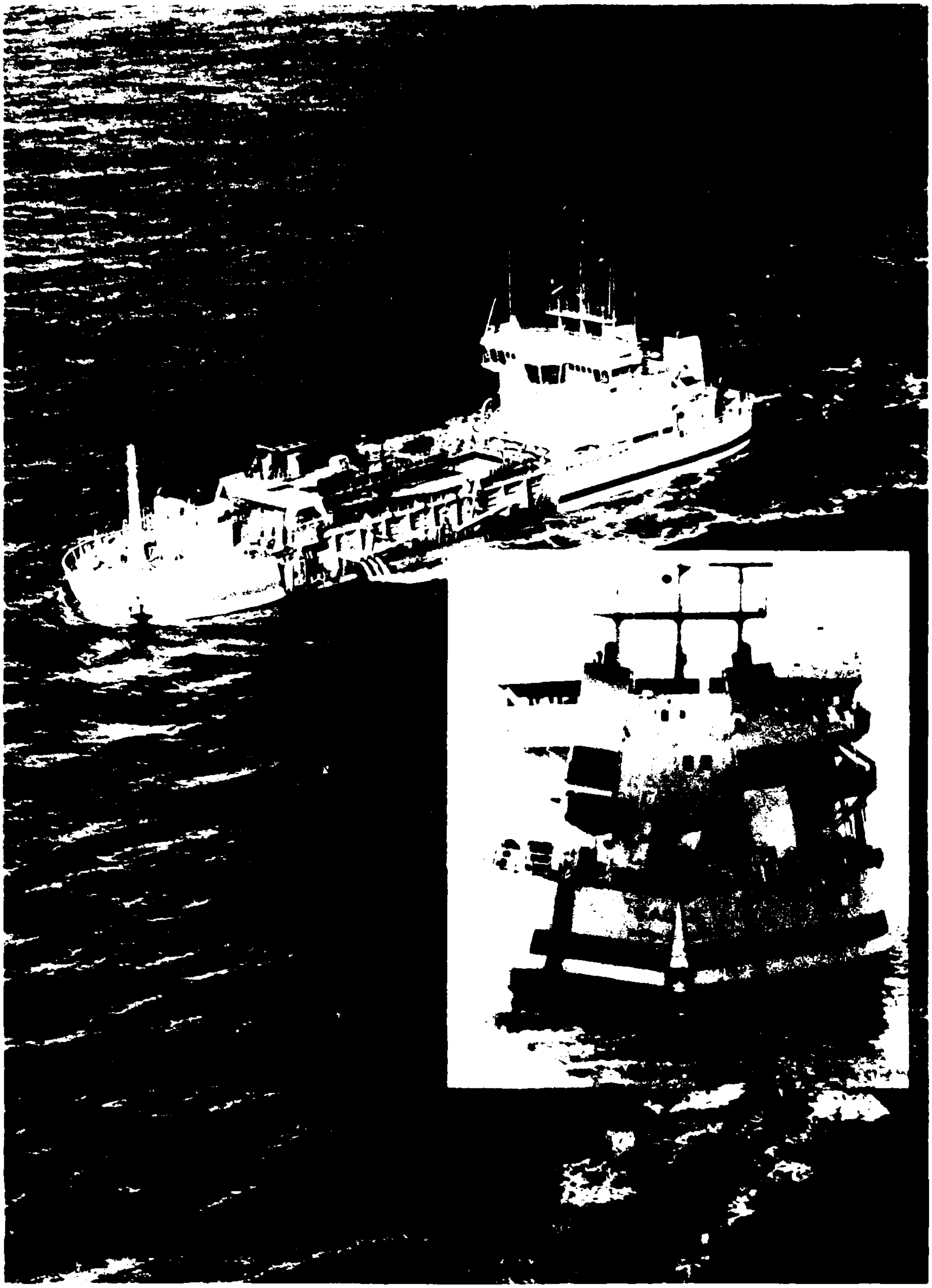


Figure [illegible]. Split-hull seagoing hopper dredge (inset shows split hull open to discharge dredged material)

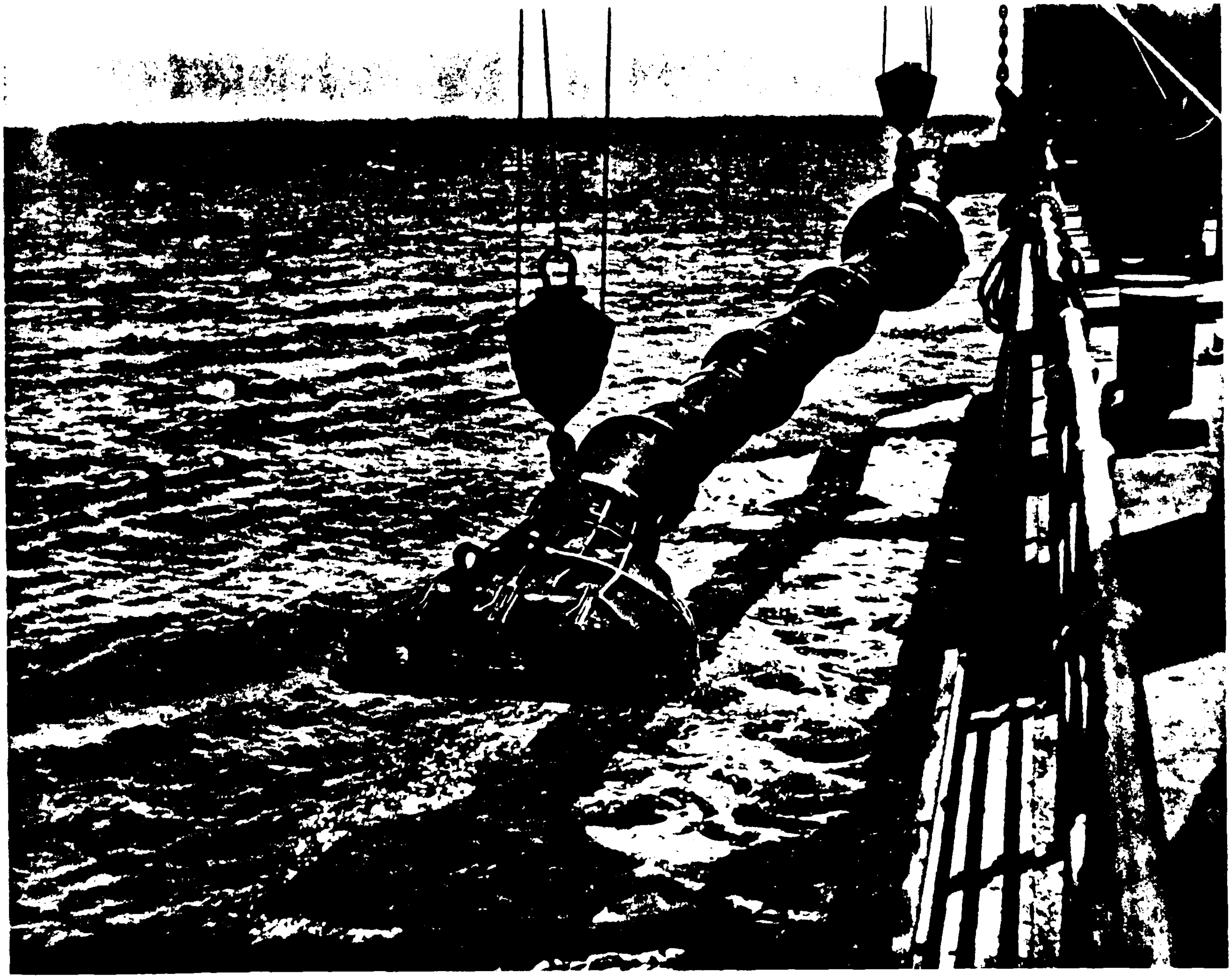


Figure 30. Draghead, hopper dredge

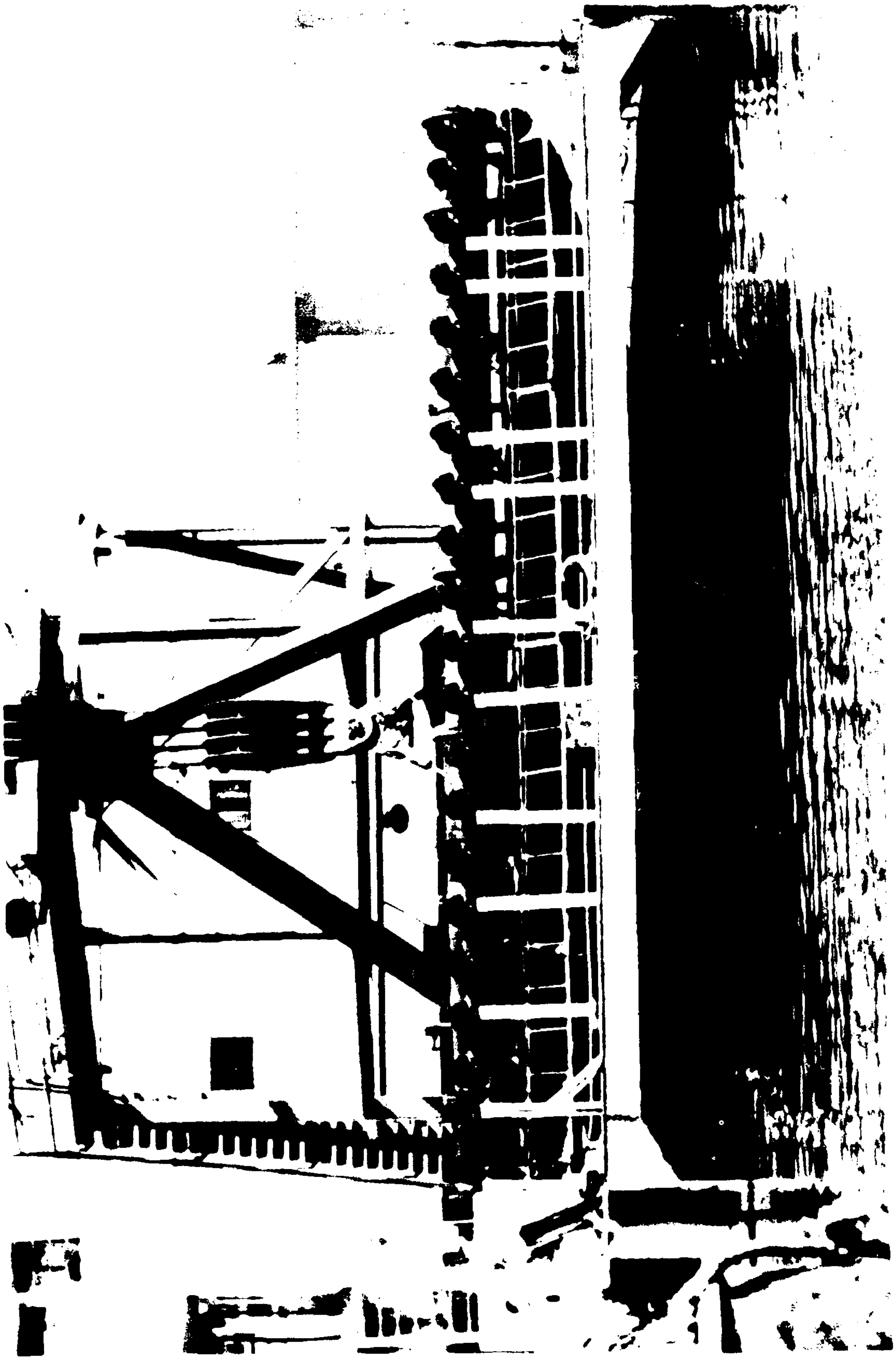


Figure 31 Hydraulic jets of dustpan dredge

Environmental Conditions. Landlocked channels present fewer problems than open channels for controlling the dredging process and for pre- and post-dredging surveys. Exposed waters allow less control of both operations. Tides, especially those of some magnitude, affect dredging and surveying, particularly if the gauge is far from the site. (See Chapter [illegible] under "Definition of Water Level.")

Where the location of the tide-gauge station is known to be unrepresentative of the dredging site, significant "no-pay" overdepths may be dredged to ensure that the required depths will be measured in the postdredging survey.

Currents have a marked effect on hopper dredge accuracy, influencing not only the movement of the ship, but the attitude of the ship in relation to the current.

New Work versus Maintenance. The accuracy of dredging is little affected by the change from new work to maintenance. However, there may be substantial variations in the no-pay yardage, depending on the type of material, side slopes, previous dredging, consistency of the material in the cut, and [illegible] material, and other variables.

Examples of Accuracy of Dredging Operations

Cutterhead Dredge. A typical section of maintenance dredging by a cutterhead dredge is shown in Figure 32. A channel such as the one shown is dredged in two passes. How the maintenance dredging is accomplished depends principally on how the original channel was dredged, the type of soil encountered within design depth (silt or sand), and the virgin material encountered just below grade. If the channel was previously well overdredged, then maintenance dredging will be easy. This is shown clearly in the cross-section, particularly on the right side (300 ft to 500 ft) of the channel. Here the maximum swing speed of the dredge is the limiting factor for production, owing to the low bank, so if no hard (virgin) material is encountered, the total pay quantity can be removed with dispatch. The channel is dredged too widely on the right side because of the previous overdredging. Almost all maintenance material must be removed to achieve grade in the corners (toes) of the cut, as can be seen on the left side, where higher banks were encountered and where the virgin slope is closer to the required prism.

New Work in Protected Waters. Figure 33 shows a typical section for new work in protected waters performed by a cutterhead dredge. Positioning was very accurate; stakes could be set out because there was no traffic, and the water was calm and shallow. The soil consisted mainly of soft to medium clays, which is ideal for cutting slopes, as can be seen in the cross-section. However, the channel is overdug on one side, owing to the inaccuracy of width indication and spud position. No electronic positioning system was used on this dredge, but the cross-section indicates very accurate dredging to the required depth, which can be attributed to good tidal information and (in this case) small tidal differences.

Figure 32 Sample maintenance dredging work by cutterhead dredge

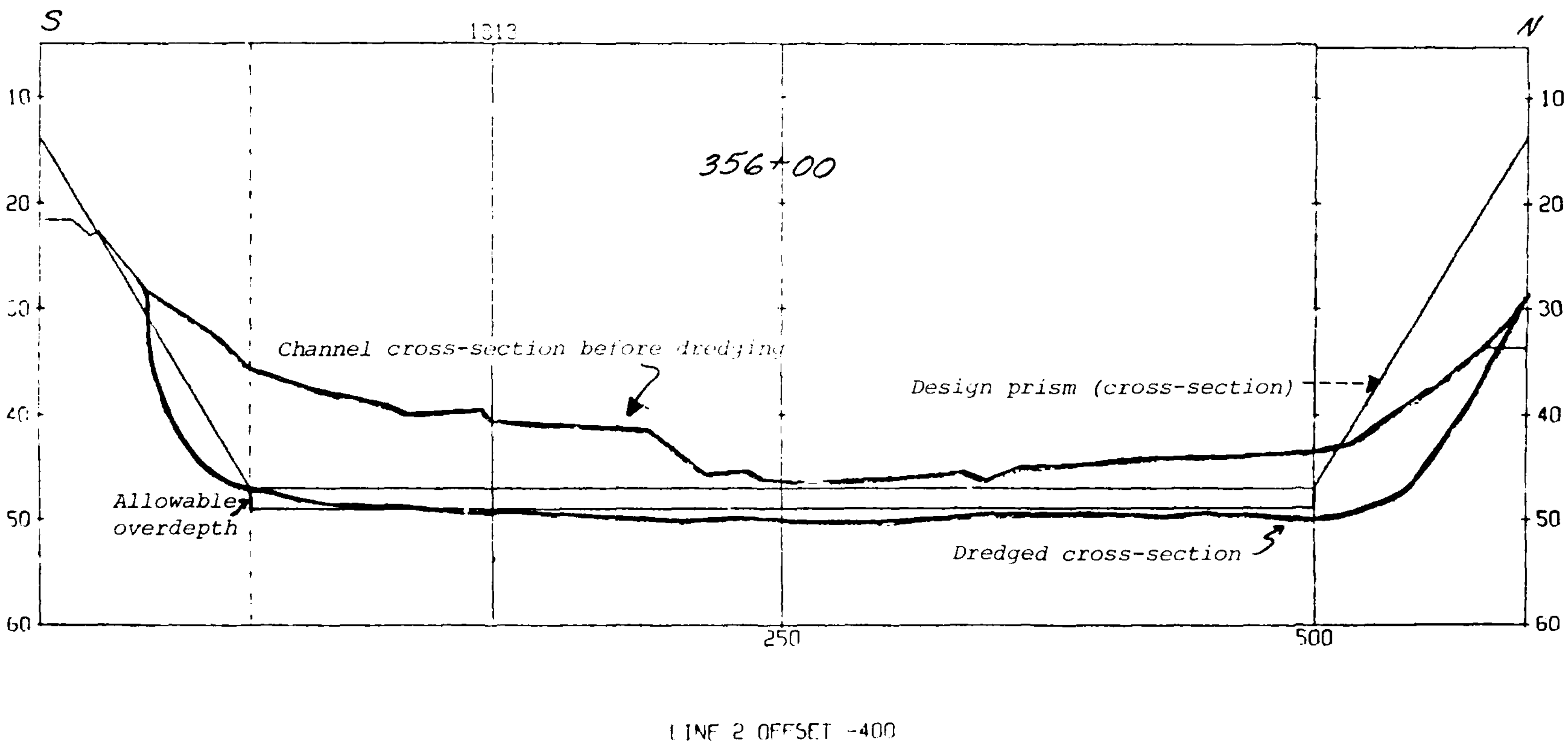


Figure 33   Sample new work in protected waters, cutterhead dredge

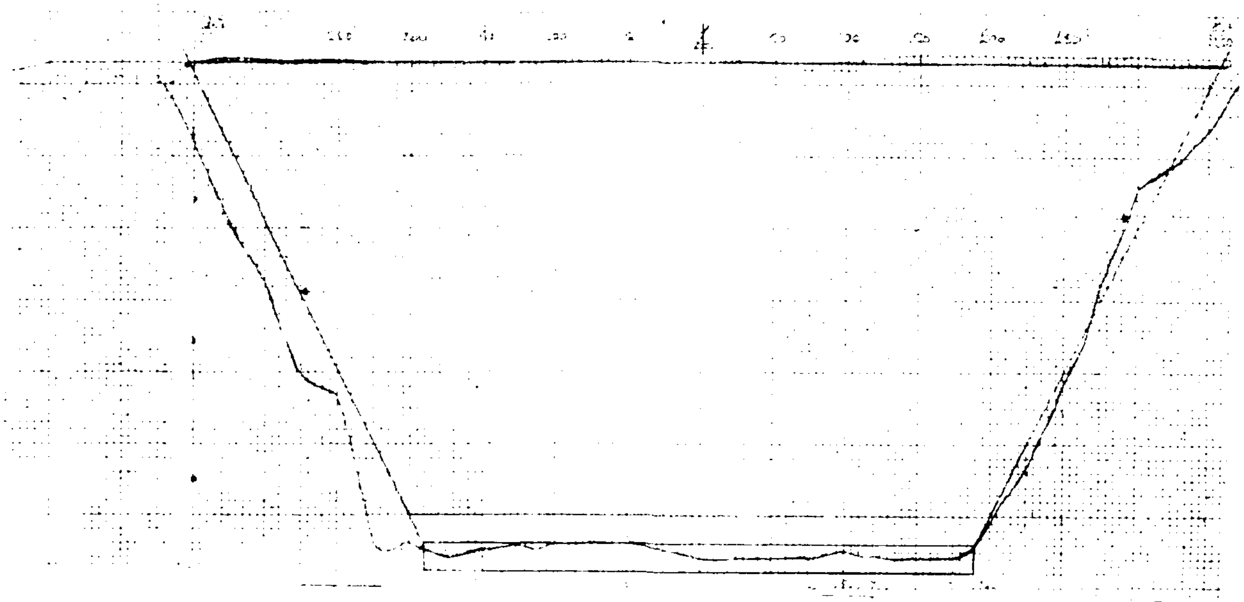
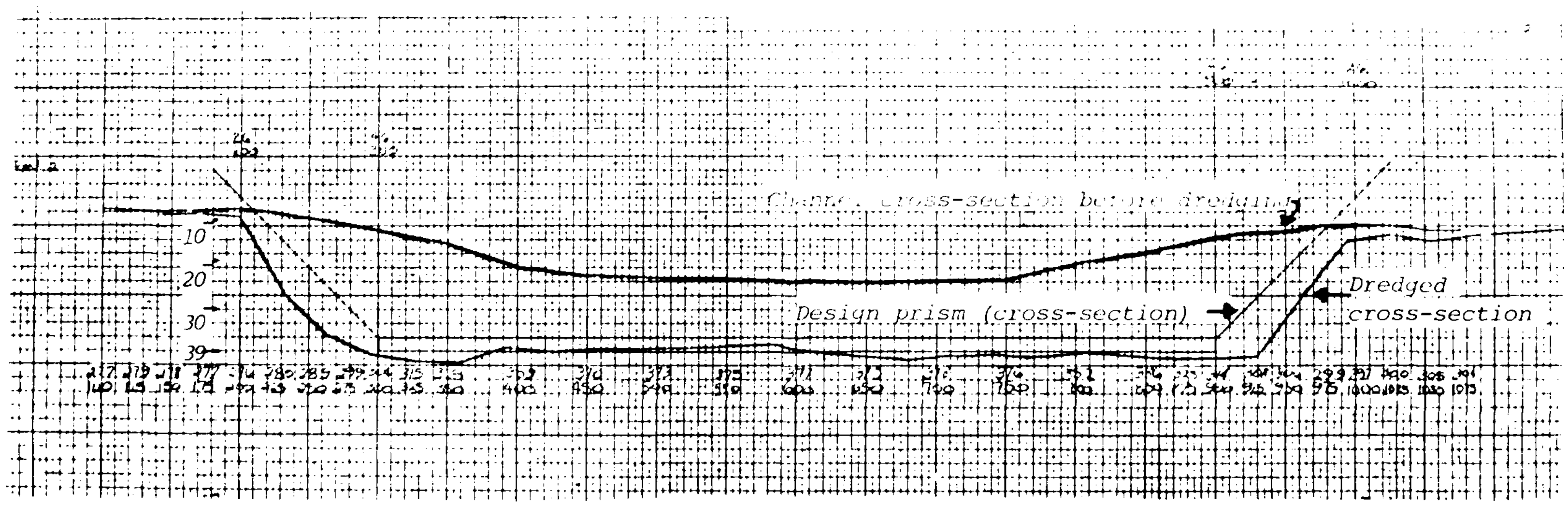


Figure 34 Offshore work in open ocean



New Work in Unprotected Waters The cross-section pictured in Figure 34 is for a hydraulic dredging project 10 miles (16 km) offshore. Use of an electronic positioning system was essential to this project, but accuracy can vary between 7 ft and 50 ft (2.1 m and 15.2 m). This explains why the channel is overexcavated on both sides. Depth control is very difficult in open waters, owing to the movement of the dredge hull and consequent problems controlling the position of the draghead.

Maintenance Work in Sand and Silty Sand The irregular bottom made by a hopper dredge in progress is illustrated in Figure 35. For width accuracy, the dredger relies on electronic positioning and thus experiences the problems noted for cutter dredges. Moreover, this type of dredge is free-sailing, which necessitates maneuvering the ship while dredging. Assuming that experienced personnel are operating the dredge, the important factors in control of the ship are currents (especially crosscurrents), winds, and swells, as these factors influence position. Another factor important to accurate work with a hopper dredge is frequent surveying, as a hopper dredge gradually brings a large area to the required depth.

Maintenance Work in Silt and Soft Clay If the material is soft, overdredging is likely, as is shown in the cross-section of Figure 36. Soft clay was encountered in the corners, which is much more difficult to remove with a hopper dredge than with other types of dredges.

Implications

The overdredged depths actually left by dredging are likely to be greater than those allowed by the pay overdepth specified. Estimates compiled by Lacasse (1981) of overdredging to achieve design prism indicate it may represent 10 percent to 15 percent of total volumes dredged. As implied by the examples, the pay overdepth specified is an incentive to dredging accuracy. Although each case will be different, accurate pre- and post-dredging surveys may yield multiple benefits--better depth information for navigation, for example, and increasingly precise pay-overdepth specifications.

Figure 35   Maintenance dredging in sand and silty sand

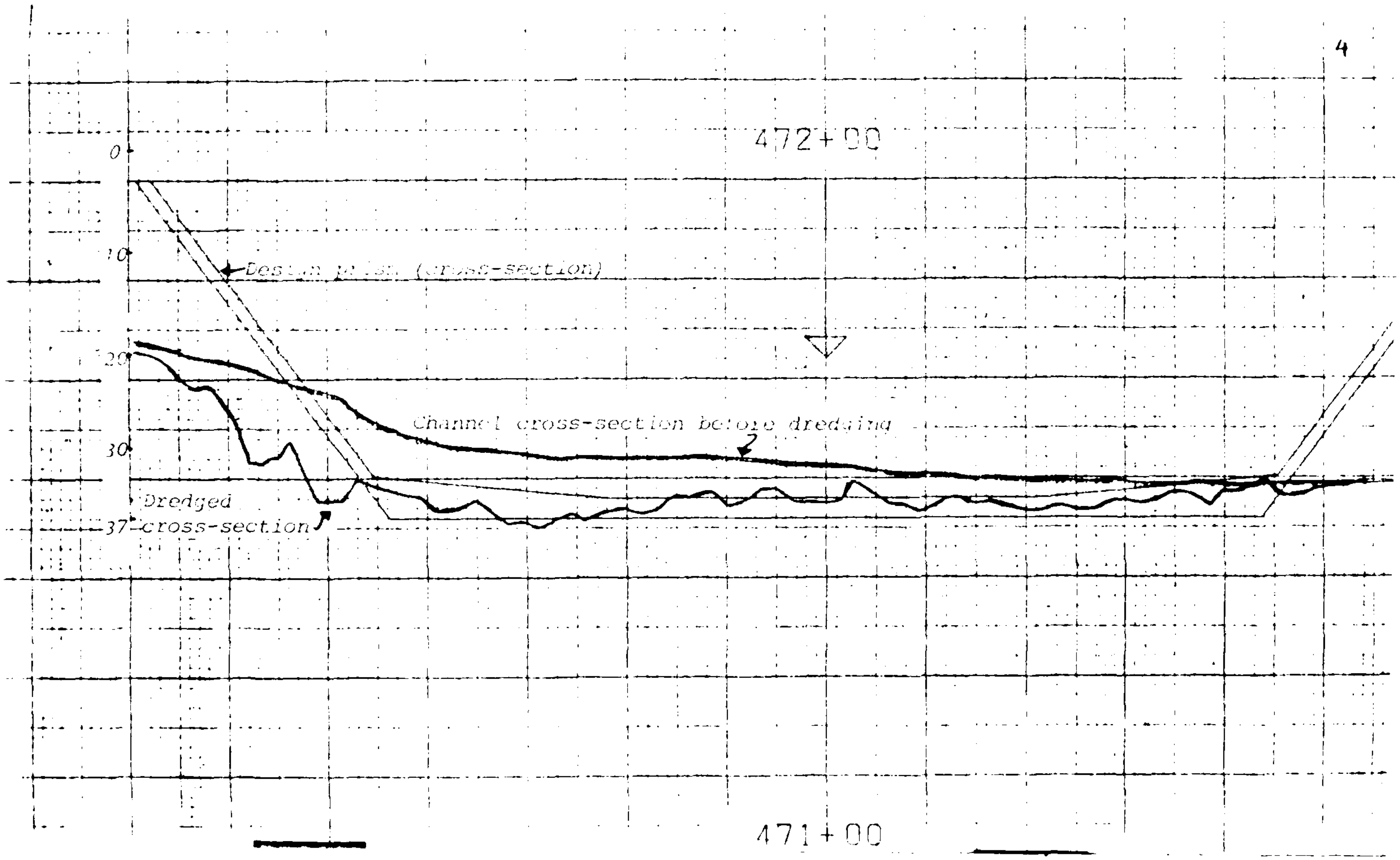
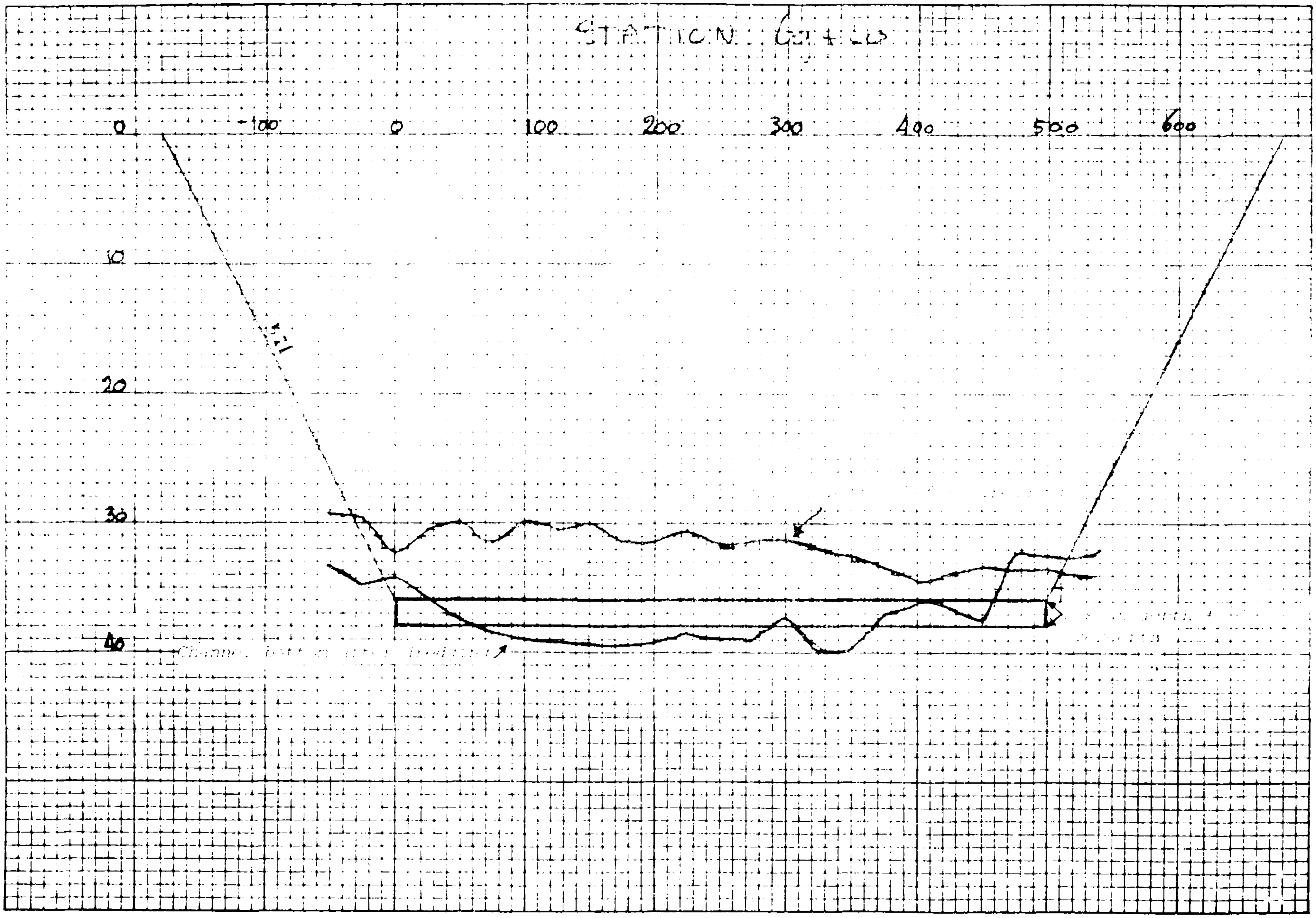


Figure 36 Maintenance dredging in silt and soft clay



4

EVALUATING THE ADEQUACY OF CRITERIA FOR DREDGED DEPTHS OF NAVIGATIONAL CHANNELS

In the course of assessing the criteria used in the United States for determining the depth of dredged navigational channels serving major ports and harbors, the panel requested information about the criteria used in other countries from two international organizations--the Permanent International Association of Navigation Congresses (PIANC) and the International Association of Ports and Harbors (IAPH)--and from several maritime countries. Shippers were also consulted for criteria respecting underkeel clearance.

The panel tested the adequacy of existing depths in the United States by taking as input to a mathematical model (developed to provide a check of channel design) the dimensions of nine representative channels of the East, Gulf, and West coasts.

The results of the simulation are presented in the succeeding section, followed by the criteria of international organizations, foreign maritime countries, and shippers.

Dredged Depths of Navigational Channels in the United States

Navigation

The criteria used to design the depths of navigational channels in the United States are described in Chapter 2, "Regulatory and Institutional Considerations." For the major channels of the United States, the pertinence of the design ships used for the original determination may have long since been superseded by the characteristics of the ships using the channels. The panel therefore tested the dimensions of nine major channels of the United States on three coasts (supplied by the U.S. Army Corps of Engineers) with passages of existing ships in a computer simulation. The computer model (described in Appendix D) is a simple technique for testing various channel designs. For each channel, the analysis was carried out using existing dimensions and using a hypothetical future depth of 60 ft. In addition, selected increments of depth for the Galveston Ship Channel were considered. The results for existing depths are set out in Table 9, and those for hypothetically deepened channels in Table 10.

For each of the analyses performed, the model evaluated specific parameters resulting from the passage of the specified vessel(s) through a specified section of the channel. These parameters serve as the basis for governing vessel operations in the channel. It is essential to note that all calculations included the effects of a 1.5 kn current and a 30 mph wind, both acting perpendicular to the vessel(s). Speed limits were supplied by the U.S. Coast Guard. Speed limits are not specified for many channels, and the following estimates were made for the purpose of squat and other computations:

Channel	Speed Limit Assumed
1. Oakland Harbor	5 kn
2. Columbia River	6 kn
3. Chesapeake and Delaware Canal	6 kn
4. Calcasieu River	6 kn

From the panel's observations and briefings during field trips, the assumptions--including the design ships--are conservative. Even so, the underkeel clearances of the ships considered are well below the minimums specified by the Corps' criteria, squat (+3 ft, or 0.9 m) + rolling and pitching estimate + clearance (2 ft, or 0.6 m, soft bottom; 3 ft, or 0.9 m, rocky or hard bottom). Although the rule of thumb is generous in squat allowance compared to the panel's results, the speeds assumed by the panel may be low. (Figures in Appendix D show how squat increases with speed for these ships in these channels.)

As indicated in the sections addressing considerations of ships in channels, the maximum vertical excursion of a ship, and the part of the ship that experiences it, is sensitive to many factors. It is clear from the results of the simulation, for example, that the amount of squat changes for the same ship in different channels of the same depth. The tanker Lenino experiences squat of 2.4 ft (0.7 m) in the Lower Columbia River Channel (40 ft, or 12.1 m, deep), but only 0.9 ft (0.3 m) in the inner Calcasieu River Channel (also 40 ft, or 12.1 m, deep), even assuming the same ship speed, current velocity, and wind. Changes in speed, traffic (passing or overtaking), and the physical environment will also affect the underkeel clearance actually available to these ships in passage through the selected channels.

Table 9 Analysis for existing channel depths

Channel (Width) ft	Depth (ft)	Ship	Length	Beam	Draft	Speed Limit (knots)	Squat In (ft)	Squat Out (ft)	Bank Suction (ft tons)	Vessel Attitude: Total Force (tons)	Vessel Attitude: Drift (deg)	Vessel Attitude: Rudder (deg)	Ship-generated Wave Height (ft)
Calcasieu River Inner Channel (400)	40	LENINO	683.1'	89.3'	36.4'	6.0	0.9	0.8	-------	82.6	11.3	1.0	1.2
Outer Channel (800)	42	CHEVRON OREGON	[illegible]	96.2'	37.3'	6.0	1.2	1.0	1075	81.6	6.4	3.0	1.1
Lower Columbia River (600)	40	LENINO	683.1'	89.3'	36.4'	6.0	2.4	0.9	3600	14.4	2.0	10.0	1.1
Delaware River (800)	42	CHEVRON OREGON	625'	[illegible]	37.3'	6.0	0.6	1.4	260	47.7	5.3	1.0	1.1
Mobile Harbor (600)	42	CHEVRON OREGON	625'	96.2'	37.3'	5.0	0.9	0.8	-2550	77.0	8.8	13.0	0.9
Norfolk Harbor (800' section)	45	CHRISTOS BITAS	731.7'	102.5'	40'	5.0	0.8	0.75	-5000	89.7	11.4	26.0	0.75
(1500' section)	45	CHRISTOS BITAS	731.7'	102.5'	40'	6.0	0.5	0.95	Small Effect	83.8	6.5	17.0	0.95
Oakland Harbor (800)	35	BEREZOVO	485.6'	75.5'	30.2'	5.0	1.0	0.8	------	4.3	5.3	1.0	0.6
San Francisco Bay (2000)	55	CONOCO BRITANNIA	848.3'	138'	50.1'	5.0	0.2	0.8	------	16.9	30.3	1.0	0.8
Thimble Shoal (1000)	45	CHRISTOS BITAS	731.7'	102.5'	40'	6.0	1.2	0.5	------	9.4	4.3	1.0	1.05
Galveston Channel Section 6-6 (800)	40	LENINO	683.1'	89.3'	36.4'	5.0	1.2	0.3	------	-0.6	-0.4	-1.0	0.65
Section 8-8 (1020)	50	EUROPRIORITY	767.8'	124.9'	45.1'	5.0	1.3	0.5	------	62.9	3.7	0.0	0.85

Table 10 Analysis for channels deepened to 60 ft., except Galveston

Channel All deepened to 60'	Ship	Length	Beam	Draft	Speed Limit (knots)	Squat In (ft)	Squat Out (ft)	Bank Suction (ft tons)	Vessel Attitude: Total Force (tons)	Vessel Attitude: Drift (deg)	Vessel Attitude: Rudder (deg)	Ship-generated Wave Height (ft)
Calcasieu River												
Inner Channel	CONCORDIA	836.6'	135.8'	55.1'	6.0	1.5	1.2	0	108.9	5.6	27.0	1.9
Outer Channel	CONCORDIA	836.6'	135.8'	55.1'	6.0	1.9	1.5	90000	142.5	6.0	11.0	1.5
Lower Columbia River	CONCORDIA	836.6'	135.8'	55.1'	6.0	4.5	1.5	78727	-188.6	0.0		1.7
Delaware River	CONCORDIA	836.6'	135.8'	55.1'	6.0	0.9	2.0	39000	84.4	5.4	7.0	1.5
Mobile Harbor	CONCORDIA	836.6'	135.8'	55.1'	5.0	1.3	1.2	15000	127.8	7.8	27.0	1.1
Norfolk Harbor												
800' Section	CONCORDIA	836.6'	135.8'	55.1'	5.0	1.2	1.0	15000	127.3	8.8	31.0	1.0
1500' Section	CONCORDIA	836.6'	135.8'	55.1'	5.0	0.7	0.8		111.8	5.4	24.0	1.2
Oakland Harbor	CONCORDIA	836.6'	135.8'	55.1'	5.0	3.0	0.8	18000	-34.5	0.0	24.0	1.2
San Francisco Bar	CONCORDIA	836.6'	135.8'	55.1'	5.0	0.2	0.7	Outside Range	18.4	31.0	1.0	0.8
Thimble Shoal	CONCORDIA	836.6'	135.8'	55.1'	6.0	2.0	0.7	3100	5.7	0.0	2.0	1.4
Galveston[a]												
Section 6-6 (45')	CHRISTOS BITAS	731.7'	102.5'	40'	5.0	1.2	0.3	20.5	-0.9	0.0	0.0	0.7
Section 6-6 (50')	EUROPRIORITY	767.8'	124.9'	45.1'	5.0	1.4	0.4	185	-1.6	0.0	0.0	0.85
Section 6-6 (55')	CONOCO BRITANNIA	848.3'	138'	50.1'	5.0	1.1	0.3	680	-3.2	-0.1	2.0	0.9
Section 6-6 (60')	CONCORDIA	836.6'	135.8'	55.1'	5.0	1.2	0.3	------	-1.3	0.0	0.0	0.9
Section 8-8 (55')	CONOCO BRITANNIA	848.3'	138'	50.1'	5.0	1.3	0.5	------	76.7	3.7	0.0	0.9
Section 8-8 (60')	CONCORDIA	836.6'	135.8'	55.1'	5.0	1.1	0.4	------	18.1	1.0	2.0	0.9

[a] Analysis for new authorized depths and theoretical deepening to 60' by channel segment

Overdredged Depths

Many local conditions affect the accuracy of dredging processes, and the range of various kinds of dredging equipment is not precisely known. Nevertheless, the evidence cited in this report ("Dredging" in Chapter 3) suggests that the "plus 2 ft" rule of thumb (actually 0 ft to 8 ft, or 0 m to 2.4 m; but generally 2 ft, or 0.6 m) allowed by the Corps to achieve the design prism is within the order of dredging accuracy but may need to be adjusted in particular channel sections or for certain types of work.

For advance maintenance overdredging, the procedures outlined by Trawle (1981b) and described in Chapter 2, "Regulatory and Institutional Considerations," offer appropriate guidance for shoaling analysis and progressive improvement in estimation through frequent surveys. Frequent surveys may also yield needed information to adjust the "plus 2 ft" pay-overdepth specification.

Criteria of International Organizations, Other Maritime Countries, Shippers

Criteria of International Organizations

PIANC Criteria In 1974, the Permanent International Association of Navigation Congresses (PIANC) sponsored an International Commission for the Reception of Large Ships (ICORELS). Working Group IV was charged with the optimal layout and dimensions for large ships in shallow waterways. Group IV published a final report (ICORELS, 1980) designed to establish criteria to regulate the problem of navigation of large ships in shallow seas and sea straits (e.g., North Sea, Baltic Sea, Straits of Dover, Straits of Malacca). In this report, PIANC gives advice about technical aspects of the possible works to be undertaken, such as the dimensions of dredged channels, navigational aids, wreck removal, and evaluation of safety. Approximately 20 countries participated as members of ICORELS.

The report of Working Group IV includes a summary of studies and developments pertinent to various aspects of channel design, navigation in sea straits, and dredging for construction and maintenance, together with conclusions and recommendations in each area. A set of recommendations is given for determining the depth of channels:

> Recommendations The conclusion [section 2.1.1.3] drawn by ICORELS is that it is not possible to state a general rule for minimum underkeel clearances and port approaches and maneuvering areas, because of the influence of local conditions, currents, and swell. The Commission does note that general criteria for gross underkeel clearances [section 2.2.2.8] can be given for drawing up preliminary plans:

Open sea area-When exposed to strong and long stern or quarter swells where speed may be high, the gross underkeel clearance should be about 20 percent of the maximum draft of the large ships to be received.

Waiting area-When exposed to strong or long swells, the gross underkeel clearance should be about 15 percent of the draft.

Channel-Sections exposed to long swells, the gross underkeel clearance should be about 15 percent of the draft.

Maneuvering and berthing areas-Protected gross underkeel clearance to be about 7 percent of the draft. [Figure 37] shows the definition of underkeel clearances used by the Commission in their recommendations and are described as follows (section [illegible].2.4):

THE GROSS UNDERKEEL CLEARANCE is by definition the margin between the keel of a vessel and the nominal channel bed level, considering the water reference level during its passage and the [illegible] of the vessel, measured at rest in calm water.

THE NET UNDERKEEL CLEARANCE is by definition the minimum margin remaining between the keel of the vessel and the nominal channel bed level, [illegible] at planned speed under the [illegible] wind and wave conditions [illegible] operational limit conditions).

The net underkeel clearance, which should be at least 0.5 m (1.7 ft), has to be assessed as a safety margin against striking the bottom. Other factors are also involved--types and sizes of ships, commodities transported, environmental consequences, and density of traffic.

Summary The recommendations of the Commission are for gross underkeel clearances in restricted channels of approximately 15 percent, a factor that allows for the admissible draft of the ship plus its vertical motions due to swells, squat, due to speed, and net underkeel clearance. Further tolerances are added to this nominal channel bed level to allow for sounding accuracy, sedimentation deposits between two dredging campaigns, and tolerances for dredging, to produce the final channel dredged level.

IAPH Criteria The International Association of Ports and Harbors (IAPH) also assembled a Committee on Large Ships (COLS), now the Committee on Port Safety, Environment, and Construction. In the section "Depth of Entrance Channel," COLS (1981) cross-references

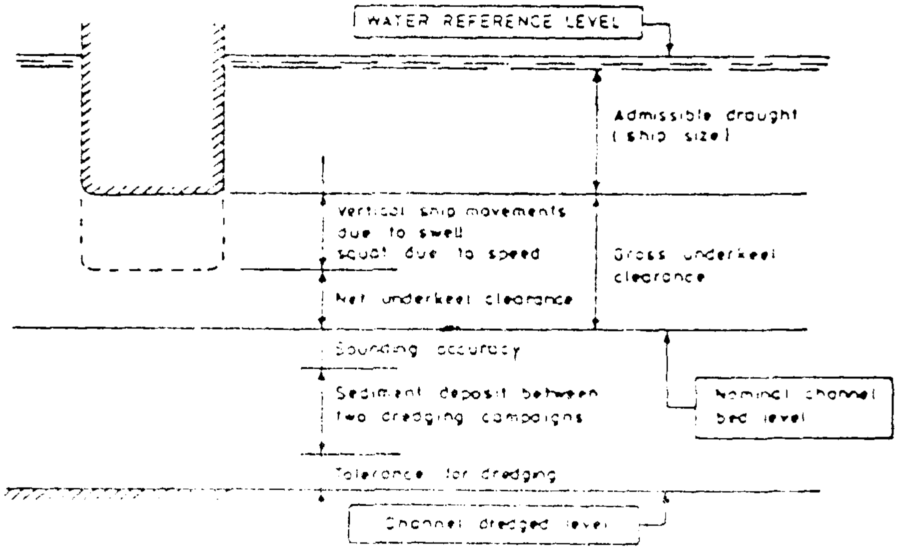


Figure 37 Underkeel clearances as defined by PIANC[a]*

[a]Permanent International Association of Navigation Congresses

*SOURCE: [illegible] (1981), Guidelines for Safety and Environmental Protection in Ports and Harbors (Tokyo: International Association of Ports and Harbors).

AD-A135 628 CRITERIA FOR THE DEPTHS OF DREDGED NAVIGATIONAL CHANNELS(U) NATIONAL RESEARCH COUNCIL WASHINGTON DC MARINE BOARD MAY 83 N00014-82-G-0032

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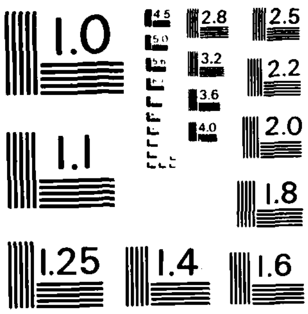


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

the ICORELS recommendations:

5.3.1.2.1 The depths of entrance channels are determined by allowing a minimum margin between the lowest point on the keel of the vessel and the channel bed (underkeel clearance) in addition to the draught of the design vessel. There are two types of underkeel clearance, one gross and the other net:

Gross underkeel clearance is the margin remaining under the keel when the ship is motionless in quiet waters and net underkeel clearance is the margin which continues to exist under the keel when a vessel moves at a scheduled speed and when it undergoes the expected maximum influence of swell and wind.

The net underkeel clearance must be at least equal to 0.5 m (1.7 ft) for a sandy seabed and 1.0 m [3.5 ft] when it is rocky.

5.3.1.2.2 The minimum value of the gross underkeel clearance taken, consistent with compliance with the lowest value of the net underkeel clearance, depends upon the following factors:

- Factors related to channel bed;
  *the level of the channel bed below chart data,
  *the allowance made for the degree of accuracy in hydrographic surveys (chart data) and dredging tolerances,
  *the incidence and degree of channel silting between maintenance dredgings and dredging tolerances,
  *the latest maintenance soundings and
  *the eventual percentage of suspended silt.
- Factors related to tide;
  *tidal variations (maximum and minimum),
  *tables of predicted tide levels,
  *details of any tidal surges, wind and atmospheric pressure effects on water level and
  *the accuracy of predicted tidal heights and the predicted times of high and low water (for particular tides).
- Factors related to the ship;
  *the actual maximum draught of the design ship,
  *the increase in effective draught due to the rolling, pitching and heaving of the ship under wave action within the channel,
  *the estimated squat and change of trim for the design ship calculated for each critical depth area based on the maximum permissible operating ship speed and the most constricted channel section within the critical depth area,
  *the normal loaded condition of the design ship and
  *the draught and trim changes attributed to any change in water density.

5.3.1.2.3 It is not possible to establish accurate rules concerning the minimum depth of port channels because of the major importance of local conditions.

In the initial planning stages, the following generalizations may be valuable:

- sections exposed to strong and long swell - gross underkeel clearance to be about 15 percent of the maximum draught,

- sections less exposed to swell--gross underkeel clearance to be about 10 percent of the maximum draught.

5.3.1.2.4 Detailed recommendations for the depth of channels are given in ICORELS Report of PIANC (Working Group No. IV)....

In order to define the nominal level of dredging, it would be advisable to allow for the accuracy of the soundings, for siltation between maintenance dredging and for dredging tolerances.

Criteria Used in Other Maritime Countries

Canadian Criteria for Underkeel Clearance Canada's design criteria for channel depth primarily address the need for precise and reliable measurement of the environmental risks associated with the location and operation of marine terminals, particularly those for large oil tankers. They can be found in the "TERMPOL" Code of Recommended Standards (Canadian Coast Guard, 1977). The Ministry of Transportation, through the Canadian Coast Guard, established the code (TERMPOL) in coordination with other departments.

The TERMPOL code is a set of recommended standards used in Canada for the prevention of pollution in marine terminal systems. The code outlines acceptable ship terminal standards, defines the required ship terminal system analysis and assessment criteria, and sets out operating practices and procedures for ship terminals.

Although published by the Canadian Coast Guard, the TERMPOL code is a coordination and correlation of the separate requirements of the Canadian Department of Fisheries and the Environment, Public Works, Industrial Trade and Commerce, and Regional and Economic Expansion. Each participating department is individually responsible for all contributions made and decisions taken within its area of responsibility.

Provisions of the code are not themselves mandatory, but the assessment criteria of the code are used by the Ships Safety Branch of the Canadian Coast Guard to determine the technical needs, if any, for making regulations or implementing special precautionary measures to limit navigation within the ship terminal system under review.

The "TERMPOL" Coordinating Committee (T.C.C.), composed of representatives of the participating government departments, performs the assessment and can require terminal planners to submit data for environmental impact assessment.

Port authorities seeking to improve their waterways may be called upon by the TERMPOL Assessment Committee to provide the following surveys:

- o Origination and Destination Survey;
- o Transit Time and Delay Survey;
- o Marine Traffic Volume Survey;
- o Fishing Vessel Operation Survey;
- o Approach Characteristics and Navigability Survey;
- o Special Underkeel Clearance Survey;
- o Site Plans/Technical Data;
- o Environmental Studies.

Thus, the Canadians use a systems approach in which the specification of underkeel clearance is integrated with studies of marine traffic and required navigability.

For the purposes of this report, the study of direct interest is the Special Underkeel Clearance Survey. The requirements are as follows: Nominally, the design ship's minimum underkeel clearance should be 15 percent of her maximum permissible draft. A proposal for a minimum underkeel clearance in approach channels of less than 15 percent of the design ship's deepest draft will be considered but should be supported by explicit details or calculations for each of the following factors:

o Minimum chart datum measurements supplemented with tidal heights over a specified period;

o Accuracy of predicted tidal heights and the predicted times of high water and low water;

o Details of any tidal surges and wind setup;

o Allowances for the degree of accuracy in the hydrographic survey (chart datum) and for that of dredging processes;

o Incidence and degree of channel silting between maintenance dredgings and the identification of all critical depth areas;

o Increase in effective draft due to the rolling, pitching, and heaving of the ship under wave action within the ship channel;

o Estimated squat for the design ship calculated for each critical depth area based on the maximum permissible operating ship speed and the most constricted channel section within the critical depth area;

o Nominal trim and changes of trim experienced by the design ship;

o Draft and trim changes attributed to any changes in water density;

o Climatological and related depth anomalies; and

o Nature of the bottom (rock, sand, mud, etc.).

Underkeel Clearance and Depth Criteria in Japan The Japanese Ministry of Transport has established its criteria for marine facilities through joint action of its Bureau of Ports and Harbours and its Port and Harbour Research Institute. These are summarized in a booklet entitled "Technical Standards for Port and Harbour Facilities in Japan" published in English in 1980. The Japanese version, published in March 1979, represented the first compilation of all advanced Japanese port and harbor engineering techniques. The English version differs from the Japanese version only in that it excludes the official procedures for compliance with the standards.

The Japanese relate the depth of channels to their basic specification for depth of harbor basins. The design criteria for basin depth, in turn, are (Bureau of Ports and Harbours and Port and Harbour Research Institute, 1980):

DEPTH OF BASIN

1) The depth of basin shall be 1.1 times full load draft of the ship below the datum level, in considering the extent of the oscillatory motion of the ship due to the natural conditions such as waves and tidal currents. However, this provision shall not apply to a basin for outfit of ships and a basin used for special anchorage or mooring of ships. In the case of a basin for ferryboats, the draft difference between stern and bow during cargo handling, should be considered to determine the depth of the basin. Furthermore, where the sea level of a basin may be below the datum level, because the seasonal changes of mean sea level are larger than the tidal level change due to astronomical tide, or where the basin may be attacked by high waves and swells, these influences should be considered.

2) The depth of a basin can be determined in reference to the values given in [Table 11] when the full draft of the ship is not known.

The depth of waterways is related to that of basins as follows:

DEPTH OF WATERWAY

1) The depth of waterway shall be an appropriate value of no less than the full load draft of the ship in consideration of the extent of oscillatory motion of the ship due to the natural condition such as waves, winds, and tidal currents and the trim. In this case, "a proper depth" means a depth obtained by an allowance added to the depths specified in [DEPTH OF BASIN]. The allowance varies with such conditions as roll and pitching, trim and squat of the ship and the conditions of seabed materials. This provision may not apply to a special waterway where the draft of the ships using this

Table 11 Standard depth of basins, Japan*

KIND OF SHIP	DRAFT (M)	SIZE OF SHIP
PASSENGER SHIP		Gross tons (GRT)
	5.0	1,000
	6.0	3,000
	7.5	5,000
	9.0	10,000
	10.0	20,000
	11.0	30,000
GENERAL CARGO SHIP		Deadweight tons (DWT)
	4.5	700
	5.0	1,000
	5.5	2,000
	6.5	3.000
	7.5	5,000
	9.0	10,000
	10.0	15,000
	11.0	20,000
	12.0	30,000
	13.0	40,000
	14.0	50,000

KIND OF SHIP	DRAFT (M)	SIZE OF SHIP (DWT)
OIL TANKER	4.5	700
	5.0	1,000
	5.5	2,000
	6.5	3,000
	7.5	5,000
	9.0	10,000
	10.0	15,000
	11.0	20,000
	12.0	30,000
	13.0	40,000
	14.0	50,000
	15.0	70,000
	16.0	100,000
	20.0	150,000
	21.0	200,000
	22.0	250,000

KIND OF SHIP	DRAFT (M)	SIZE OF SHIP
ORE CARRIER		Deadweight tons (DWT)
	9.0	10,000
	10.0	15,000
	11.0	20,000
	12.0	30,000
	13.0	50,000
	15.0	70,000
	16.0	90,000
	18.0	100,000
	20.0	150,000
FERRYBOAT		Gross tons (GRT)
	5.0	1,000
	5.5	2,000
	6.0	3,000
	6.5	4,000
	7.5	6,000
	8.0	13,000

*SOURCE: Bureau of Ports and Harbours and Port and Harbour Research Institute (Ministry of Transport, Japan) (1980), "Technical Standards for Port and Harbour Facilities in Japan," p. 151.

waterway is always smaller than the full draft, such as an approaching waterway to dock of shipyard or a waterway exclusively for partially loaded ships.

WATERWAY MAINTENANCE

1) The depth and width of a waterway shall be maintained properly for the smooth use of harbour and the safe navigation of ships.

When a waterway is planned on a river mouth or a beach where a big amount of littoral drift is expected, the degree of maintenance dredging required in the future should be forecasted by estimating the rate of sediment transport by a flood or the rate of littoral drift by waves and tidal current.

Presumably, this latter calculation is used for an initial schedule of maintenance dredging or for determining additional depth for advance maintenance dredging.

Channel Depth Criteria, Port of Zeebrugge, Belgium The Belgian approach to channel depth criteria is outlined in a 1980 bulletin of the Permanent International Association of Navigation Congresses.

Waters of the Belgian coast experience dense marine traffic. As a result, traffic has been channeled into compulsory routes. One of the main routes through the North Sea arrives at the frontier of France and Belgium approximately 16 miles off the coast, then runs east/northeast to the "Scheur," which is the access channel to the River Scheldt estuary and the Port of Zeebrugge. The channel continues to its terminus at Antwerp.

In 1970, the Belgian government decided to extend the port of Zeebrugge, using a sea lock to connect the inner port with the sea (Simoen, 1980). The seaward extension was to accommodate vessels up to 125,000 DWT and, specifically, to accommodate roll-on, roll-off (RO-RO) cargo vessels and containerships. The port will also have an LNG terminal. Since the projected traffic involved large vessels with drafts of 50 ft or more, the Administration of Waterways, Ministry of Public Works, initiated a study of needed channel dimensions.

The study plan included a preliminary phase to define the design criteria and to choose the channel route. More detailed studies were then made for the design of the chosen channel route which included the determination of the channel cross-section profile, various studies of sedimentation, the removal of wrecks and mines, and the study of required nautical equipment.

The dredged channel depth criteria were derived in this second phase as follows:

Channel Depth Methodology The provisional channel depth was first determined on the basis of a combination of design draft and tidal "windows" for the design vessels. The necessary keel clearance was then calculated in accordance with the recommendations of PIANC, in comparison with other harbors, and by using the wave and tide records taken at Zeebrugge.

Provisional channel depths were then selected ranging between 13 m and 16.7 m (43 ft and 55 ft) for a variety of design ships (LNG tankers, VLCCs, containerships).

More detailed studies were used to determine the cross-section profile of the waterways. Basic data were gathered in these studies for the determination of the cross-section:

- o The velocity and pattern of the current in different parts of the access channel, as well as variation during the tidal cycle (influence on channel width);
- o The wave heights induced by different wind forces and tide-level records (influence on channel depth);
- o Regularly taken soundings of the channel bottom. These echo soundings provided information about the variation of the channel bottom (influence on clearance and channel depth).

Keel Clearance Criteria The channel depth needed in the access route to Zeebrugge was determined as a function of:

- o The draft of design vessels;
- o The keel clearance to be observed in the access to Zeebrugge;
- o The water level at the time of entering or leaving the harbor, which is a function of the tidal windows for each type of ship.

Keel clearances for good and bad weather were calculated separately. The criterion for good weather conditions is normal maneuverability. The criterion for bad weather is "the chance of the ships' touching bottom should be acceptably small." Figure 38 shows the method used to determine keel clearance.

Starting from a reference water level, vertical ship motion due to squat and waves is added to ship draft. This incremental value of keel clearance is described as a net keel clearance (about 4 ft for LNG carriers). Further allowances are added to the clearance to allow for the accuracy of soundings and tide measurements.

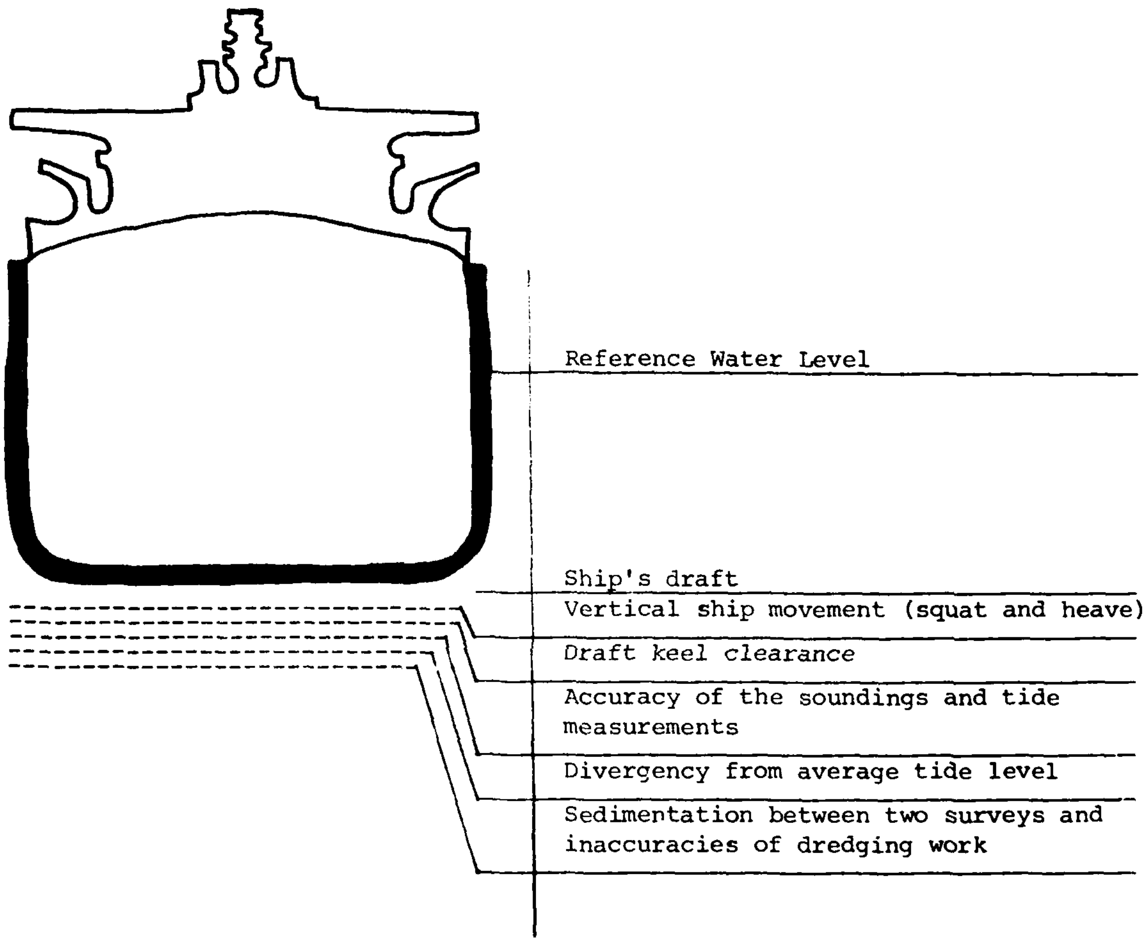
Still another allowance is made for divergence from average tide levels, and an allowance is made for sedimentation between two sounding campaigns, plus a tolerance for dredging work.

Finally, during bad weather conditions, it is recognized that the ship may experience increased draft owing to wave-induced motion. Additional allowances are specified to prevent the ship from hitting the bottom. Given the wave characteristics, it is possible to calculate the probability of a ship's vertical movements.

Each of these individual allowances is determined by calculation or measurement.

Summary The keel clearance criteria used by the Belgium Port Authorities are experimental and analytic, rather than regulatory, and are determined for both good and bad weather.

Figure 38 Access route to Zeebrugge, Belgium: prescription of the underkeel clearance



Calculations are made of all key factors affecting vertical ship movement (design draft, squat, waves, maneuverability requirements, accuracy of soundings, and tide measurements) on an analytical or statistical basis, or both.

Additional allowance is made for maintenance dredging to provide for sedimentation between two sounding campaigns.

The result for the channel leading to Zeebrugge is the specification of depth, 13.4 m (44 ft), and gross keel clearance for normal and bad conditions of 1.4 m and 2.75 m, respectively (5 ft and 9 ft).

Inasmuch as the design draft of the vessel was 11 m (36 ft), this underkeel clearance amounts to 12.7 percent of ship draft for normal conditions and to 22 percent for bad weather conditions.

One notes that the Belgian design criteria for underkeel clearance approximate those of other countries, although the allowance for bad weather conditions is more conservative.

"Nautical Depth" Concept, Europoort and Rotterdam, Netherlands The "nautical depth" concept (described in a preceding section) evolved from study of the behavior of vessels in Europoort and Rotterdam harbors. The present operational practice in the Europoort/Rotterdam area requires that supertankers approaching Europoort from the North Sea to the Maas-Center Buoy (Eurogeul) have a minimum underkeel clearance of 20 percent of their draft, and from the Maas-Center Buoy to the pierheads an underkeel clearance of 15 percent of draft.

The approach channel is maintained at 23.5 m (78 ft) depth. From the buoy to the pierheads, the channel depth is 22.5 m (74 ft). The Caland and Beer channels allow vessels to proceed at an underkeel clearance of 10 percent of draft. Supertankers with a maximum draft of 20.7 m (68 ft) are required to proceed very slowly with a minimum underkeel clearance of 10 percent (2.1 m, or 7 ft).

The nautical depth is defined as the depth to silty layers of specific gravity 1.2. The specific gravity of bottom sediments is monitored weekly by survey vessels, and decisions are made each Friday about maintenance dredging for the following week. Density charts are prepared showing the variations throughout the channels, as shown in Figure 39.

Underkeel Clearance Criteria, Port of Hamburg, West Germany The approach channel to the Port of Hamburg from the North Sea is 60 miles long and 13.5 m (44 ft) deep at MLW. The tidal range is 3 m (9.9 ft). The port is now conducting tests for squat in various conditions; in the meantime, allowances for vessels have been determined from experience, taking into account greater squat at the higher speeds in the approach channel, insufficient depth, and narrow curves. For arriving vessels, the depth of the River Elbe (13.5 m, or 44 ft) and tidal range (3 m, or 10 ft), as well as tidal uncertainty, are considered, with the following results:

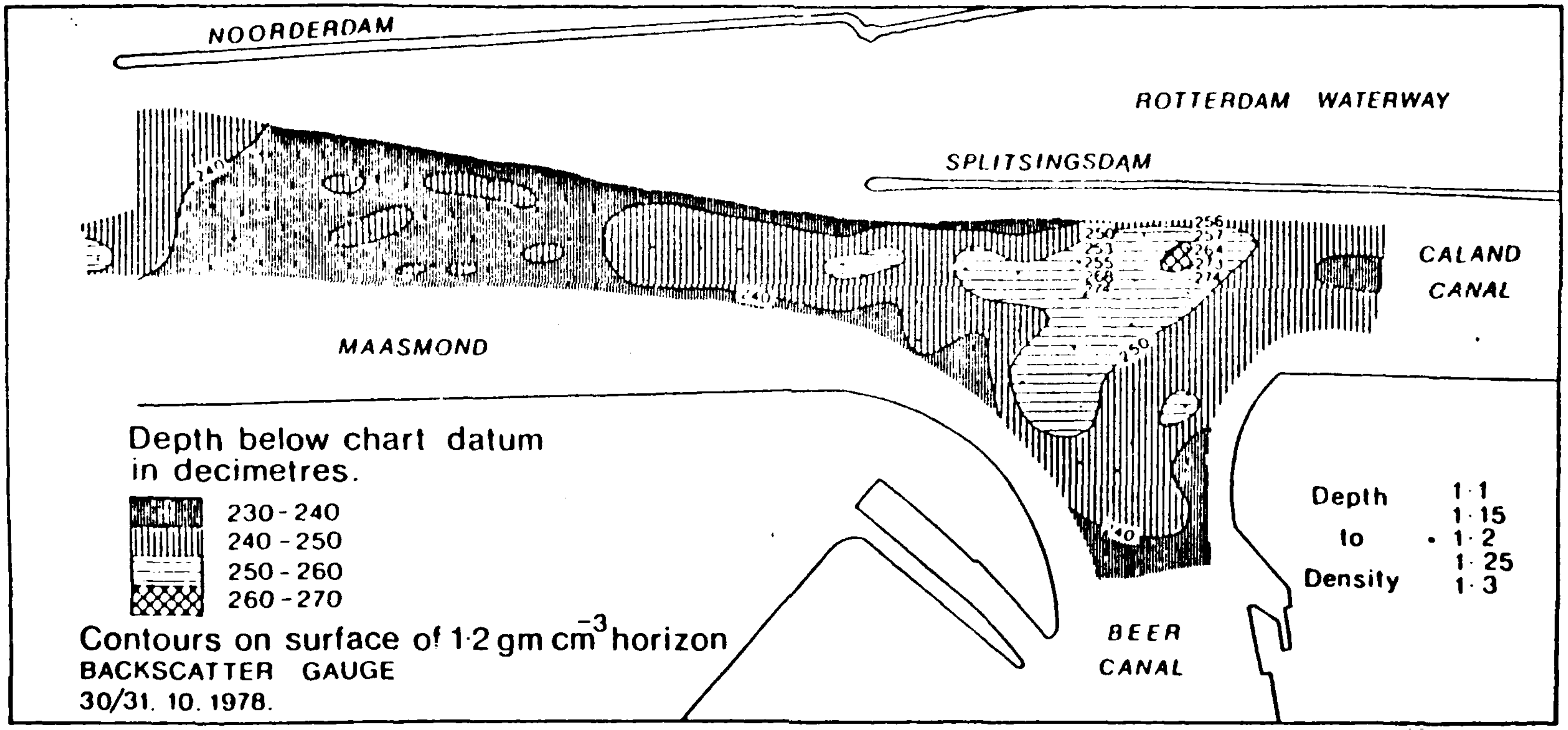


Figure 39 Modern density chart contoured to show the depth of the 1.2 g/cm^3 density horizon. Numbers adjacent to sample stations provide additional data on layer thickness. For clarity, data for only two vertical traverses are shown.*

*SOURCE: W. R. Parker, et al. (1975), "In Situ Nuclear Density Measurements in Dredging Practice and Control," BHRA Fluid Engineering, 1st Int. Symp. on Dredging Tech., Vol. B.3, pp. 25-42.

Maximum draft of vessels up to 300 m (990 ft) in length:

13.72 m (45 ft) arriving at Hamburg
Pilot Station 2 hours before high water

Maximum draft of vessels more than 300 m (990 ft) in length:

12.5 m (41 ft), arriving at Hamburg
Pilot Station 2 hours before high water.

The largest ship allowed in Hamburg has a draft of 14 m (48 ft) and must be brought in at high water. Containerships must have an underkeel clearance of at least 1 m (3 ft). These are, of course, operational rather than design criteria.

The Port of Hamburg does not pay for overdredged depths.

Underkeel Clearance Criteria in the United Kingdom Ports and harbo in the United Kingdom generally apply one standard for underkeel clearance to sheltered waters and another to open waters, but other criteria are occasionally used. The British Ports Association offer the following summary to the panel:

	Traffic	Underkeel Clearance
Port A	Almost exclusively VLCCs	10% in excess of draft for well-sheltered channel
Port B	VLCCs, bulk carriers, general cargo ships	0.9 m (3 ft) for sheltered waters; 2.3 m (8 ft) for ships to 150,000 DWT in open waters; 10% in excess of draft for ships 150,000 DWT to 250,000 DWT in open waters
Port C	VLCCs, containerships, general cargo ships and passenger ships	1 m (3 ft) sheltered waters; 1.6 m (5 ft) open waters
Port D	VLCCs, bulk carriers, general cargo ships	1.2 m (4 ft) in relatively sheltered channels
Port E	VLCCs, bulk carriers, general cargo ships	For VLCCs in excess of 12 m (39 ft) draft only: 0.9 m (3 ft) on the flood tide, 1.5 m (5 ft) on the ebb tide
Port F	RO-RO ferries and general cargo ships (to 4.8 m, or 16 ft, draft)	0.3 m (1 ft) over muddy bottoms (but often less); 1 m (3 ft) over sandy bar
Port G	(Similar to Port F)	0.6 m to 0.8 m (2 ft to 3 ft) in sheltered harbor

The Association points out that "open" and "sheltered" may be variously interpreted from port to port, that depths change more rapidly in some ports than in others, and that traffic conditions, channel width, and the nature of the cargo may imply a need for different standards. The National Ports Council and the Department of Transport have sponsored studies to improve understanding of ship behavior and channel characteristics (e.g., National Ports Council, 1976).

In the Port of Southampton, the design channel depth is 50 ft (15.2 m). The maximum draft allowed is 48.5 ft (14.7 m) at high tide. Minimum underkeel clearance required by the port is 4.2 ft (1.3 m). The overdredged depth is 0.3 m (1 ft). The South Wales Ports specify overdredging depths of 0.7 m (2 ft); in areas of high shoaling, 1 m (3.3 ft). The ports operator, the British Transport Docks Board, owns and operates the dredges.

Shippers' Criteria

Ship operators must appraise ports to decide their suitability for ships of particular dimensions. Among their concerns is channel depth. Crane (1981) gives a brief summary of the methods shippers use to make such appraisals, including extension of experience, hydraulic model studies, and simulations of varying sophistication. For bottom-clearance appraisals, Crane points out, there are several procedures, the simplest being experiences of other ships and the reports of pilots. Another simple technique is essentially similar to the criteria used for designing channel depths: addition of allowances for squat, trim, and other factors to the ship's static draft (Figure 40). This method will produce overly conservative results for a particular ship, Crane notes, because it assumes the coincidence of maximum vertical excursions. "Therefore, statistical addition of allowances for each factor should be substituted [Figure 41]."

This statistical method has been elaborated by Kimon (1982) for comparison against a standard for underkeel clearance, namely a very small probability of grounding. The generalized method is a statistical combination of all the factors known to be most important in determining the depth of water required by ships of certain drafts (or required underkeel clearance, or both). The statistical combination produces an acceptably small probability of grounding in conjunction with a semiempirical coefficient, whose value is derived from known ports (similar to that in question) with many ship-entry years' experience. The method can be applied by a ship's master to a particular port using preprinted worksheets, simple arithmetic calculations, and a series of graphs developed by Kimon.

The uncertainty associated with some factors is as great as a factor of 10, and judgment is inevitably decisive in certain cases, but the characterization of various factors (such as ship response to waves) can be updated as data become available.

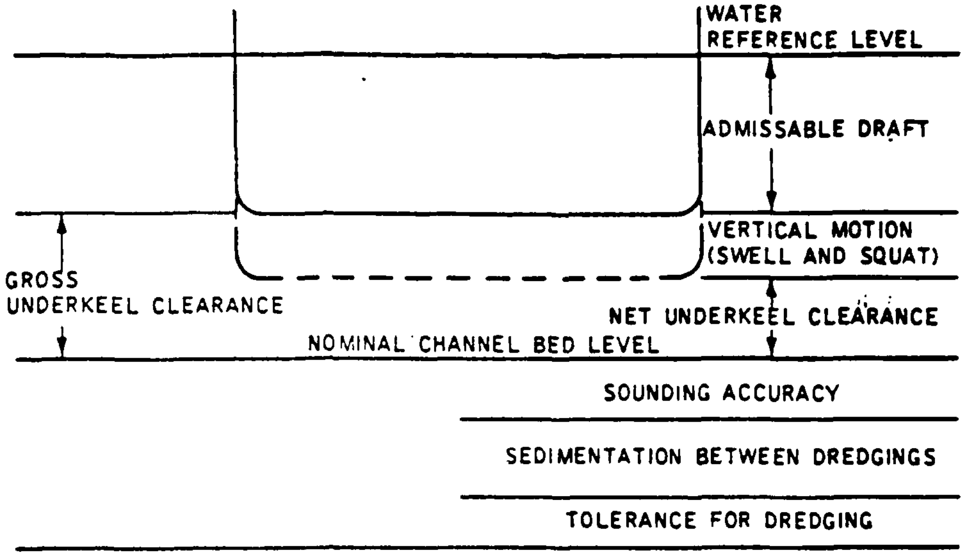


Figure 40 Conventional net underkeel clearance calculation, definitions from PIANC[a]*

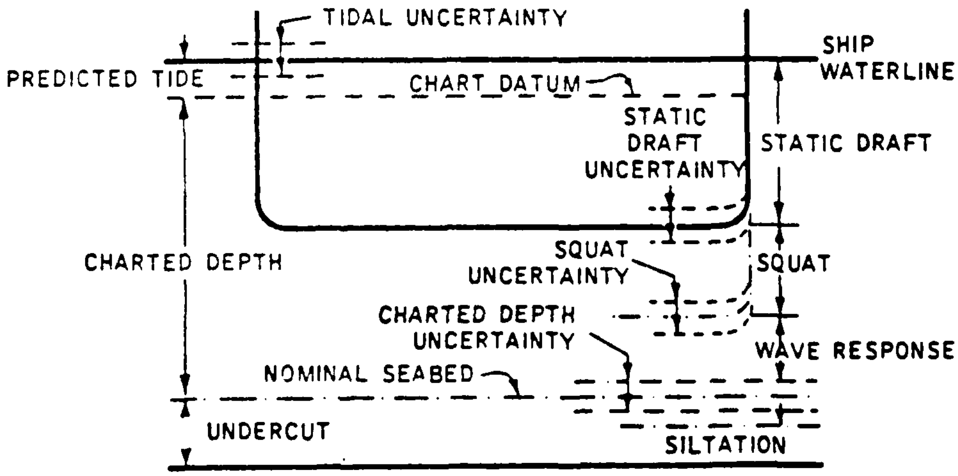


Figure 41 Statistical underkeel clearance calculation*

[a]Permanent International Association of Navigation Congresses

*SOURCE: C. Lincoln Crane, Jr. (1981), "Concerns of Ship Owners," Problems and Opportunities in the Design of Entrances to Ports and Harbors (Washington, D.C.: National Academy Press), pp. 45-52.

This statistical technique could prove useful in the validation of channel design. While Kimon's analysis and results are specific to tankers, the generalized method could be applied to other ships (or the design ship). It is interesting to note that a similar method was used to design the channels of the Port of Zeebrugge, with a similar aim: a very small statistical probability of grounding.

Discussion

The criteria recommended by PIANC were developed by reference to recent research and approved by voluntary consensus of many nations (including representation from the United States) and the IAPH. Particularly for advance maintenance dredging, the criteria assume more frequent bottom surveys than is normal practice in the United States, which is no more often than annual or semiannual.

Taking the largest vessel in 1980 (by draft) that transited each of the nine channels selected by the panel, underkeel clearance was calculated by the lower value of the U.S. rule of thumb and of PIANC criteria in Table 12. These channels were designed long ago (20 years or more), and vessels have been built that are much larger than the design ship or ships. The margins of safety that were assumed in the original design are no longer offered to the vessels using these channels.

Actual use of the U.S. rule of thumb in the design of channel depths today would prove cumbersome, as it relies on several estimates for ship behavior. Substitution of the PIANC criteria seems a reasonable step. The statistical technique also offers attractive features--for example, incorporation of a subjective judgment of safety (an "acceptably small probability of grounding")--that could prove useful in building consensus among ship operators, pilots, and local Coast Guard officials about the otherwise vexing question, How safe is safe enough?

Table 12 Design depths for underkeel clearance of maximum-draft vessel using selected U.S. navigational channels

Channel	Maximum draft vessel using channel in 1980	Required channel depth, PIANC/IAPH*	Required channel depth, U.S. rule of thumb	Project depth of channel (controlling depth)	Number of vessels transits, drafts exceeding U.S. rule of thumb**	Total vessel transits
Delaware River	40	44	45	42 (38.7)	639	12,408
Norfolk Harbor	45	50	50	45 (45)	300	66,681
Hampton Roads	47	52	52	45 (45)	453	80,265
Mobile	40	44	45	42 (39)	202	31,286
Calcasieu River	40	44	45	40 (40)	144	31,613
Houston	40	44	45	40 (38)	1,088	68,826
Galveston	41	45	46	42 (38)	817	16,865
Oakland	39	43	44	35 (33)	655	6,043
San Francisco	52	57	57	55 (52.6)	4	9,123
Columbia River, Lower	44	51	49	48 (40-47[a])	0	6,002

*10% of ship's draft; 15% for areas subject to long or strong swells (applied in table only to Columbia River)
**Ship's draft +5 ft, without estimate for pitching and rolling
[a]Depending on side of channel, inside or outside

5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

General

1. The uniqueness of the physical environment and characteristics of each port must be appreciated. One factor or some combination of factors such as swell, wave climate, tides, or currents may dominate in a particular location. Thus, criteria of channel depth are site-specific. Overdredging depth considerations are also site-specific.

2. General criteria have been developed to provide guidelines and procedures: those of the United States can be improved.

Institutional Factors

3. The characteristics of design ships which have been used to determine the dimensions of channels in the United States no longer correlate with the characteristics of ships that use them.

4. Criteria for the dredged depths of navigational channels are strongly influenced by the uncertainties of sediment deposition and the irregular time constraints imposed by financial and institutional needs and procedures.

5. The time lapses of 15 years to 20 years between initial studies of navigational projects and the initiation of work do not allow for changes in ship technology.

6. Despite skills of pilots and improved aids to navigation, most major navigational channels have experienced such increases in traffic and changes in ship characteristics that the channels no longer offer the underkeel clearances for which they were designed, or those recommended by international organizations. Underkeel clearances in the United States are as little as 2.5 percent of ship draft; international criteria specify a minimum of 10 percent to 15 percent of ship draft.

Design of Depth

7. The ratio of water depth to ship draft is important in navigation: course stability is enhanced with decreasing ratio of water depth to ship draft--e.g., 1.2 or 1.1--but turning performance is much reduced.

8. Depth cannot be considered in isolation from other dimensions and features of the channel, of ships, and of ships in the channel.

9. The "nautical depth" concept is important to defining the usable depth of "silty" channels.

10. Physical models and full-scale trials, particularly for passing, overtaking, and turning, assist understanding of ship behavior, and the results also assist in mathematical modeling and in simulation.

11. There seems to be little exchange of information or correlation between ship owners, pilots, and ship channel designers in the design of channels.

Surveys and Overdredged Depths

12. In the United States, the practice is to rely on historical data rather than channel surveys to determine dredging frequency (except for emergencies). European practice is to survey certain channels more frequently, e.g., weekly.

13. Dredging accuracy appears to be of the same order as specified overdredging depths.

Recommendations

1. For adequate channel design, intensive site studies must be made, and the design criteria based on the results of the studies.

2. It is suggested that the recommendations of ICORELS* (Working Group IV of PIANC**) be substituted for the several criteria now used for channel depth and underkeel clearance in the United States.

3. It is recommended that immediate steps be taken to reduce the amount of time between identification of physical (and other) constraints against major dredging projects and the time that work can begin.

4. Frequent surveys should be made in known, high-snoaling areas.

5. The nautical depth concept should be adopted for silty channels of the United States.

6. Better information about operational practices and the hydrodynamic behavior of ships needs to be collected and incorporated in channel design.

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*International Commission for the Reception of Large Ships
**Permanent International Association of Navigation Congresses

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APPENDIX A

ABSTRACTS OF PERTINENT ARTICLES AND REPORTS

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Anonymous (1971), "Squat," Commandant's International Technical Series, Vol. I, Report No. USCG-CITS-71-1-1 (Washington, D.C.: U.S. Coast Guard).

Author's Abstract

The report contains four papers on squat in shallow water as follows: from the Federal Republic of Germany, a paper on the results of model tests of a 700,000 DWT tanker; from France, a paper on the results of model tests of a 500,000 DWT twin-screw tanker; from Poland, a paper on the results of model tests of two ships with large block coefficients, one with bulbous bow; and from the United Kingdom, a paper on the results of model tests of two ships, one in the naked hull condition, and the other equipped with self-propulsion gear, twin screws, twin rudders, and bulbous bow.

Anonymous (1979), "Automatic Survey Techniques on the Waterways and Approaches to Rotterdam" (Netherlands: Rijkswaterstaat, Direktie Benedenrivieren, Meetdienst).

Abstract

Automation in survey and maintenance dredging activities was introduced at the end of 1974 to supply depth information on the waterways and approaches to Rotterdam. This report gives a brief description of the "Waterweg" system which has been installed on trailing dredgers and survey vessels. The shore-based processing system is described, as well as the incorporation of radioactive density meters into the system.

Anonymous (1981), "A Report on Bed Density Measurements and Echo Sounding at Humber Ports," Report No. R. 286 (United Kingdom: British Transport Docks Board, Research Station).

Author's Abstract

Following the introduction of echo sounders to assist with the production of hydrographic sounding charts, depths--particularly in soft bed areas--have become more variable and generally less deep.

This report describes a series of field measurements which were designed to determine the variation of density with depth, and to establish the density horizon that echo sounders record as "the bed."

Throughout the period of study, developments have been made both with the instrumentation (particularly that used to measure the density of the bed) and with operational techniques. As a consequence greater attention has been given to the more recent observations.

In soft bed areas the echo sounder records the bed at varying density horizons. Time, location, density and acoustic gradients within the bed are some of the factors which affect the measured depth.

The study concludes that in soft bed areas the depth recorded by echo sounders does not correspond to any specific horizon. It can be significantly above or below the water column/bed interface. Consequently, it is recommended that in these areas conventional echo sounding is supplemented by routine densimeter observations.

Anonymous (N.D.), "Density Measurements in Situ," (Netherlands: Public Works Department, Lower Reaches Directorate, Surveying Division, Research Section).

See also: Hellema, J. A. (1981), "Silt Density Measurement," The Dock and Harbour Authority, January 1981, pp. 282-284.

Abstract

Excessive siltation takes place in Europoort, and the very thin silt is inefficient to dredge. After extensive tests, the nautical bottom was defined as the depth at which a density of 1200 kg/m^3 was measured. Since a normal echo sounder cannot detect this nautical depth, because of the loss of signal in the silt, a radioactive density probe has been developed for this purpose. The probe is lowered into the silt, and the amount of radiation reflected by the silt defines the measured density. This report describes the practical tests of radioactive density measurements since the end of 1973, together with the findings during the ensuing operational period.

As these point-measurements are time-consuming, a special subbottom profiler with parametric transmitter has been developed to provide continuously available subbottom information. This system is believed to be the first of its kind in Western Europe.

Anonymous (1981), "New Non-Linear Sub-Bottom Profiler System," International Dredging & Port Construction, April 1981, pp. 29-30.

Author's Abstract

This brief article presents the technical details of a non-linear sub-bottom profiler to be developed by Ulvertech Ltd. of Ulverston, Cumbria, for deployment in and around both Europoort and Rotterdam. The profiler will be housed in a gyro-stabilized platform so that it will not be affected by the roll and pitch motion of the survey craft. The system will provide a very acurate contour of the seabed and show the different density layers to a depth of about 20 m below the seabed. Details of a dual mechanical scanning sonar system and a sonar video system developed by Ulvertech are also presented in the article.

Berriman, J. W., and J. B. Herbich (1977), "Major Port Improvement Alternatives for the Texas Coast," COE Report No. 197, TAMU-SG-77-205 (College Station, Tex.: Texas A&M University).

Abstract

With the advent in recent years of very large crude carriers (VLCC) and ultralarge crude carriers (ULCC), the United States has fallen behind many other maritime countries in providing suitable docking facilities. The shortfall in port facilities capable of handling the deep-draft vessels, coupled with rapidly growing volume of imports and exports of bulk commodities, has resulted in a critical need for improved port facilities in this country.

The lack of port facilities capable of handling VLCCs and ULCCs, coupled with a rapidly growing volume of imports and exports of bulk commodities, and projected growth in oil importation and refining levels, make it imperative that port facilities be further improved along the Texas coast. The onshore deepwater port has the advantage of being able to accommodate the larger carriers of bulk commodities as well as large tankers which transport petroleum products. The port improvements for the Texas coast are deemed to be necessary to provide modern and efficient port facilities to shippers and ensure continued economic well-being for the regions served by these ports.

Ship channel design criteria are discussed in terms of minimum width and depth requirements for various size vessels. A portion of the design work contained in this paper was checked using a mathematical model developed by Mr. Edward T. Gates of the U.S. Army Corps of Engineers and a graduate student at Texas A&M University. It is recommended that this mathematical model be utilized extensively in any future work dealing with channel design.

The following channel design criteria are necessary to provide for the safe navigation of VLCCs and ULCCs:

1. Channel Width

   Maneuvering Lane (A) = 2.0 x Beam + L sin 10°, where L sin 10° applies to channels with strong yawing forces.

   Bank Clearance Lane (B) = 1.5 x Beam
   Ship Clearance Lane (C) = 1.0 x Beam
   One-Way Traffic Width = A +2B
   Two-Way Traffic Width = 2A + 2B + C

2. Channel Depth

   Channel Depth in Inner Channel = f (loaded draft, squat, and minimum keel clearance)

   Channel Depth in Outer Channel = f (loaded draft, effect of pitch and roll, and minimum keel clearance), where effect of roll and pitch = L/2 sin 1°.

Improved channel designs are presented for the ports of Port Arthur, Galveston, Freeport, and Corpus Christi.

Bijker, E. W. (1978), "Science and Design of Navigation Trenches and Offshore Trenches," Proc. 8th World Dredging Conf., pp. 69-76.

Author's Abstract
The general requirements of shipping lanes are that they guarantee a safe passage of the ships with regard to navigation in general, and width and depth in particular. The impact of science as discussed in this paper means that under more or less normal conditions, empirical knowledge may be sufficient; for extraordinary new situations, however, a basic knowledge of the physical phenomena determining the situation will be required. This implies that theories should be available or developed to elaborate wave and current data in order to predict the behavior of the channel and of the ships in the channel.

Bijker, E. W. (1980), "Sedimentation in Channels and Trenches," Proc. 17th Coastal Eng. Conf., Vol. II, pp. 1708-1718.

Abstract
In this paper, the siltation in approach channels and trenches due to crosscurrents and waves is discussed. When the current crosses the channel obliquely rather than at a right angle, a greater distance over which the water flows over the greater depth is introduced. Deviations in the flow pattern due to the channel are neglected. However, when the flow pattern is known, either from measurements in nature or in the model, this effect can easily be introduced. The influence of the waves is introduced through an increased bed shear and subsequently higher diffusion coefficient. Although computer programs are available to calculate the siltation under the above described circumstances, the paper presents a relatively simple method which permits a quick estimate of the siltation to be expected without the use of a big computer. This method could be useful for a first appraisal for the various solutions, by the engineer in the field.

Blaauw, H. G., J. W. Koeman, and J. Strating (1981), "Nautical Contributions to an Integration Port Design," Publication No. 251 (Netherlands: Delft Hydraulics Laboratory).

Abstract
This paper presents a harbor design strategy in which the nautical aspects are treated as an integral part. A harbor is designed to ensure the safe and efficient transport of goods, and these goals are, to a large extent, determined by the behavior of ships. The paper shows that different nautical research tools should be used at the various design phases. In the initial phase, several design

alternatives are produced using rules of thumb, engineering experience, or mathematical models. An initial master plan is selected, and in the final stage, advanced hydraulic models and maneuvering simulators may be used to optimize the initial master plan. The nautical research tools are described in detail, and the setup is illustrated with the results of research programs and recent case studies.

Bos, H. (1979), "Marketing Research and Business Economics," Land and Water International, pp. 20-22.

Abstract

The Dutch dredging market is divided into three sectors: (1) the sand sector (mining of sand, clay, gravel, etc.), (2) the maintenance sector, and (3) the capital sector (new works). The price development for trailing-suction dredging work in the Netherlands indicates that the average level of prices is continually rising, while the mutual differences between the observed market prices have increased. The effect of recent changes in the dredging market on the relationship between contractors and principals in various sectors of the market is discussed. Methods for minimizing the cost of maintenance dredging for the principal by reducing the quantity to be dredged and the price per unit of spoil are suggested.

Eden, E. W. (1971), "Vessel Controllability in Restricted Waters," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 97(WW3): 475-490.

Abstract

A discussion of vessel controllability in restricted waters is presented, and the factors influencing controllability are considered in detail. The motion of a vessel generates pressures, currents, and waves which, after impingement upon restricting boundaries, will create secondary reactions. Those forces vary with the clearance between the vessel and fixed boundaries and the speed of and distance to other vessels, if any. The controllability of the vessel depends upon the rudder power, the reaction of the pilot, and the speed with which changes in vessel speed and heading can be made. The hydrodynamic characteristics of vessel motion through the water and the effects of rigid boundaries and passing ships are explained. The action of a single propeller or twin propellers is another factor which affects the shape and magnitude of pressure and velocity fields.

Methods of evaluating the controllability of a vessel are described. Standard maneuvers such as the zig zag, spiral, or sine test are used to determine the reaction of the vessel in full-scale, deepwater trials or in hydraulic model tests in the laboratory. Another index used by naval architects to define controllability is the turning circle at full ahead speed with a 35° starboard rudder.

The stopping distance is also an important element of controllability. Experimental data indicate that at least four factors important in the controllability of any vessel vary with the relative channel dimensions.

These factors are (1) sinkage or squat, (2) lateral forces and turning moments, (3) directional stability, and (4) resistance, or drag.

The research needs are briefly reviewed and a program to reduce uncertainties and improve theoretical appraisals of vessel controllability under given conditions is described.

Gates, E. T., and J. B. Herbich (1977a), "Mathematical Models for the Design, Operation and Economic Analysis of Deep-Draft Navigation Channels," Proc. 24th International Nav. Cong., PIANC, Leningrad, U.S.S.R., pp 175-181.

Abstract

Engineers generally determine the dimensions of a navigation channel by design policy and by use of standard ratios of proportions of the selected design vessel. Because of the great changes in relative dimensions of the world's marine fleets, these techniques should no longer be universally applied. This criterion--ratio approach to design--also does not take into consideration the individual characteristics (prevailing winds and currents) of each separate channel location. A channel design model and a channel operations model (under development) are described in this paper. These models are modular in structure and include theory limitation indicators.

The channel design model determines the design vessel's reaction to the effects of squat, changes in water salinity, boundary layers due to vessel motion, current, wind, changes in neutral steering line due to asymmetry in the channel cross-section, bank suction, and other phenomena. The squat module computes the increase in vessel draft due to brackish water, then computes the squat for the primary (design) vessel alone and when in a passing or overtaking condition with a secondary vessel for each speed in a designated range. The bank suction module computes the lateral forces and turning moments due to the bank suction phenomenon. The neutral steering line module computes the distance between the neutral steering line and the channel centerline for a given cross-section and then adds this distance algebraically to the given ship off-centerline distance.

This new distance is used by the bank suction module in computing lateral forces and turning moments. The vessel attitude module determines the magnitude of the drift angle and rudder angle required to neutralize the lateral forces and turning moments caused by the effects of bank suction, crosswinds, and lateral current components. The ship-generated waves module calculates the magnitude of the ship-generated wave at the vessel and at each cusp point as the wave propagates out from the vessel sailing line. The stopping distance module computes the astern thrust per ton displacement ratio required to stop a vessel in a given required distance.

The channel operations model mathematically simulates the movement of vessels and barge trains in and out of a specified port. This model accumulates and reports operational, safety, and cost data for delays due to passing traffic including barges, one-way traffic, passing fixed objects such as bridge piers, accidents, insufficient draft due to wind and tides, bad weather, unavailable dock facilities, and traffic saturation.

The channel design model is being used by the Galveston District; U.S. Army Corps of Engineers; the Galveston, Texas, City Port Safety Advisory Council; and the U.S. Coast Guard, and the results to date have been good. The channel operations model is expected to be operational in the near future.

Gates, E. T., and J. B. Herbich (1977b), "Mathematical Model to Predict the Behavior of Deep-Draft Vessels in Restricted Waterways," COE Report No. 200 (College Station, Tex.: Texas A&M University).

<u>Author's Abstract</u>

Presently deep-draft navigation channel analysis, design and review is based on empirically derived ratios of the design vessel's dimensions. Because of radical changes in vessel operation purposes and characteristics, these ratios can no longer be safely or economically applied.

The mathematical model and related theory described in this document provide the engineer with a comprehensive tool in the design and review of deep-draft navigation channels. Through its use he will be able to predict values of squat, bank suction forces and moments, equilibrium drift and rudder angles, and heights of ship-generated waves for varied channel configurations, ship positions and ship velocities. Through the determination of channel section configuration sensitivity, an optimal design both operationally and economically can be achieved.

Gates, E. T., and J. B. Herbich (1978), "A Mathematical Model for the Review or Design of Deep-Draft Navigation Channels with Respect to Vessel Drift and Rudder Angles," <u>Proc. Symp. on Aspects of Navigability</u>, Delft, Netherlands, April.

<u>Author's Abstract</u>

A comprehensive mathematical model has been developed for the design and review of deep-draft navigation channels. Input to the model consists of the channel configuration, the design vessel dimensions and environmental considerations such as winds and currents. The output consists of squat values, neutral steering line variations, bank suction forces and turning moments, drift and rudder angles required to overcome the various forces and turning moments, ship-generated wave heights and stopping distances, all for varying speeds and varying distances from the centerline of the channel.

This paper deals predominantly with the theory involved with the variation of the neutral steering line caused by the asymmetry of the channel cross section and with the determination of bank suction forces and turning moments and the required vessel drift and rudder angles to overcome these forces and moments. Lateral currents and wind can also be considered.

The Houston Ship Channel has been used as a prime example of the model's application. The deviation of the neutral steering line from the centerline of the channel in passing or overtaking is traced for the Houston Ship Channel. Design procedures are presented to demonstrate what changes can be made to the channel cross-section to shift the neutral steering line back toward the centerline of the channel, thereby reducing any excessive drift and rudder angles to allowable values.

Hellema, J. A. (1979), "Density Measurements in Situ" (Netherlands: Public Works Department, Lower Reaches Directorate, Measuring Division, Research Section).

Abstract

The rapid increase in the draft of ships was one of the factors that prompted the construction of the Europoort harbor area and the Maas Flats. The original aim of the design was 57 ft, but at the opening of the permanent entrance in June 1971, Europoort was capable of handling ships of 65 ft draft. The everincreasing scale of the ships led to Europoort's access channels and harbor basins being further deepened so that at the end of 1974, ships of 68 ft draft could be accommodated.

As the harbor depth increased, a new problem emerged: each year millions of cubic meters of silt had to be dredged to maintain the guaranteed depth of Amsterdam Ordnance Datum--22.5 m in Europoort.

The cost involved led the National Public Works Department and the municipality of Rotterdam to initiate a joint research project at the end of 1973 entitled "Minimizing the Costs of Maintenance Dredging Work."

The working party on "Silt Soundings and Density Measurements" recommended the radioactive density meter of the Atomic Energy Research Establishment (AERE) at Harwell, England, as a means of measuring the silt density for the study. This report describes the development and methodology of the density measuring system.

Herbich, J. B., W. R. Murden, and C. C. Cable (1981), "Factors in the Determination of a Cost-Effective Dredging Cycle," Proc. XXV Int. Nav. Cong., Inland and Maritime Waterways and Ports, PIANC, Section II, Vol. 2, Edinburgh, Scotland, May 10-16.

Abstract

In determining a cost-effective dredging cycle, one should consider and include the different stages involved:

1. The definition of requirements for the navigation channel characteristics and for the method of disposal of the dredged material.

2. The design and specifications, which includes the geotechnical site investigation, project design elements, optimization of the dredging system, and the method for measuring progress and for determining satisfactory completion of a project.

3. The execution of the work in accordance with the environmental laws of the United States.

4. The design and construction of dredges in the United States.

The report discusses the research needed to improve the efficiency of the dredging cycle, save fuel, and reduce dredging costs.

Huval, C. J. (1978), "Mathematical Models for Navigation Channel Design," 26th Proc., Annual ASCE Hydraulic Civ. Spec. Conf., Verification of Math. and Phys. Models in Hydraulic Eng., University of Maryland, August 9-11, pp. 273-279.

Abstract
The U.S. Army Engineer Waterways Experiment Station (WES) has undertaken a study to determine the minimum dimensions of deep-draft navigation channels compatible with the assurance of safe operating conditions. The factors influencing ship control and the design of navigation channels are discussed, with emphasis on the piloting and navigation aspects of the control system. Some of the critical maneuvers during the port approach and exit phases are also described.

The advantages and disadvantages of alternative research techniques are evaluated and compared. The main advantage of physical models is the ability to observe the channels and the ship maneuvers, while the disadvantages are the model-to-ship resistance differences and the time-scale distortion due to Froude scaling between velocity and distance ratios. The model piloting behavior is dependent on the time scale, and the effects of time-scale distortion on scale model test results are not presently known. Mathematical models use the equations of ship motion together with captive model test data. A complete mathematical model with complex bank suction effects requires the detailed specification of many hydrodynamic coefficients and involves many towing tank test conditions. If hydrodynamic data are available, however, the ease and speed of solution make this technique attractive for an exploratory study of navigation aid aspects of piloting ships into channels. Ship simulators have been developed for study of channel design. A dedicated computer is necessary for ship motion calculations and to control simulated ship bridge nautical equipment and the image of the projection system. The use of

mathematical models at WES is briefly discussed, and the development of a ship research simulator is considered. The three research methodologies should be used jointly in a complementary fashion.

Iijima, Y., and K. Honda (1973), "Channel Width of Harbor Entrance," J. Naut. Soc. Japan, 50: 91-103.

Author's Abstract

The design of harbor entrances must be dictated by the size and maneuverability of the largest vessel anticipated to enter the harbor and also the local factors, but it does not seem that the design of existing harbors considers very many of the above factors. This paper describes how a criterion of harbor channel width is expressed as a numerical formula based on the above factors. The total width of channel is divided into three widths whose clearances are based upon a study of the Panama Canal, that is, (a) width of maneuvering lane, (b) width of the bank clearance lane, and (c) width of the ship clearance lane.

A computer program called TRANSAP-LNG is used for system design and economic evaluation of LNG transportation systems. The system model includes all the stages related to LNG transportation, such as gas wells, gas pipelines, liquefaction stations, LNG tankers and gasification stations. Since these sub-systems, either single or multiple, are linked together as a total system, optimization of the total system of multiple projects can be made as well as optimization at lower system levels. Particularly, an optimized LNG tanker can be designed in view of optimization of the total transportation project.

International Association of Ports and Harbors (1981), "Special Care Measures for Safe Disposal of Polluted Dredged Material in the Marine Environment," Submitted to the Ad Hoc Scientific Group on Dumping--5th Meeting, Halifax, Canada, May 4-8.

Abstract

The need for dredging of ports and harbors both for enlargement and for maintenance of existing channels is expected to increase in the 1980s and beyond. Ways must be found to permit ports and harbors to continue the dredging of new and existing waterways to assist in achieving safe passage of vessels of commerce. A certain percentage of this dredged material, particularly that derived from maintenance dredging, can be expected to be polluted with Annex I substances, which must be disposed in such manner as to cause the receiving environment as little degradation as is reasonably possible.

Public and economic pressures against use of some present-day types of land environments are increasing the difficulty of finding and using disposal sites on the land that can be considered safe and within reasonable distances from ports and harbors. Examination of the marine environment reveals that it has a high potential for assimilating dredged material without creating undue environmental risk. This paper examines the problem and delineates possible solutions. It is concluded that if "special care" measures are used in disposal and in dumpsite selection, the disposal into the marine environment of dredged material containing Annex I substances would in many cases present no greater risk of environmental harm than the disposal of Annex II substances.

Kirby, R., W. R. Parker, and W. H. A. van Oostrum (1980), "Definition of the Seabed in Navigation Routes through Mud Areas," International Hydrographics Rev., Monaco, LVII (1): 107-117 (Also First International Hydrographic Technical Conference, Ottawa, May 1979).

Author's Abstract

Over most types of seabed the interface between the seabed sediment and the overlying sea water column is sharp and clearly identified by survey echo sounders. However, in areas with a large mobile population of cohesive sediment (mud), dense layers of suspended sediment occur which are intermediate in character between muddy seawater and the settled mud of the bed.

Such suspensions (fluid mud) may create a surveying problem, owing to the multiple layering they produce on echo sounder records. Echo sounders alone do not allow an objective decision on which reflector should be regarded as the seabed for navigational purposes.

A new technique has been devised involving detailed profiles of in situ density through the suspensions using gamma-ray densimeters. This information, together with knowledge of ship behavior in dense media, facilitates decisions on what values of in situ density should be defined as the seabed. A density value of 1.2 gm/cm^3 is now used by the Netherlands Rijkswaterstaat to define the "nautical depth," since research has shown that suspensions of lower density do not significantly impede the passage of ships.

In Europoort sudden influxes of sediment during storms produce layers up to 3.0 m in thickness which are detected by echo sounders, and once the presence of such a suspension resulted in the temporary closure of the port to supertanker navigation. However, density surveys reveal that on arrival these suspensions are of very low density and thus do not present a hazard to navigation.

Density surveys are also used to guide the maintenance dredging fleet to areas where the 1.2 gm/cm^3 density level is shallower than the nominal datum for the channel or to areas where consolidation has progressed to a point where high production is possible.

Kondstaal, R., and J. van der Weide (1981), "Systems Approach in Integrated Harbor Planning," Publication No. 250 (Netherlands: Delft Hydraulics Laboratory), presented at the Seatech III Conference in Asian Ports Development and Dredging, Singapore, March.

Abstract

Port design and operation consists of an integrated series of multidisciplinary interests and requires a variety of input design criteria and boundary conditions. A systems analysis approach to port planning is presented in this report. The port is first considered as a system in the transport network linking production and consumption and the minimization of costs is discussed. The three steps in the systems approach to port planning are analysis of cargo flow, preparation of a master plan, and design of the harbor. The main elements of the master plan are shipping, site selection, conceptual plans, and dimensions. The costs of port facilities and vessels are considered, and various simulation techniques used in port planning are discussed.

Kray, C. J. (1973), "Design of Ship Channels and Maneuvering Areas," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 99(WW1): 89-110.

Abstract

In view of the constant increase in vessel sizes, projects for improving channels and maneuvering areas, straightening of curves and deepening, as well as increasing the widths of the various sections of channels are being requested by navigation interests. There are basically two kinds of channels: (1) open-type, in wide waters, natural or dredged channels, often constituting the deepest portions of a bay or river, strait, or maneuvering area; and (2) restricted-type, in confined waters, excavated channel or canal, restricted inland sea extension, canal between islands, or between mainland and islands. Factors influencing the design of width and alignment of channels and dimensions of maneuvering areas required for vessels are discussed in detail in this paper.

The controllability of a ship in open and in confined water is affected by the vessel's characteristics and speed, winds, waves, currents, visibility, solid obstructions, shoaling, and traffic. The vessel behavior in channels and maneuvering areas is influenced by bottom and bank suction, interference of passing ships, rudder response, and increase in required driving power in shallow, confined waters. The human element involves ship operators, pilots, their reactions and attitudes, time lapse in communication, errors of judgment, and their knowledge of ship properties and the channel's configuration and peculiarities.

Forces external to the ship include the effects of wind, waves, and currents on the path of ships in entrance channels and in the open-type and restricted-type waterways.

The effect of the underkeel depth in channels for ships in motion, the effects of ship location in the channel, and the effects of passing ships are also considered.

The optimum direction of the entrance channel depends on forces external to the vessel, the human element, and the vessel's controllability. Turns in the channel direction should not be employed unless necessary, since any change in channel direction causes changes in flow and velocities as compared to the straight section and makes navigation more difficult. The increase of channel width in bends can be considered as a function of the angle of deflection, length, beam, and controllability of the vessel, radius of curvature, and environmental conditions. The turning basin's size is a function of the length and maneuverability of the ships using them. It also depends on the time permitted for the execution of turning maneuvers.

Research needs to produce reliable design criteria are identified as (1) influence of channel dimensions and layouts on handling of vessels, predicting their motions and rudder response, hydrodynamic mass evaluation, and optimization of geometry for channels and maneuvering areas; (2) establishment of maximum safe speeds and evaluation of increase in required driving power of ships in shallow and restricted waters; (3) ship passing phenomena, and bank suction in restricted waterways; (4) effects of reduced visibility, wind, wave, and current on vessels, particularly in difficult sections of channels; and (5) ship clearance requirements and alignment of channels and maneuvering areas.

McDonald, R. M. (1977), "Development of the Ship Channel between Montreal and Deep Sea," <u>Marine Tech.</u>, <u>14</u>: 192-197.

<u>Author's Abstract</u>

The dredged channel of the St. Lawrence River between Montreal and Ile aux Coudres forms part of one of the largest inland navigation systems in the world. From the Gulf, ships can travel almost 2000 miles to the head of the lakes. The various stages of development of the channel to obtain a controlling depth of 25 ft between Montreal and Quebec City and a sufficient depth for a draft of 48 ft--with the aid of the tide--from Quebec City eastward are discussed in this paper.

Mikkelsen, L., P. Mortensen, and T. Sorensen (1980), "Sedimentation in Dredged Navigation Channels," <u>Proc. 17th Coastal Eng. Conf.</u>, Vol. II, pp. 1719-1734.

<u>Abstract</u>

The feasibility of a harbor project, which involves dredging of an access channel, may to a large extent depend on the future maintenance dredging in the channel. It is therefore important to be able to calculate sedimentation in dredged channels with sufficient accuracy.

In 1974 and 1975, the Danish Hydraulic Institute (DHI) carried out a study of the most feasible access channel to Warri Port situated in the Western Niger Delta, Nigeria. Two alternative entrances were studied, and in conclusion it was recommended to improve the existing access channel through Escravos Entrance, as this solution would yield much smaller maintenance dredging quantities as compared to an access channel through Forcados Entrance.

In 1978, it was decided to improve the accuracy of the sedimentation estimates for a dredged channel through Forcados Entrance, and therefore it was recommended by DHI to dredge test pits in the alignment of the channel and to carry out a pertinent monitoring program.

The paper presents: (1) The test pit monitoring program and results, including a discussion of measurement techniques, and (2) calculation of sediment transport in combined currents and waves and comparison with the monitoring results.

On the basis of the test pit monitoring and the measured current and wave parameters it has been possible to calibrate the sediment transport rates in combined waves and currents. The test pit results have been used to obtain a satisfactory expression for the sediment diffusion coefficient ε_s and hence the concentration profile.

Using the calibrated transport rates, the theoretical sedimentation model, and the wave and current statistics, it has been possible to calculate the expected annual sedimentation in the dredged channel. Further, it has been possible to predict the consequences of changes in the depth ratio D_1/D_2 and in the channel width and hence to produce an optimal design of the channel.

In conclusion, the sedimentation model has proved itself to be a very useful tool for studies of expected sedimentation quantities, particularly if the transport rates can be calibrated through pertinent field studies.

Minorsky, V. U. (1977), "Grounding Probability Studies," Final Report on Task IV, Feb. 76 - Jan. 77, prepared for U.S. Maritime Administration by George C. Sharp, Inc., New York.

Author's Abstract

Grounding statistics for vessels over 6000 G.T. were compiled for the 6 years 1970-1975. Results were analyzed for tankers and non-tankers, each in four gross tonnage groups as to location, cause, and result. Groundings were studied in detail on proposed nuclear vessel routes with an approximate calculation of casualty probability based on route casualties and ship traffic flow.

Recommendations are given to help reduce the frequency of groundings for the nuclear vessels.

Muir, William C., G. D. Pence, and J. R. Pomponio (1981), "Deepening the Hampton Roads--The EIS Process," Proc. 14th Annual Dredging Seminar (College Station, Tex.: Texas A&M University).

Abstract

Since 1973 the foreign demand for coal has risen dramatically. The oil embargo of that year forced Europe and Japan to convert most of their energy demands from oil to coal. That demand for coal has stimulated growth in many U.S. ports, the greatest of which is the Hampton Roads complex. Last year over half of the nation's coal exports, approximately 50 million tons, came from Newport News, Norfolk, and Portsmouth which make up the Hampton Roads complex. Over the next five years, that volume is expected to double.

The existing channel depth in the Hampton Roads is 45 ft. This depth severely limits the ability of larger coal colliers, greater than 80,000 DWT, to load. The U.S. Army Corps of Engineers (COE) extensively studied the feasibility of deepening the channel to 55 ft and found it economically justifiable. In 1980 the COE prepared a Draft Environmental Impact Statement which proposed expansion of the channel to 55 ft but which presented a myriad of environmental concerns. These included such considerations as filling 6000 acres of the Dismal Swamp, the potential contamination of groundwater supplies from spoil disposal, and the changes in salinity in the tributaries to the Hampton Roads.

Through the efforts of the U.S. Environmental Protection Agency and the Fish and Wildlife Service working with the COE, an extensively modified Final Environmental Impact Statement has been prepared. The final plan relies upon a mixture of dredged material disposal alternatives, including beach nourishment of clean sand, containment of contaminated sediments, and ocean disposal of the remaining material, most of which is uncontaminated. Channel deepening induced salinity changes should be more thoroughly understood as a result of extensive modeling required prior to dredging. Monitoring programs will be established to gain further insight into chemical and physical changes associated with the project.

Nederlof, L. (1979), "Sailing Through Water Rich in Silt: A Vessel Behaves Differently but Remains Manageable," Rotterdam Europoort Delta, pp. 19-22.

Author's Abstract

The State Waterways Department and the City of Rotterdam recently completed a study on the behavior of vessels in rivers or ports with very muddy beds. Sandy beds have a reasonably firm structure and a

clearly defined surface, but the composition of muddy beds is quite different. In that case there is no question of any clear profile.

The vessel meets a body of water with floating particles of silt, which become more dense toward the bed. Finally there is a body of silt which may be regarded as more or less consolidated.

The composition of such muddy beds had been hard to measure in the past, but recent new measuring techniques are making it possible to probe the structures of muddy beds thoroughly. New insights resulted which were related to the maneuvering possibilities of (very large and deep-drawing) vessels.

The study was part of a joint research project entitled "Minimization of the Cost of Maintenance Dredging" and has given birth to different ideas about the required depths of ports and rivers.

This is of interest to nautical experts because it has extended the "available water depth" notion which from now on should be judged somewhat differently insofar as muddy beds are concerned. For port managers the information is important from the viewpoint of fixing the time for new dredging.

Nederlof, L., and G. van Bochove (1981), "Maneuvering Behavior of Ships in Muddy Canals and Harbors," The Dock and Harbor Authority, Netherlands, Vol. LXII, No. 726 (May), pp. 2-6.

Abstract

Maneuverability of mammoth tankers (VLCCs) in silty waters has been shown to create many problems in certain harbors throughout the world. A group of researchers and scientists at the Netherlands Ship Model Basin have conducted a series of tests which are broken up into three categories or parts. The tests involve the investigation of the composition of the bed in the approach channel, the investigation of the maneuvering pattern of deep-draught tankers when passing over silt, and the investigation of the maneuvering pattern of deep-draught tankers above silt in the model tank.

Tests were run to determine the composition of the bed using a radioactive density indicator, and the results showed that deposition of silt was particularly heavy in the period toward the end of the year.

Test results of a deep-draft tanker when passing over silt showed that the passing vessel sets up a stern wave at the interface of water and silt, the density of the silt does not change during the passage, and when the ship is passing, a layer of silt is brought into suspension.

The model results showed that the resistance is much greater in silt and requires higher propeller revolutions, the stopping distance is reduced, the squat and trim are less, the effectiveness of the rudder increases sharply, and the effectiveness of the propellers is not constant.

Ottevanger, G. (1979), "Dredging Operations in the Approaches to Rotterdam," Land and Water International, pp. 27-32.

Abstract

The advantages of the trailing-suction hopper dredger over dredging equipment used prior to 1957 in the Nieuwe Maas and the Rotterdam Waterway are discussed in detail. A description of the electronic position-fixing equipment used on these dredgers is presented. Details are given of the execution of the dredging and disposal operations, as well as of the supervision of the maintenance dredging. New developments for trailing-suction hopper dredgers include the recording of positional and loading data on magnetic tape for computer analysis, and a probe which continuously monitors the loading pattern of the dredger. Survey echo sounders and systems for position-fixing of the draghead are now being developed.

Trawle, M. J. (1981a), "Prediction of Shoaling Rates for Deepened Estuarine Navigation Channels," Proc. 14th Annual Dredging Seminar (College Station, Tex.: Texas A&M University).

Abstract

This paper presents an empirical method of shoaling analysis based on historical dredging and shoaling records that results in reliable predictions of future shoaling for deepened channel conditions occurring either from an increase in authorized channel depth or from advance maintenance. The method presented was designed to be general enough that it can be applied to most navigation projects without difficulty. To demonstrate how the method would be applied to real navigation projects, the Texas City Channel in Galveston Bay, Texas, was evaluated and results were discussed.

Trawle, M. J. (1981b), "Effects of Depth on Dredging Frequency: Methods of Estuarine Shoaling Analysis, Technical Report H-78-5 (Vicksburg, Miss.: U.S. Army Engineer Waterways Experiment Station).

Author's Abstract

Whenever deepening of a dredged channel is under investigation, a prediction must be made as to the effect of the deepening on the existing dredging requirements. If the deepening is related to advance maintenance dredging rather than to an increase in authorized depth, the prediction becomes even more difficult because the project is allowed to shoal over a wide range of depth. Currently, a variety of arbitrary, rule-of-thumb procedures are used for predicting the effect of increasing depth on dredging requirements.

The overall objective of this investigation was to evaluate the effectiveness of advance maintenance dredging in reducing dredging frequency and/or costs in the maintenance of coastal channels and harbors and to establish necessary guidelines for governing the practice. This report, the second of a series, presents an empirical method of shoaling analysis based on historical dredging and shoaling records that results in reliable predictions of future shoaling for deepened channel conditions resulting either from an increase in authorized channel depth or from advance maintenance. The method presented was designed to be general enough that it can be applied to most navigation projects without difficulty. The procedure was described step-by-step using an example (fictitious) project. To demonstrate how the method would be applied to real navigation projects and to point out problems that occur when evaluating real projects, selected Galveston Bay, Texas, navigation projects were evaluated and the results discussed.

Trawle, M. J., and J. B. Herbich (1980), "Prediction of Shoaling Rates in Offshore Navigation Channels," Center for Dredging Studies, Department of Civil Engineering Report No. 232 (College Station, Tex.: Texas A&M University).

Abstract

This report discusses several techniques in use for prediction of future dredging requirements whenever enlargement of estuarine/coastal entrance channels is considered. The dredging requirements of six selected entrance channels for both the existing dimensions and the immediately previous dimensions were determined to evaluate the "volume of cut" prediction technique. The six projects, selected on the basis of availability of historical dredging data, were the Wilmington Harbor entrance channel in North Carolina, the Pascagoula Harbor entrance channel in Mississippi, the Calcasieu River entrance channel in Louisiana, the Sabine-Neches entrance channel and the Galveston Harbor entrance channel in Texas, and the Yaquina Bay and Harbor channel in Oregon. The adequacy of the "volume of cut" technique is investigated by predicting the dredging requirements for the existing project from the previous project dredging requirements. The results, although based only on a limited number of projects, suggest that the "volume of cut" technique can be a valuable tool during the preliminary analysis of a proposed entrance channel enlargement.

While the "volume of cut" procedure for predicting future dredging requirements for enlarged entrance channels, as described by the limited investigation conducted for this paper, is a rather simplistic approach to a very complex problem, analysis of the data does indicate a significant correlation between "volume of cut" and dredging requirements. A more detailed examination of the reliability of this method of prediction would necessitate the inclusion of other factors, not considered here, which can affect shoaling in an estuarine/coastal environment. Such factors include the effects of tidal action, channel alignment, littoral drift, storms, and wave action. The results of this report indicate that even a basic

analysis using the "volume of cut" procedure, without considering any of the above-mentioned factors, would aid significantly for prediction purposes in the preliminary stages of project design.

Troesch, A. W., and S. Cohen (1980), "Relationship of Underkeel Clearance and Vessel Speed to Grounding," Report No. 017999, Ship Hydrodynamics Lab, University of Michigan.

Abstract

The sinkage, trim and underkeel clearance of the lead barges in a 3 x 3 barge train were measured. The barges represented typical Mississippi River barges. The tests were conducted in response to a USCG request to investigate groundings due to channel depth decreases. The water depth varied from 2.6 to 1.05 times the barges' draft. There were two bottom contours: one with constant depth and one with an underwater obstacle in the form of a step. The speed of the barge train was varied from 2 kn to 8 kn, full scale.

Turner, H. D. (1978), "Physical Model Study for Improved Navigation Channel Design," 26th Proc., Annual ASCE Hydraulic Div. Spec. Conf.: Verification of Math. and Phys. Models in Hydraulic Eng., University of Maryland, August 9-11, pp. 265-272.

Abstract

The U.S. Army Engineer Waterways Experiment Station (WES) is conducting a study to determine the minimum dimensions of deep-draft navigation channels for safe and efficient navigation. The model study is focused on the improvement of navigation channel design methods and uses free-running, remote-controlled scale models of prototype ships as a means of evaluating the channels being tested.

Present navigation channel design criteria in the United States were formulated in 1965 and are based on the 1948 tests during the Panama Canal sea level project. The width allowance is from 2.8 to 5.0 times the design ship's beam for one-way traffic and 5.2 to 8.0 times the beam for two-way traffic. The width criterion depends on judgment factors relative to design ship controllability, strength of yawing forces, quality of navigation aids, type of channel, and bank orientation. The depth allowance is the sum of ship draft, salinity effects, wave action, squat, and underkeel clearance. The design of navigation channels is influenced by many factors, such as ship dimensions, ship power to weight ratio, ship rudder and propeller assemblies, type of traffic (i.e., one-way, two-way, overtaking), ship speed, pilot ability, and environmental conditions (i.e., wind, waves, fog).

In the model testing program, changes in ship draft, ship speed, channel width, and channel depth will be evaluated. The testing facility consists of two straight channel reaches connected with a typical bend in the middle and a turning basin at each end. Later in

the study, wind generators and a wave generator will be placed in the turning basin to simulate wind and wave effects on navigation at entrance channels. During a typical test run, time-based data such as ship speed, rudder angle and ship heading will be collected and analyzed to determine the safety of the channel. A test channel will be declared unsafe if an excessive amount of rudder is required to successfully navigate the cannel or if the model ship comes too close to either the side or the bottom of the channel. The test results will be compiled and used to construct design curves which define both channel and ship parameters. Similar design curves will be developed for various types of traffic, ships, navigation aids, pilot skill, and environmental conditions.

van de Ridder (1979), "Rotterdam and the Harbor Silt," Land and Water International, pp. 23-26.

Abstract
Maintenance dredging in the Rotterdam harbor basins is carried out by two methods: (1) bucket dredger operations and storage of spoil ashore and (2) trailing-suction dredger operations and dumping at sea. This paper describes the technical aspects of both of these methods.

The advantages of bucket dredgers are discussed, and the increased production obtained after introduction of density measurement instruments for determining nautical depth is outlined. The transportation of the spoil to the discharge area by barges and pipelines is also discussed.

Trailing-suction dredging operations are described for the period from 1963 to 1977 in the Europoort and Botlek areas. The problems involved in utilizing the full hopper capacity in both the winter and the summer months and in disposing of silt contaminated by pollutants are also discussed.

van Donselaar, H., et al. (1981), "The Maritime Impact of Liquid Energy Gases--the Planning and Operational Aspects," Maritime Ports and Seaways, Vol. I, Permanent International Association of Navigational Congresses, XXV, Sec. II.

Abstract
This report treats a certain number of aspects concerning the large-scale importation of liquefied gas into the Netherlands. The world's energy situation is briefly described, and arguments are presented for the importation of energy gases by the Netherlands. The risks involved in the transport of liquefied gases by seagoing vessels are discussed, and the factors governing the dimensions of channels and harbors are outlined. Information is given on the relationship between the ship behavior and the dimensions of the navigation

channel. Operational aspects, such as the regulation of traffic and ship-related safety measures and procedures are also considered. The results of traffic simulations of ships transporting liquefied gas are presented. Various implementation aspects are discussed with reference to existing harbors, a new shore-based harbor and an offshore harbor. The report concludes with some comments on dredging aspects of the activities involved with the adaptation of existing harbors or the construction of new ones.

van Oostrum, W. H. A. (1979a), "Maintenance Dredging in Soft-Bedded Navigation," Control Dredging Association (CDEA) Conf., Netherlands.

Abstract

This paper describes the problems and solutions in the process of maintenance dredging. The discussion includes the siltation process and the concept of nautical depth in a soft-bedded channel. A comparison of the advantages and disadvantages of density measuring probes and echo sounders is presented. The automation of data collection, data handling, and data presentation is discussed for the dredging and surveying operations. The dredging program and dredging decision are considered in terms of a programmed decision making model. The final item considered is the marketing policy, especially the ways in which to acquire the necessary capacity for dredging.

van Oostrum, W. H. A. (1979b), "MKO Project," Land and Water International, pp. 17-19.

Abstract

The aim of the MKO project is to study scientific, technical and economic possibilities for reducing the costs of maintenance dredging operations. The research project has been divided into three main parts: (1) studies of the morphological--and other--aspects of sedimentation, (2) research into dredging techniques, and (3) research into marketing and business economics. This paper considers part 1 in detail and briefly discusses part 2.

The sediment transport balance in the waterway area is analyzed, and several means of reducing the amount of sediment to be dredged are suggested. The effects of a silt trap placed at the mouth of Europoort are described, and the methods of measuring the density of silt deposits are outlined. The paper indicates possible solutions to the problem of recirculation of silt from the dumping ground at sea to the harbor entrance. A brief discussion of the programming dredging method and continuous hopper measurement system is included.

van Oostrum, W. H. A. (1979c), "Operations Research in Dredging," Terra et Aqua, 18: 2-15.

Author's Abstract

Modern dredging equipment constitutes a large capital outlay and is expensive to run. Therefore attempts are being made continuously to boost and to raise efficiency. In particular, attention has been given to improving the mechanical and technical components of the dredging system. During the last decade more and more electronics have entered dredging technology. Parallel to this, extensive developments have taken place in the field of hydrographical surveying. More recently attempts have been made to raise output in paid m^3 by improvement of the management of dredging operations. Computerized data-handling systems form the unavoidable basis for a further integration of the basic activities of dredging work.

The large capital and maintenance dredging works in the Rotterdam-Europoort area form an ideal test field to develop more efficient dredging methods. Operations research techniques are playing an increasingly important role and several projects in this field have already led to practical results such as programmed dredging, flight recorders, survey and positioning automation routing programs and navigation programming. As a binding element, computerized data-flow connects all these applications.

Although most applications are related to dredging works executed by self-propelled suction hopper dredgers, the methods are suitable for stationary dredging as well.

van Oostrum, W. H. A., W. R. Parker, and R. Kirby (1980), "Maintenance Dredging in Fluid Mud Areas," Third Int. Symp. Dredging Tech., Bordeaux, France, pp. 177-190.

Author's Abstract

Recent work has shown that most mud dredging problems arise from the penetration of harbor basins and channels by dense mobile near-bed layers. When these layers stagnate, rapid deposition occurs, forming fluid mud layers which exhibit characteristics transitional between true seawater and the seabed. These deposits present particular dredging problems and cannot be dredged efficiently at the present time.

As a result of the inefficiency of conventional maintenance dredging other alternatives may be adopted to decrease the dredging requirement. Examples discussed are the location of port facilities in zones of low sedimentation or prevention of silt penetration using locks, bubble curtains or removable barriers. Where siltation cannot be avoided it may be handled more efficiently, depending on local circumstances, by other concentration into traps or spreading. In many areas of very high sedimentation the only way to cope with the large sediment flux is by agitation dredging.

In fluid areas still dredged by conventional trailer-suction dredgers, increases in efficiency and production must be sought in improvements in surveying methods and in the design of dredging plant. In this connection density measurements are replacing conventional echo sounding surveys. The value of density surveys is that they provide repeatable information on seabed characteristics which are directly applicable to dredging requirements and to the navigation of ships. Complementary developments of dredging systems directed both to trailer-suction dredgers themselves and also to the development of novel concepts such as stationary dredgers with the complete removal of spoil from the local water circulation, point the way to major increases in efficiency.

van Oostrum, W. H. A., et al. (1981), "Dutch Efforts for Optimization of Marine Dredging," Proc. XXV Int. Nav. Cong., Inland and Maritime Waterways and Ports, PIANC, Section II, Vol. 2, Edinburgh, Scotland, May 10-16.

Abstract

A review of the present state-of-the-art in various fields of the dredging industry is presented. The discussion includes surveying methods, the nautical depth concept, overdredging, positioning system, sampling techniques, dredging automation, and cost estimates.

Wang, S. (1980), "Full-Scale Measurements and Statistical Analyses of Ship Motions in a Navigational Channel," Marine Tech., 17: 351-370.

Author's Abstract

Due to the trend of large dry and liquid bulk carrier construction in recent years, safe navigation in ports and channels has been a great concern to both the governmental regulatory agencies and the maritime industries. This paper presents the results of a study on motions of deep-draft vessels in a navigation channel. The objective of this study was through measurement and analysis of the vessel motions to validate the design assumptions for a specific channel as well as to establish the general design information on channel width and depth requirements, with respect to the ship characteristics and channel environments.

Full-scale measurements of motion characteristics for 29 vessel transits through the Columbia River Entrance Channel have been conducted. The measurements include pitch, heave and roll motions, vessel heading angles and position tracks. Analyses of the measured data have been conducted with the objective to derive both the short-term and long-term statistics. For short-term correlations, all the motion variations have been assumed stationary, and comparisons of the histograms of motion amplitudes with the theoretical Rayleigh

distribution have been conducted and found satisfactory. As to the long-term statistics, it is found that the measured data can be very well represented by the log-normal distribution.

Waugh, Richard G., Jr. (1971), "Water Depths Required for Ship Navigation," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 97(WW3): 455-473.

Abstract

The state-of-the-art in the selection of channel depth is briefly reviewed to emphasize the fact that channel depth design in the United States has been more a matter of judgment than one of rigorous engineering analysis. The factors influencing the choice of channel depth are discussed in detail. The recent increase in ship sizes is outlined and a tabulation of channel depths in world ports is presented in the Appendix. While the largest man-made federal navigation channel in the United States to accommodate bulk commerce has an effective depth of 45 ft, excluding additional clearances over the ocean bar, several dredged channels in foreign ports have depths exceeding 60 ft.

Changes in water salinity and temperature influence the density of water and vessel draft. The trim of the vessel as loaded must also be considered in channel depth design. For many vessels, trims of 1 ft to 2 ft at rest are not uncommon. Normally, a 1 ft allowance is provided in selecting the channel depth.

Vessel squat is a function of the vessel speed, water depth, wetted cross section of the vessel, and the width and section of the waterway. It can be shown that squat is also affected by the location of the vessel in the waterway, the trimness of the vessel's lines, and the presence of other vessels in the same cross-section. Although vessel squat can be computed accurately in well-defined, regular sections, little is known of vessel squat in deep and wide waterways.

Changes in trim while under way may cause the stern of the vessel to slam the bottom as its speed increases. As the vessel approaches the channel banks, its squat will tend to increase. The presence of passing vessels will also increase the squat due to the reduction of water area. The influence of waves on the ship motion and draft must be taken into consideration, particularly in the ocean entrance channels.

After allowances have been made for increases in a vessel's draft due to squat, trim, freshwater density, and wave motion, an additional allowance is added by the Corps of Engineers. The general practice has been to provide 2 ft of clearance between the vessel's keel and the channel bottom in soft material and from 3 ft to 4 ft where rock is encountered. Although primarily for safety, this clearance increases vessel operating efficiency because under shallow water conditions, the speed decreases, the resistance increases, and the rudder response becomes more sluggish.

The information available is inadequate to determine the safe navigation depth required for vessels moving in restricted channels. It is believed that the most critical single factor in channel depth design is vessel squat. While some data have been accumulated for vessels in canals, little is known of the vessel phenomena that take place in irregular-shaped channels and estuaries.

Wicker, C. F. (1971), "Economic Channels and Maneuvering Areas for Ships," J. Waterways, Harbors and Coastal Eng., Proc. ASCE, 97(WW3): 443-454.

Abstract

The state-of-the-art involved in the design of a ship channel is briefly reviewed to stress the lack of knowledge concerning the channel depths, widths, and alignments necessary for safe navigation. The selection of the channel depth depends on factors such as squat, changes in draft, due to differences in water density, ship response to waves, and underkeel clearances required for large vessels to maintain a given speed in shallow depths. However, little is known about squat in narrow, deep channels in estuaries, or the effects of passing vessels, channel banks, and poor trim on squat. Ship response to waves and power requirements for large vessels in shallow waters are also not well defined. The design width of a channel depends on the handling characteristics of the vessels using the waterway and the effects of winds, waves, and currents on vessel heading. However, reliable information on the effects of passing vessels, channel banks and varying conditions of operation and loading is not provided to channel designers. The width of the channel at the turns is considerably wider than the straight reaches. Although the vessel length, speed of travel, rudder response, and proximity of the banks should be considered in determining the amount of turn, there are no data on the coefficients to be applied in the relationship. As a result, channels are generally planned in accordance with the best depths in a natural waterway, or to minimize excavation, with little attention to the needs of navigation.

A comparison of costs for a hypothetical excavation using 2 ft overdepth with maintenance dredging is made for an overly conservative channel design and an adequate, safe channel to illustrate the excessive cost of making the channel wider and deeper than necessary. Another cost comparison is made between an unsafe channel and an adequately safe channel, to demonstrate that the apparent savings involved in a minimal channel are likely to be exceeded by the potential losses due to accidents, loss of life, loss of vessels, costs of removal of wrecks, vessel delays, and cleanup of pollution.

A discussion of the factors involved in the design of navigation channels includes environmental considerations such as the tidal range, currents, waves, water densities, ice conditions, meteorological conditions, geometry of the waterway, bottom materials,

and shoaling potential. Vessel considerations such as length, beam, static draft, trim, cruising speed, and controllability are also discussed. Factors to be considered for vessel operation in channels include speed and spacing regulations, density and frequency of transits, overtaking or meeting vessels, and mix of vessels in the traffic pattern. The human factor of pilot decisions must also be included. Human failures can involve a lack of knowledge of the channel inadequacies or the vessel peculiarities, a lack of skill, a tendency to risk-taking, or a lack of complete attention.

With increasing vessel size and cost, navigation channels must be deepened and widened, and the designer must be provided with the necessary knowledge to design safe and economic channels.

Yeung, R. W. (1978), "On the Interactions of Slender Ships in Shallow Water," J. Fluid Mech., 85: 143-159.

Author's Abstract

The unsteady hydrodynamic interaction of two bodies moving in a shallow fluid is examined by applying slender-body theory. The bodies are assumed to be in each other's far field and the free surface is assumed to be rigid. By matched asymptotics, the inner and outer problems are formulated and a pair of coupled integro-differential equations for determining the unknown cross-flows is derived. The degree of coupling is shown to be related to a bottom-clearance parameter. Expressions are given for the unsteady sinkage force, trimming moment, sway force and yaw moment. Numerical calculations for two weakly-coupled cases are presented. One corresponds to the interaction of a stationary body with a passing one; the other to the interaction of two bodies moving in a steady configuration. Theoretical results are compared with existing experimental data.

Zahn, A. S. (1977), "Grounding Characteristics and Effects," Final Report on Task 5, Oct. 76 - Jan. 77, prepared for U.S. Maritime Administration by George C. Sharp, Inc., New York.

Author's Abstract

Data on the details of 52 groundings were collected from the files of IMCO and USCG from 1944 to 1975. Cases are identified by number or name, flag, type, tonnage and characteristics. Information lists repair costs, location of casualty, weather, cause of grounding, speed of impact, information on double bottom condition; damage location, description, length, width and depth; also type of sea bottom.

The data have not been analyzed.

APPENDIX B

SELECTION FROM ENGINEER MANUAL*

CHANNEL AND HARBOR DESIGN

5. CHANNEL WIDTH, DEPTH, ALIGNMENT, AND ORIENTATION. *a.* **Based on navigation requirements.**

General Channel width is premised on the beam and steering characteristics of the design vessels, the traffic density and the characteristics of other vessels encountered in the channel, the characteristics of the waves likely to be experienced in the several reaches, as well as the characteristics of the banks. Channel depth is determined by the in-motion draft of the design vessel, the density of the water, wave characteristics, the tidal characteristics, the characteristics of the bottom, and the economics of greater depth as a factor in reducing power requirements for the propulsion of the design vessel. Channel alignment and orientation from the viewpoint of navigation are determined on the basis of the length of the design vessel, the characteristics of the waves in the several reaches, and the strength and direction of the currents. It will be noted that the characteristics of the design vessel enter into every aspect of channel design.

The design vessel. It is well known that there are nationwide and worldwide trends towards larger general cargo and bulk-carrying vessels. Similar trends may or may not be applicable to traffic on the waterway under consideration, due to peculiarities of the commerce that is expected. For example, if the existing depths in the other ports of call involved in the prospective commerce are not likely to be increased, then it is probable that the characteristics of the vessels will remain constant throughout the economic life of the project The selection of the design vessel will be made realistically, as it would be wasteful to provide a channel of greater depth and width, or a better alignment, than is necessary to accommodate the vessels likely to use it. The initial step should consist of an examination of general trends in the classes of vessels involved, then determinations may be made as to their applicability. Data on general trends may be seen in "General Cargo Vessels—Trends and Characteristics,"[18] "Study of Trends in Petroleum Supply and Requirements and Tanker Fleets and Characteristics,"[17] and "Trends in Dry Bulk Carriers."[19]

Channel depth. The design depth of the channel will be premised upon the drafts of the design vessel while in motion, including the effect of squat, rolling, and pitching; plus a nominal clearance of 2 or more feet; plus an allowance for frequent low tides that are below mean low water, when vessel delay is uneconomical, or minus an allowance for some stage above mean low water when the resulting delay of vessels is not uneconomic. Consideration will be given to the provision of greater depths than those required for safe navigation, as determined by the foregoing considerations, when it can be shown that the reduced power required to propel the vessel at a maximum safe speed at the greater depths produces savings commensurate with the costs of providing the greater depths.

The draft of a vessel in motion is determined by the static draft of the vessel in water of the density of that which will be in the channel to be designed; the speed of the vessel relative to water, in the channel to be designed; the distance between the channel bottom and the vessel keel; the characteristics of the vessel; the characteristics of the channel, i.e., whether it is located in open waters or is fully restricted; the likelihood that the vessel will meet and pass other large vessels; and the amount of the roll and pitch of the vessel due to wave action. The draft of the vessel while transiting the channel to be designed may vary from reach to reach depending on the safe speeds for the various reaches, water speed variations, water density variations, and variations of the geometry of the waterway and the navigation channel.

*U.S. Army Corps of Engineers (1965), Tidal Hydraulics, Engineer Manual EM 1110-2-1607 (Washington, D.C.: U.S. Army Corps of Engineers), pp. 7-12.

The static draft of the design vessel will not necessarily be assumed to be that in its fully loaded condition. In many instances, it has been found that the draft on both arrivals and departures is less than that of the fully loaded ship. On the other hand, it may be found that the as-loaded condition results in a greater draft aft than forward, or vice versa. The static drafts taken for channel design purposes will be those considered to be normal for the particular operations of the design vessel in the channel under consideration.

The static draft of a ship is usually stated with reference to its flotation in "summer salt water." In passing from sea water of normal ocean salinity to fresh water, a ship having a static draft of 35 feet in sea water at 15 degrees centigrade (density 1.026) will have a static draft of 35.9 feet in fresh water at the same temperature. If the channel to be designed traverses a waterway having brackish or fresh water, care will be taken to assure that the static draft to be used in the design of the channel is commensurate with the normal density of the water in the proposed channel. In some waterways, the density may vary from mouth to head of tide.

The increased draft of a vessel while under way, or "squat," as it is more commonly known, is a variable depending on many factors including the characteristics of the vessel itself. It must be evaluated based on conditions likely to be experienced in the operations proposed in the channel to be designed. It sometimes happens that the owners of the design vessel have data on its squat under various conditions, but it is likely that dependence will have to be placed on estimates. Chapter X of Reference 4 provides information that will facilitate making estimates of the squat, and References 19, 20, and 21 go into the theory of the phenomenon. A squat of about 3 feet is likely to be the maximum.

The speed at which the design vessel will be operated in the proposed channel should be selected very carefully. It will normally be less than the full speed possible in the open ocean, as both squat and vessel-generated waves become excessive at high speeds in a relatively shallow and narrow waterway. It is unlikely that it will be economic to design a channel of such depth and width as to permit full speed of the design vessel, and such speed in most waterways would not be permitted because of the hazards. Large waves may damage shore establishments and moored vessels, and they could be very hazardous for small craft.

The rolling and pitching of vessels due to wave action causes parts of the vessel to descend to depths greater than that due to squat alone. For example, a 5-degree roll of a vessel with a 100-foot beam would increase the draft of the vessel about 3.5 feet. The increase in draft due to pitching could be even greater, depending on the height and length of the waves experienced, and the length of the vessel. Consultation with masters of ships similar to the design vessel may yield reliable information on the amount of roll and pitch under conditions likely to be experienced in the channel under design. This subject has been given considerable study; see "On the Motion of Floating Bodies," [22] or "The Motion of a Ship, as a Floating Rigid Body." [23]

Determination of minimal channel depths will be premised on the drafts of the design vessel under normal operating conditions in the channel. They will include allowances for sinkage due to fresh or brackish water, squat, rolling, and pitching. In addition, an allowance of 2 feet will normally be added to the draft of the vessel while in motion, including increments due to rolling and pitching. As a safety precaution, this clearance between the keel and the bottom will be increased to 3 or more feet if the bottom is rock.

Examples of the computations that should be made for several reaches of a hypothetical channel follow:

Reach 1. Entrance channel, full speed permitted, severe wave action possible, sea water of normal ocean salinity, sandy bottom.

Design vessel static draft	29.0 feet	(Summer sea water)
Squat for economic speed	3.0 feet	
Rolling and pitching	6.0 feet	
Clearance	2.0 feet	
Required channel depth	40.0 feet	

Reach 2. Intermediate reach, shoreline undeveloped, traffic density low, full speed permitted, moderate wave action, water of half-normal sea water salinity, sandy bottom.

Design vessel static draft	29.0 feet	(Summer sea water)
Sinkage due to brackish water	0.5 foot	
Squat for economic speed	3.0 feet	
Rolling and pitching	2.5 feet	
Clearance	2.0 feet	
Required channel depth	37.0 feet	

Reach 3. Terminal section, shoreline highly developed, traffic density great, reduced speed required, no wave action, fresh water, rock bottom.

Design vessel static draft	29.0 feet	(Summer sea water)
Sinkage due to fresh water	1.0 foot	
Squat for safe and economic speed	2.0 feet	
Rolling and pitching	0.0 foot	
Clearance	3.0 feet	
Required channel depth	35.0 feet	

The depths thus determined may be referred to mean low water (or mean lower low water on the Pacific coast of the United States) or above or below these datums. In cases where design vessel traffic will be low, it may be in order to provide a channel of the design depth when the tide is, say, at half tide level. Where the number of transits of the design vessel and other vessels of comparable draft will be large, and the frequency of tides below mlw or mllw also is large, consideration will be given to the provision of the design depth when the tide is at some stage below mlw or mllw. In all cases, the basis of the decision will be an economic analysis involving the delays that will be experienced by vessels and the saving in dredging costs. In making such an analysis, it must be kept in mind that a vessel can ordinarily carry a given tidal stage throughout most of its journey upstream in the majority of estuaries of the United States, but this cannot be done during downstream passages in the longer estuaries.

In waterways where the selected plane of reference for providing the design depths varies significantly in absolute elevation from reach to reach, the waterway should be sectionalized and a separate datum used for each section rather than a single datum for the entire waterway. In some cases, local mean low water is as much as a foot higher in the upstream reaches as compared with the lower sections. If the design depth is excavated relative to a common datum throughout such a waterway, the resulting depth would be 1 foot greater in the upper section than would exist in the lower section. This useless increment of depth could be very costly.

Channel width. The width of the channel is measured at the bottom of the side slopes, i.e., at the design depth. The design width depends on whether the design vessel is likely to meet and pass other vessels that must stay in the main navigation channel, whether the channel is in a wide waterway, the characteristics of the bed and banks, the design depth, the existence of yawing forces such as currents and waves at angles to the channel, and the characteristics of the vessels and their operators. There is no formula for evaluating all of these factors and their complicated interrelationships, but Reference 4 should be consulted for guidance. In addition, study of other waterways having commerce similar to that expected in the channel being designed may be helpful. However, it should not be assumed that the proper width is necessarily that of an accident-free channel in another waterway with similar characteristics; it may be that that channel is uneconomically wide.

Channel alignment. Knowledge pertaining to this area of channel designing is presently inadequate. Experience has shown that it is more difficult to navigate a vessel on a curve than in a tangent reach; that the difficulty increases as the radius of curvature decreases, also as the size of the deflection angle increases; that reverse curves are undesirable; and that sighting distances in the curve must be adequate for the safe passing of other vessels in the curve. It is thought that the radius of curvature should be related to the lengths of the larger vessels expected to use the waterway, but there is little experimental or theoretical data available for determinations of limiting values for the radius of curvature, the deflection angle, the tangent length between curves, and the sighting distance. In Reference 19, it will be found that conclusions were reached, based on judgment alone, that the minimum radius of the proposed sea-level Panama Canal should be 12,500 feet, the maximum deflection angle 26 degrees, the minimum tangent length 4.2 miles, and the minimum sighting distance 1.52 miles. Channel widening at turns should be accomplished in accordance with the criteria presented in chapter X of Reference 4.

It is noteworthy that the channel alignments of important existing projects in the United States are often inferior to those proposed by the Panama Canal engineers. In brief, if curves must be used, the best practice will be to lay out the channel with the maxima radii and the minima deflection angles, and the maximum tangent distances that the physical conditions permit, without incurring excessive first or annual costs. A radius of less than 5000 feet appears undesirable for major commercial waterways for vessels over 500 feet in length.

Channel orientation. The orientation of the channel within the waterway depends largely on the orientation of the natural deep reaches. In general, these follow the direction of the currents, which is desirable from the viewpoint of navigators. If the current is at an angle to the channel, steering will be somewhat more difficult. The orientation of entrance channels should be such as to head them into the direction of storm waves, if practicable.

b. **Channel width, depth, alignment, and orientation based on ease of maintenance.**

General. The design of a channel for ease of maintenance must of course go hand in hand with design in the interest of navigation. It is rare that the channel which is most favorable to navigation is also the one that requires the least maintenance, and it is therefore sometimes necessary to consider a channel that is less than the optimum, from the viewpoint of navigation, to keep annual costs of maintenance within reasonable bounds. For example, channels that do not follow the natural thalweg usually are more subject to shoaling than those that are located generally along its course but as the thalweg is often somewhat sinuous, it is more difficult to navigate than a channel with longer tangents. Commercial or recreational needs often indicate the desirability of extending a channel into the upper limits of the estuary, or into coves, tributary streams, or interior basins, but it often happens that such channels shoal much more rapidly than the existing downstream channel.

Channel depth. The construction of a channel that is appreciably deeper than the natural depths along the course of the thalweg, or the deepening of an existing channel, may engender a difficult maintenance problem. After the depth required for safe navigation of the design vessel has been determined, it may be found that such a channel cannot be justified. Consideration will then be given to channels of lesser depths that would be suitable for the design vessel when advantage is taken of the tide. The governing considerations frequently are the natural depths of the thalweg, the depths beyond the limits of the proposed channel, the magnitudes of the changes in the cross sections of the estuary if the proposed channel is constructed, and the kinds of material available in the waterway beyond the limits of the channel for transport into the channel by density flows and by the tidal currents. For example, the shoaling rate of a channel of a given width and 40-foot depth located in a relatively very wide waterway may not be appreciably greater than that of a channel of the same width but 37 feet deep. The resulting cross sectional areas created by the two channels may not be significantly different. On the other hand, if the range of tide is large it may be possible to serve the design vessel reasonably well with a channel depth of 30 feet instead of the optimum of 40 feet. In this case, the resulting cross sectional area may be sufficiently closer to the natural or pre-improvement cross sectional area to effect a considerable saving of maintenance costs. Similarly, if the natural depths along the thalweg are 10 feet and a channel of 40-foot depth is the optimum, it is unlikely that there would be much difference in maintenance costs between a 40- and a 37-foot channel, other factors being equal, but the difference could be appreciably between 40- and 30-foot channels.

Channel depth sometimes has a profound effect on the distribution of shoaling as well as the rate of shoaling. For example, a channel 40 feet in depth may cause the bulk of the shoaling to occur in a place where there are no disposal areas, while a channel depth of 35 feet may shift the location of the heaviest shoaling to a location downstream, where disposal areas are plentiful, or the effects of the two depths could be reversed from those discussed here. Distance of the disposal area from the bulk of the shoaling is, of course, a factor in the cost of maintenance. Channel depth helps determine the location where the upstream predominance of bottom currents over downstream bottom currents occurs. References 8 and 15 should be consulted for additional information on this matter.

Channel width. While channel width and channel depth are factors of equal significance insofar as cross sectional area is concerned, it appears that inadequate depths are much more hazardous than inadequate widths, and they cause greater delay to vessels. On the other hand, a choice between the provision of a channel of width adequate to permit two-way traffic and inadequate depths at low tide, as compared with a channel suitable for one-way traffic of design vessels and of adequate depth even at low tide, must take cognizance of the possibility that the greater depth may cause a shift in the location of the bulk of the shoaling.

Channel alignment. Channels should be located as closely to the alignment of the thalweg as is practicable, keeping in mind that the larger vessels cannot navigate the sharp bends that sometimes are characteristic of the alignment of the thalweg. In cases where there are two deep areas of approximately equal depth, the relative merits of each should be considered before selecting one of them for improvement. When it is found that the alignment of a channel located on the thalweg would be too sinuous to serve the design vessel reasonably, consideration will be given to the use of training works having for their purpose the shifting of the current, and with it the location of the natural thalweg, more nearly to conform with the necessary alignment of the channel for navigation. Local interests may desire to have the channel located adjacent to the inside bank of the waterway in order to permit development of the frontage for docking facilities. This is fundamentally unsound; both the channel and the water areas adjacent to the docks will shoal rapidly and there is generally no satisfactory remedy.

Entrance or approach channels to tributary streams, harbor areas in coves or in canals, and docks located on the inside of curves, must be aligned across the currents of the main waterway. If the natural depths along the course of such channels are inadequate to serve the navigation for which the facility is designed, it must be expected that the dredged channel will be subject to rapid shoaling. As it is unlikely that a practicable remedy for this shoaling can be found, the channel may as well be aligned to follow the shortest path to the facility, consistent with the needs of navigation.

c. **Channel width, depth, alignment, and orientation based on effect of water quality.** Changes in the geometry of tidal waterways caused by deepening, widening, or extending channels in the interest of navigation may have an important and far-reaching effect on the salinity of the water and on the flushing and dispersal characteristics of the regimen. These effects may cause pollution of water that formerly was used for domestic and industrial purposes, and thereby cause a severe economic loss. The change in the salinity may affect the hydraulics of the waterway in a manner that will cause shoaling.

These possibilities should be evaluated very carefully in formulating conclusions as to the advisability of modifying a channel. References 4, 8, and 15 should be consulted for guidance in setting up the study. In the event it is found that a channel modification of the nature most desirable for navigation will have adverse effects on the quality of the water and hence on its value as a source of water supply, further study may consider possible reductions of the dimensions and/or extent of the channel, barriers to exclude salinity, upland reservoirs to enhance low fresh water flows, or the provision of an alternative source of water supply to replace the tidal waterway as a source of water supply.

APPENDIX C

ENVIRONMENTAL PROTECTION LAWS REQUIRING
COMPLIANCE, MAJOR NAVIGATIONAL PROJECTS*

National Environmental Policy Act (NEPA)

- Requires preparation, filing, and review of Draft and Final EIS with agencies and the public. NEPA actions run concurrently with Feasibility Report preparation. Final EIS accompanies Final Report.

Fish & Wildlife Coordination Act (FWCA)

- Requires coordination, preparation, and review with Fish and Wildlife Service, National Marine Fisheries Service, and the head of the State Wildlife Resource Agency. FWCA planning actions run concurrently with Feasibility Report preparation. Final FWCA report accompanies Final Report and EIS.

Endangered Species Act

- Requires coordination and preparation of a Biological Assessment with the Fish and Wildlife Service. Coordination and consultation (if necessary) runs concurrently with Feasibility Report. Final Determination (and Conservation Plan, if necessary) accompanies Final Report and EIS.

Clean Water Act

- Requires assessment, preparation and review of Section 404(b)(1) Evaluation Report in accordance with EPA guidelines. EPA has veto over disposal operation. Document prepared concurrently with Feasibility Report. Final EIS with 404 Report may be submitted to Congress under 404(r), or a State Water Quality Certificate may be obtained under Section 401.

National Historic Preservation Act and the Preservation of Historical and Archeological Data Act

- Requires reconnaissance studies and consultation with Advisory Council on Historic Preservation, National Park Service, and State Historic Preservation Officer. Results of coordination and consultation documented in Feasibility Report and Final EIS. Actions run concurrently with Feasibility Report.

Coastal Zone Management Act (CZM)

- Requires coordination with State agency administering CZM to ensure compliance with Consistency Provisions of the Act. Coordination runs concurrently with Feasibility Report.

Marine Protection Research and Sanctuaries Act (*Ocean Dumping Act*)

-Compliance required if ocean disposal is recommended. Requires application of EPA ocean dumping criteria. Undertake necessary bioassays and prepare evaluation and findings for inclusion in Feasibility Report and EIS. EPA has veto over disposal operations.

Summary

All necessary coordination, evaluation, and review of the above-listed environmental laws is undertaken concurrently with the planning of a Corps project and compliance documented in the Feasibility Report and EIS. Depending on the scope and complexity of the proposed project the preparation of the Feasibility Report may take from 24 to 48 months.

*Source: E. R. Heiberg III (1981), Testimony before Subcommittee on Water Resources, Committee on Public Works and Transportation, U.S. House of Representatives, 97th Congress, 1st Session (June 16, 17-July 14, 15, 1981). Report 97-26, Port Development, pp. 606-607.

APPENDIX D

Description of Mathematical Model

The navigation channel design model is intended to simulate the reactions of the design vessel(s) in a given set of conditions. The model is composed of several modules intended to evaluate squat, bank suction, vessel attitude, thrust for a specified stopping distance, and ship-generated waves (Figure D-1). The modular construction allows for changes to be made with relative ease as advances are made in an area of analysis.

As specified by the control cards, data are read in and distributed by the main module to the respective modules. After the specified modules have completed their evaluation, control is transferred back to the main module.

The input data consist of eight cards. The purpose of each card is listed below:

Card #1 specifies the analysis to be performed and the azimuth of the inbound vessel. In addition, it specifies whether an inbound, an outbound, or a combination analysis is to be performed.

Card #2 specifies title information which would identify the channel analysis being performed.

Card #3 specifies the section geometry for the channel under consideration.

Card #4 specifies the magnitude and direction of both the current and the wind. In addition, the water density and temperature are given.

Card #5 specifies the navigable channel limits, the thickness of the channel boundary layer, and the bank elevations.

Card #6 specifies the primary vessel characteristics, e.g., draft, beam, length, minimum and maximum speeds, vessel boundary layer thickness, position from centerline, maximum rudder angle, wind area, displacement, and stopping distance.

Card #7 specifies the secondary vessel characteristics, if the passing condition has been specified.

Card #8 specifies the entrance length of the primary vessel.

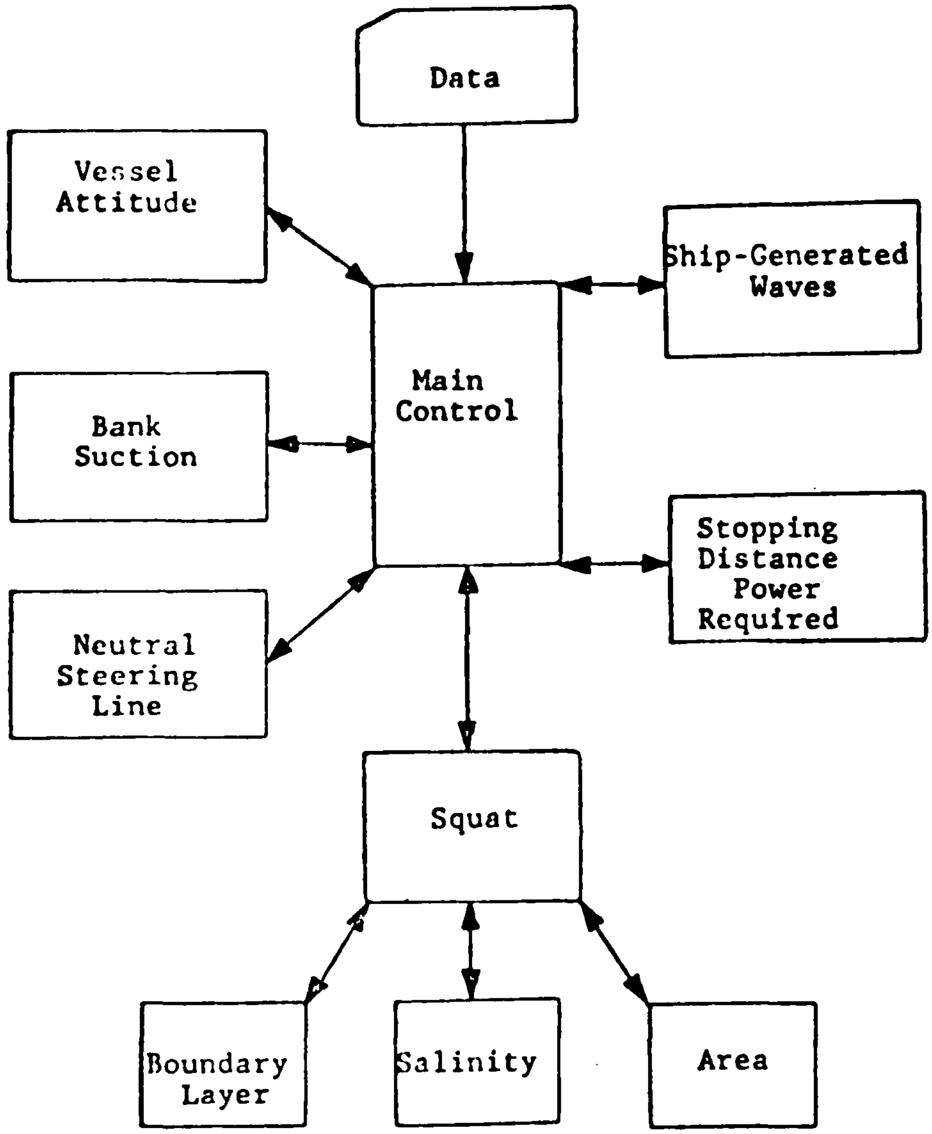


Figure D-1   Channel design evaluation model

Description of Modules

<u>Squat computation module</u> The squat module checks the salinity of the water to determine if vessel draft needs to be adjusted. Squat is computed for the primary vessel at various speeds for the on-centerline or passing case (or both). The basic equation (Gartnune et al., 1948; Tothill, 1966) is

$$\Delta d = \frac{V^2}{22.6}\left[\left(\frac{A}{A'}\right)^2 - 1\right]$$

where Δd = squat (in ft)
V = velocity (in kts)
A = cross-sectional area of flow in channel, absent vessel (in ft^2)
A' = cross-sectional area of flow with ship in channel section, experiencing squat

The computation terminates when the incremental speed reaches one of the following:

- o maximum vessel speed;
- o critical velocity; or
- o vessel touches bottom.

In the development of the model, calculated values were compared to field measurements and found to agree satisfactorily (Figure D-2). Figures D-3(a) through D-3(1) illustrate results for squat in nine channels selected by the panel.

<u>Neutral Steering Line and Bank Suction Module</u> If bank suction is required, then the neutral steering line is calculated. This is the sailing line of a vessel along which lateral forces and turning moments owing to bank suction are balanced. If the channel cross-section is symmetrical, the neutral steering line is the channel centerline; if asymmetrical, the module calculates the distance from centerline to neutral steering line, adding this value algebraically to the distance from the centerline of the ship's position. These values are then used in the bank suction computations, which encompass lateral forces and moments due to bank suction effects for various speeds, using the method proposed by Schoenherr (1960). In validation of the model, computed and measured values (from model tests) were in satisfactory agreement for symmetric and asymmetric cross-sections of channels.

<u>Vessel Attitude Module</u> This module computes the additional forces due to current and wind and adds these values to the forces calculated in the bank suction module. The rudder and drift angles required to neutralize the total forces and moments are then calculated for selected speeds, based on the method described by Bindel (1960), and the addition of an off-centerline coefficient.

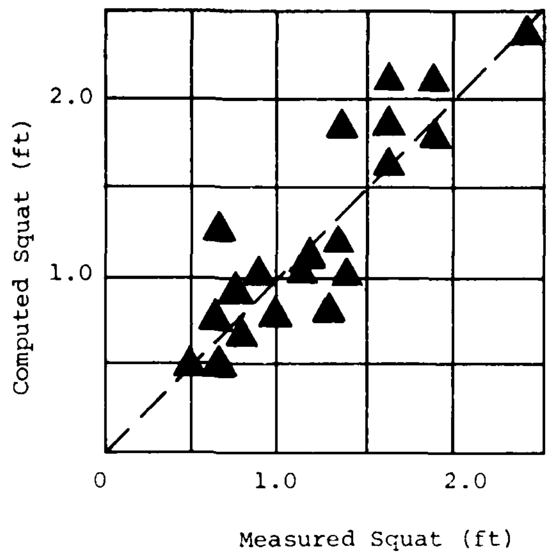
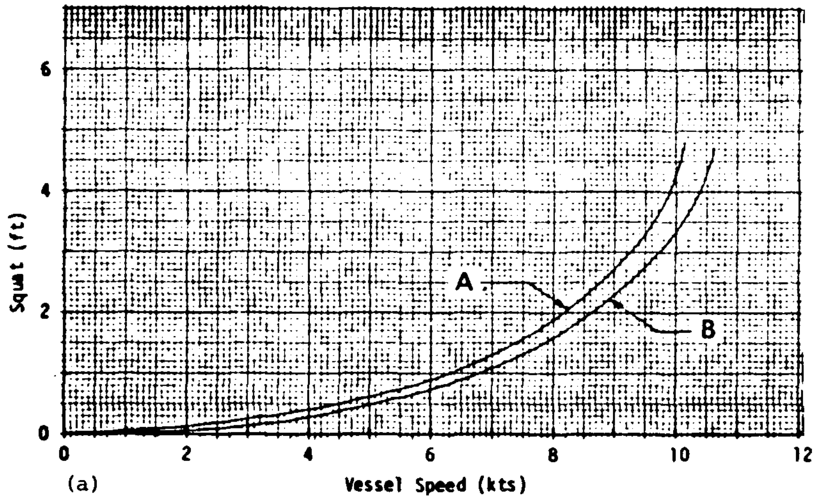
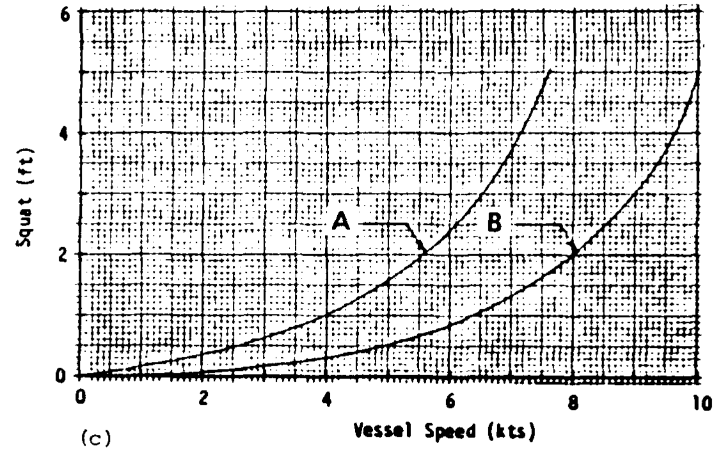


Figure D-2 Comparison of computed and measured squat

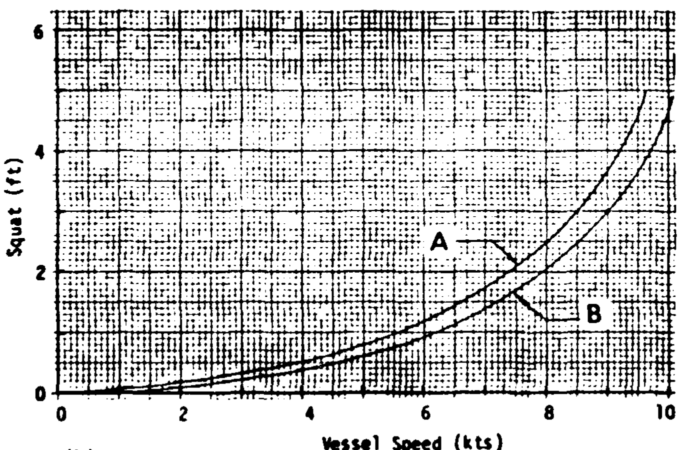
Figure D-3: Computed squat for selected channels and vessels (A = inbound; B = outbound)



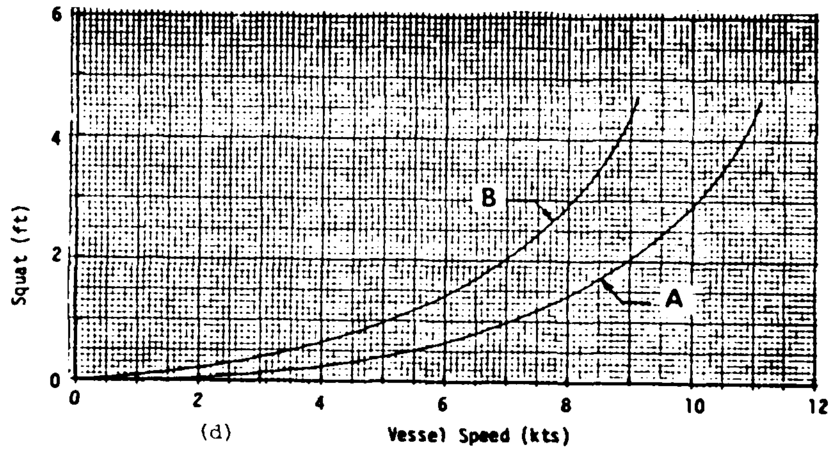
(a)
Location: Calcasieu River; Vessel: Lenino (LxBxd = 640x89x35)
Section: Inner Channel
Depth: 40 ft
Width: 400 ft
Slope: 1/2.5



(c)
Location: Lower Columbia River; Vessel: Lenino (LxBxd = 640x89x35)
Section: --
Depth: 40 ft
Width: 600 ft
Slope" 1/3

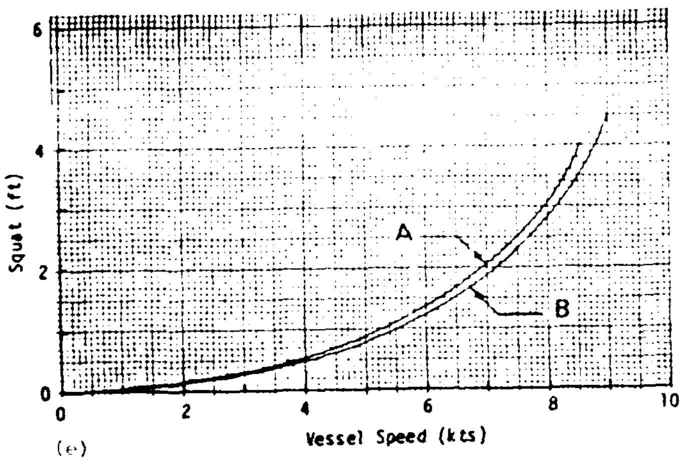


(b)
Location: Calcasieu River; Vessel: Chevron Oregon (LxBxd = 625x96x37)
Section: Outer
Depth: 42 ft
Width: 800 ft
Slope: 1/2.5

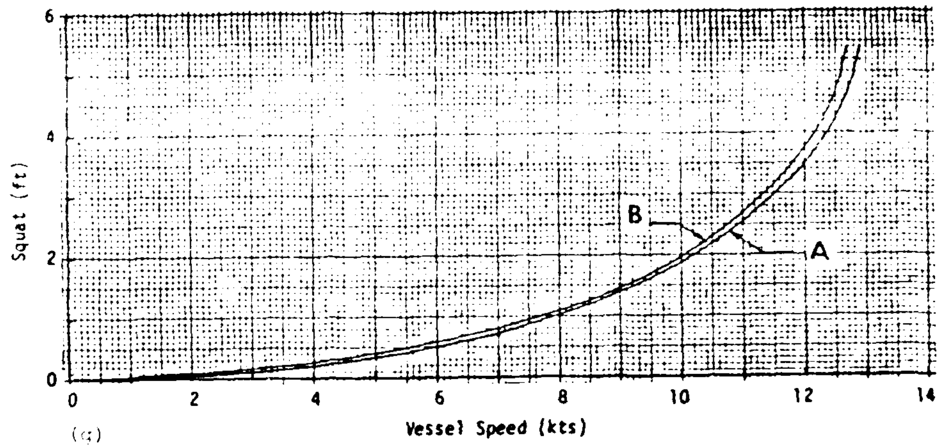


(d)
Location: Delaware River; Vessel: Chevron Oregon (LxBxd = 625x96x37)
Section: --
Depth: 42 ft
Width: 800 ft
Slope: --

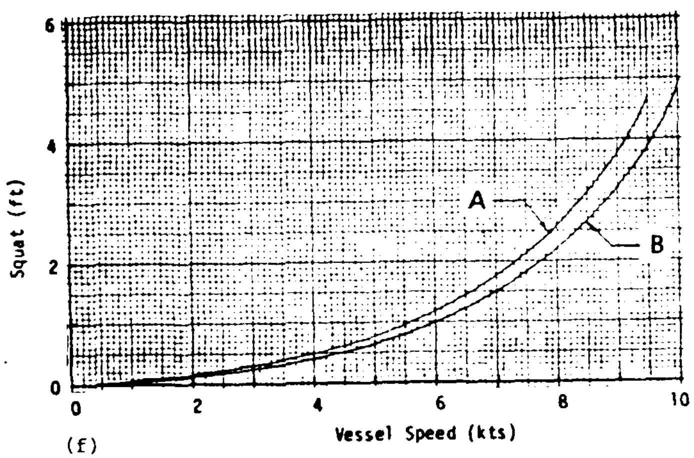
Figure D-3, continued



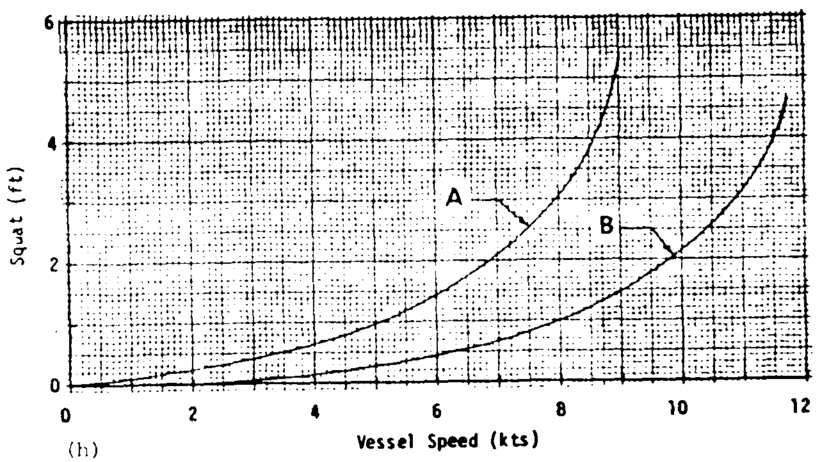
(e)
Location: Mobile Harbor; Vessel: Chevron Oregon (LxBxd = 625x96x37)
Section: --
Depth: 42 ft
Width: 600 ft
Slope: 1/5



(g)
Location: Norfolk Harbor; Vessel: Christos Bitas (LxBxd = 732x103x40)
Section: --
Depth: 45 ft
Width: 1500 ft
Slope: 1/3

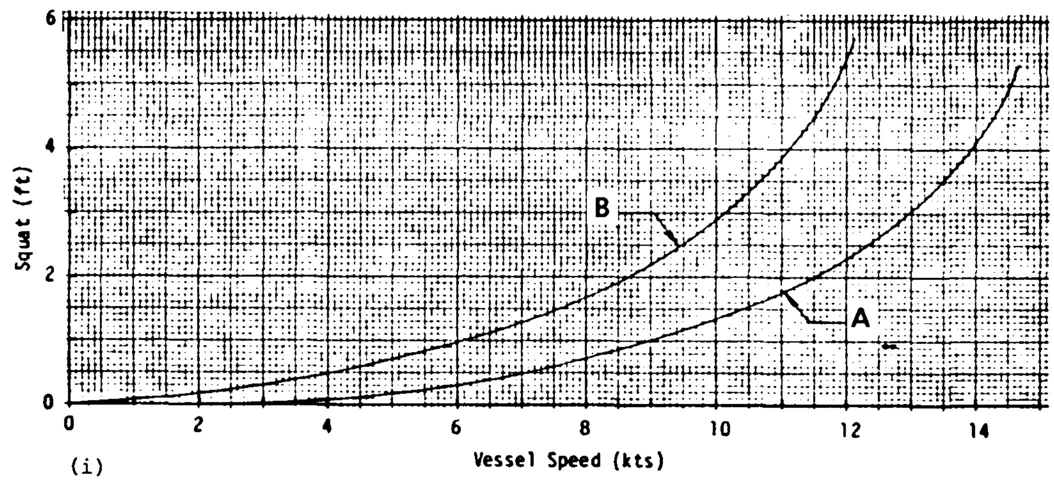


(f)
Location: Norfolk Harbor; Vessel: Christos Bitas (LxBxd = 732x103x40)
Section: --
Depth: 45 ft
Width: 800 ft
Slope: 1/3



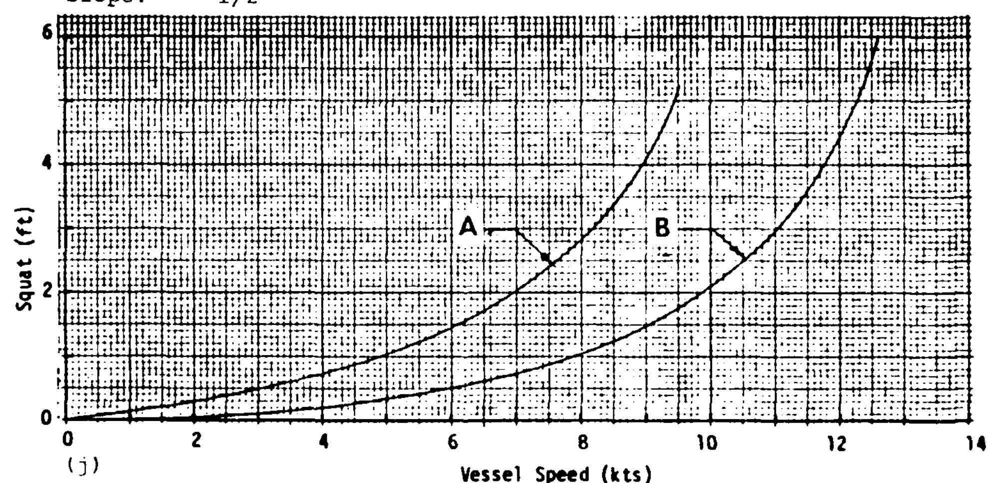
(h)
Location: Oakland Harbor; Vessel: Berezovo (LxBxd = 486x76x30)
Section: --
Depth: 35 ft
Width: 800 ft
Slope: 1/2

Figure D-3, continued



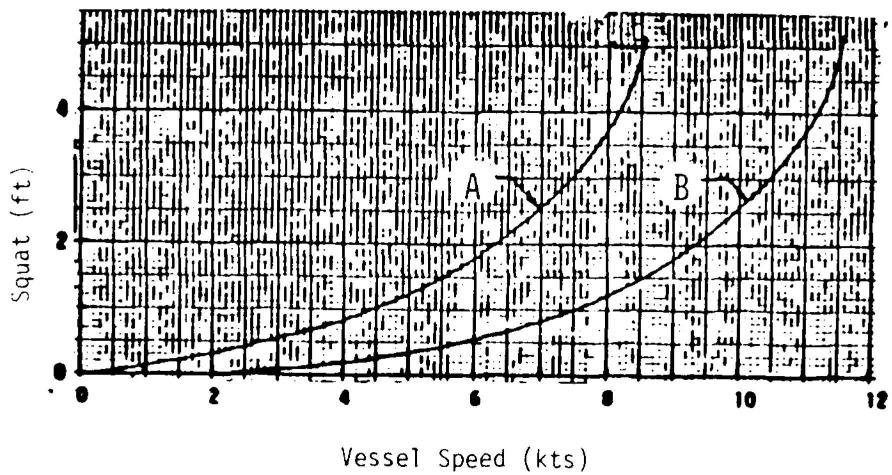
(i)

Location: San Francisco Bay; Vessel: Conoco Britannia (LxBxd = 848x138x50)
Section: --
Depth: 55 ft
Width: 2000 ft
Slope: 1/2

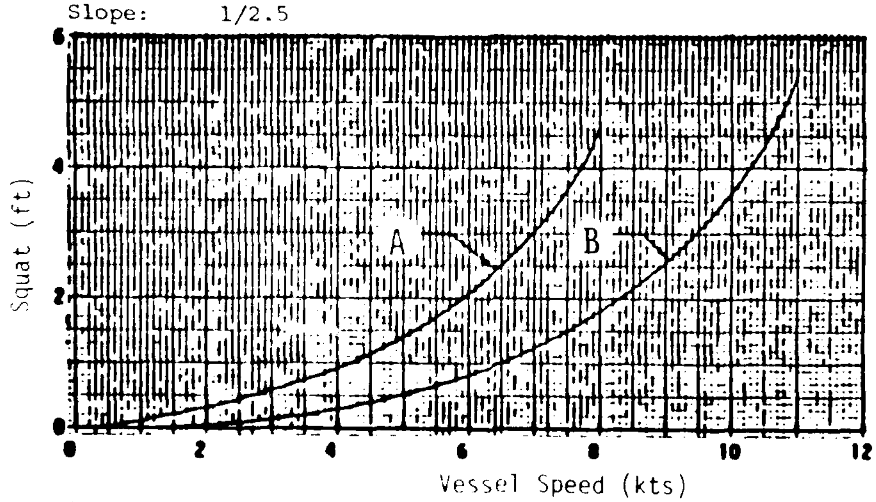


(j)

Location: Thimble Shoal Channel; Vessel: Christos Bitas (LxBxd = 732x103x40)
Section: --
Depth: 45 ft
Width: 1000 ft
Slope: 1/3



(k)
Location: Galveston Harbor; Vessel: Lenino
Section: 6-6 (LxBxd = 694x89x35)
Depth: 40 ft
Width: 800 ft
Slope: 1/2.5



(l)
Location: Galveston Harbor; Vessel: Europriority
Section: 8-8 (LxBxd = 768x125x45)
Depth: 50 ft
Width: 1020 ft
Slope: 1/2.5

Ship-Generated Waves Module The principal purpose of this module is to determine the effects of ship-generated waves on barge trains, but it also gives a general indication of other effects that may be expected in particular channels from ship-generated waves--for example, bank erosion--and may suggest operational or design changes. The module computes (for selected speeds) the ship wave height at the vessel, and the wave height at each cusp on lines of propagation. The methods are based on those suggested by Saunders (1957) and Havelock (Wigley, 1963). There are few measurement data for comparison.

Stopping Power Computation Module This module computes the reverse thrusts needed to bring the vessel (sailing at selected speeds) to a standstill in a specified distance. The computational procedure suggested by D'Arcangelo (1957) was adjusted in consultations with pilots, ship masters, and other sources of information about the behavior of ships in restricted waters.

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Dredging
Port and Harbor Design
Underkeel Clearance
Sedimentation
Nautical Depth Concept

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Assessment of criteria used in United States for depths of dredged navigational channels through review of literature, considerations of ship maneuverability, sedimentation, accuracy of dredging processes, and comparison of U. S. criteria to those of international organizations and foreign countries. Also considered are operating practices and institutional factors; economic considerations are excluded.

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