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Shiphandling Simulation: Application to Waterway Design

William C. Webster, Editor; Committee on Assessment of Shiphandling Simulation, Marine Board, National Research Council

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Shiphandling Simulation

Application to Waterway Design

Committee on Assessment of Shiphandling Simulation
Marine Board
Commission on Engineering and Technical Systems
National Research Council

William C. Webster, Editor

National Academy Press
Washington, D.C. 1992

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competencies and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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DEDICATION

Mr. C. Lincoln Crane, Jr., a world renowned expert in ship maneuverability, directed this assessment until his death in September 1989. His contributions to the committee and ship maneuvering research were substantial. His sudden, untimely and heroic death was an event that touched each committee member deeply. We have lost a good friend; naval architecture has lost a respected leader.

C. Lincoln Crane, Jr., was posthumously awarded the Gold Life-saving Medal by the Department of Transportation for his rescue of a woman swept out to sea by dangerous surf conditions.

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Preface

BACKGROUND

The nation's ports and waterways are vital links in national, regional, and local intermodal transportation and economic systems. The safety of vessel operations in these waters and ultimately the underlying waterway design are under increasing scrutiny as a result of major shipping disasters on all coasts. At the same time, the overall costs of waterway projects, increased cost-sharing responsibilities of local project sponsors, and awareness of environmental impacts has increased pressure for more efficient waterway designs. This pressure in turn has motivated new and improved techniques to offset the traditional approach to waterway design, an approach that can result in channels of questionable safety, excessive cost, or both because of uncertainty, conservatism, and reliance on rules of thumb.

The economic importance of the ports and waterways system is reflected in the flow of cargoes through the system and in the substantial national investment to support waterborne commerce. About one-third of domestic intercity trade and almost all foreign trade by weight pass through the system each year. The annual waterway investment by the U.S. Army Corps of Engineers (USACE) alone is $1.23 billion. Additional federal government investments include construction, operation, and maintenance of aids to navigation.

State, port authority, and commercial investment has until recently

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focused principally on port facilities, including berthing and cargo-handling capabilities. Funding of maintenance and modernization projects to assure efficient operation of the waterway system was primarily a federal responsibility until passage of the Water Resources Development Act of 1986. The act shifted much of the financial responsibility for expensive waterway improvement projects to local sponsors. This fundamental change in policy and escalating costs increased the importance of most-cost-effective waterway design as a means to help keep construction and maintenance costs affordable.

Shiphandling simulator technology is considered by many design engineers to be a potentially important and effective tool for waterway design. Interest is growing in the use of simulation technology to increase confidence in waterway designs and reduce the costs of construction and maintenance.

Shiphandling simulations based on available technology have been developed over the last 3 decades. Simulations have been used in a variety of contexts from training vessel crews and analyzing marine casualties to the evaluation of buoy placement. The use of simulation in the design process for modifying or developing channels and waterways is the most technologically demanding of these applications. Confidence in the application of simulators in channel design has been hampered by difficulties in assuring that the results of simulations reproduce what would have occurred in the real situation or provide sufficient value to justify their expense.

The related issues of choosing a simulator facility with suitable capabilities to address the design problem effectively, of having confidence in the results, and of integrating simulation results into the waterway design process were studied by an interagency committee in 1986. That study, convened and coordinated by the U.S. Army Corps of Engineers, recommended consultation with the National Research Council (NRC) on the role of shiphandling simulation in waterway design and supporting research (USACE, 1986b).

NRC STUDY

The NRC convened the Committee on Assessment of Shiphandling Simulation under the auspices of the Marine Board of the Commission on Engineering and Technical Systems.

Committee members were selected for their expertise and to ensure a wide range of experience and viewpoints. The principle guiding the constitution of the committee and its work, consistent with the policy of the NRC, was not to exclude members with potential biases that might accompany expertise vital to the study, but to seek balance and fair treatment. Committee members were selected for their experience in port and waterway design, hydrodynamic and mathematical modeling, computer simulation, sta

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tistical analysis, ship control design, aviation and shiphandling simulation technology, and shiphandling. Academic, industrial, government, and international perspectives were also reflected in the committee's composition. Biographies of committee members are provided in Appendix A.

The committee was assisted by the U.S. Army Corps of Engineers, U.S. Coast Guard, U.S. Maritime Administration, and the U.S. Navy's Carderock Division, Naval Surface Warfare Center (formerly David Taylor Naval Ship Research and Development Center), all of which designated liaison representatives.

The committee was asked to conduct an interdisciplinary assessment of the state of practice of simulation of ship transits in restricted waterways, the adequacy of data input to simulators, and the validity of hydrodynamic and related models. The committee was further asked to develop guidance for determining the applicability and presentation of simulation results, provide guidance for determining the required and achievable accuracy of simulator results, and recommend research to resolve any discrepancies. However, assessment of human factors in shiphandling simulations, shiphandling theory, and waterway design theory were beyond the scope of study. The issue of competitive advantage associated with the economic potential of port regions to sponsor waterway projects, although an important factor in assessing the effects of the Water Resources Development Act of 1986, was also beyond the scope of study.

The committee reviewed available data and literature to determine the state of practice of simulator use in maritime activities, including the appropriateness of various levels of simulation to different port and waterway design objectives. This examination was supplemented by visits to simulator facilities and discussions with experts in the United States, Europe, and Japan, which were documented in detailed trip reports. Case studies of shiphandling simulator application to waterway design were developed and are included as Appendix C. A source reference list on mathematical models was prepared and included as Appendix D.

REPORT ORGANIZATION

The audience for which this report was prepared consists of waterway designers, naval architects interested in the scientific issues involved with predicting the forces acting on a ship as it maneuvers in a constrained waterway, simulation experts knowledgeable in the computational and graphical presentation aspects of the technique, members of the maritime and general public who participate in the waterway design process, and decision makers affecting the use of simulation. Understanding shiphandling simulation for waterway design requires a simultaneous understanding of the science and practice of simulation and the context of waterway design in which simula

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tion is used. Chapters 2, 3, and 4 provide this information as background because suitable, concise references are not available.

Chapter 1 provides an overview of the relationship of U.S. ports to the economy, port modernization needs, trends and issues affecting port and waterway development, general goals of waterway modernization, and how shiphandling simulators are used in achieving these goals.

Chapter 2 summarizes the harbor and waterway design process. It identifies the process used, participants, and design factors and issues.

Chapter 3 describes shiphandling simulators and their use in the waterway design process.

Chapter 4 discusses the two principal types of shiphandling simulations, those operating in real-time mode with human operators in the decision-making loop and those operating in fast time with human operators replaced by computer-based pilot models.

Chapter 5 discusses and assesses mathematical models used in channel design simulation.

Chapter 6 assesses simulator technology and the validity of using this technology in the design process.

Chapter 7 discusses practical applications of simulators in harbor and waterway designs.

Chapter 8 identifies research needs, including the framework for analysis and results, mathematical models, simulator fidelity, and guidelines for the level of simulation.

Chapter 9 provides the committee's conclusions regarding the state of practice and recommendations for using simulators in the waterway design process.

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The committee gratefully acknowledges the generous contributions of time and information provided by liaison representatives, their agencies and organizations, shiphandling simulation practitioners, and the many individuals in government and other organizations interested in the application of shiphandling simulation to channel design.

Larry L. Daggett, U.S. Army Corps of Engineers, Waterways Experiment Station, participated in the site visits and in-depth interviews held in Europe, and provided technical support and reference materials. H. Paul Cojeen, U.S. Coast Guard, provided technical advice on navigational safety factors in design. Frederick Seibold, U.S. Maritime Administration, provided technical advice on his agency's prior research using simulators. David A. Walden, Carderock Division, Naval Surface Warfare Center, provided technical advice on ship hydrodynamics.

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search, Delft, The Netherlands; J. W. Koeman and W. Ph. van Maanen, Port of Rotterdam; M. P. Bogarerts, Rijkswaterstaat, Rotterdam; and Ian McCallum, Maritime Dynamics, Lantrisant, Wales.

The committee gratefully acknowledges the many contributions of the late C. Lincoln Crane, Jr. As staff study director, Mr. Crane coordinated the committee's activities including the European trip, provided expert technical advice on ship maneuvering, and supported development of background papers and case studies.

The extraordinary cooperation and interest in the committee's work of so many knowledgeable individuals were both gratifying and essential.

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Executive Summary

Ports and waterways are vital links in local, regional, and national intermodal transportation and economic systems. The safety of vessel operations in these waterways and ultimately the underlying design are under increased scrutiny as a result of major shipping disasters on all coasts. Related issues are the standard shipping practice of scheduling large ships into waterways originally designed for smaller, earlier-generation vessels, the lengthy time needed for design through construction of waterway modernization projects, and the lack of impetus for design reevaluation for safety after a waterway has been constructed or altered.

Traditional waterway design practice relies heavily on rules of thumb and conservatism for margins of safety. At the same time, the overall costs of waterway projects and expanded cost-sharing responsibilities of local project sponsors imposed by the Water Resources Development Act of 1986 have increased pressure for more cost-effective waterway designs. One effect of the revised cost-sharing responsibilities has been to stimulate efforts to develop design tools that improve the cost-effectiveness of design.

Over the past several decades, development of some waterway designs in the United States and overseas has been aided by the use of hydrodynamic physical scale model and computer-based shiphandling simulations. Each provides alternative means for achieving refinements in design not verifiable with other design tools. New attention has been focused on the potential of simulations to improve cost-effectiveness while still providing ade

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quate margins of safety. These two approaches provide different capabilities and levels of control for assessing alternate project dimensions relative to ship behavior under the influence of human operators and environmental conditions.

Interest has increased in the use of computer-based simulations. With this medium, projects can be modeled mathematically rather than physically, conceptually permitting the modeling of any waterway with the same hardware; vessel pilots can be presented with realistic representations of the operating environment under varying but controlled conditions; and the computer capability for high-speed, automated simulations using mathematical models of pilot behavior can be used to generate a large number of vessel transits that would not be feasible in real time. The use of simulation for these purposes, although promising and used in several major waterway studies, has been incorporated in only a small number of waterway projects.

This study addresses three questions about the use of computer-based simulations for waterway design:

- Does simulation work?
- When should simulation be used?
- How can simulation be enhanced as a design aid?

DOES SIMULATION WORK?

Computer-based shiphandling simulations sponsored by government, port authorities, and the maritime industry have been used effectively as a waterway design tool by planners and engineers. The technique provides an improved means to assess the operability of a proposed waterway improvement by approximating vessel behavior in the full waterway operating environment, thereby offsetting the traditional reliance on rules of thumb to provide adequate margins of safety.

Six applications of simulation to channel design were selected for detailed examination by the committee after review of over 50 different applications for which detailed results were available. The six simulation studies chosen for case study included a wide range of situations and are representative of typical applications that could be applied to design studies for U.S. waterways. The six simulations examined were:

- a study sponsored by the Exxon Corporation (1980-1981) to determine the maximum-size oil tanker that could safely transit a narrow channel cutting obliquely across the Coatzacoalcos River, Mexico, at the entrance to a tanker loading facility;
- a State of Virginia-sponsored study (1980–1986) to improve existing channel designs for Hampton Roads ports so as to permit safe transit of deep-draft coal colliers in channels with 55-foot depths.

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- A U.S. Army Corps of Engineers (USACE) study (1983–1984) performed by the agency's Waterways Experiment Station to verify the validity of the final design for a major ship channel improvement project in Richmond, California, that would permit the discharge of fully loaded 85,000-deadweight ton (DWT) tankers and partially loaded 150,000-DWT tankers.
- A Panama Canal Commission study (1983–1986) to determine the specific dimensions of the optimum navigation channel that would afford a reasonable balance between excavation cost and safety of modifications necessary to permit two-way traffic of Panamax-size vessels throughout the canal's length.
- A study sponsored by Port of Grays Harbor, Washington, (1986) and performed by the USACE Waterways Experiment Station to verify the feasibility of the final design for widening and deepening 24 miles of an estuary and bar channel, improving a highway bridge fender system, and replacing a railroad bridge.
- A study sponsored by Port of Oakland, California, (1986–1988) to develop alternative channel designs for the inner and outer Oakland harbors in order to find suitable designs that would open the port to larger, more cost-efficient containerships.

Scientific, quantitative validation of the results of simulations is not yet available. However, pilot participation in the validation process and pilot acceptance of simulations indicate that reasonable success can be achieved with the existing state of practice by re-creating a realistic piloting experience through modeling of waterway complexities, the physical environment, and operational factors. The case studies revealed that simulations can effectively aid in decision making by providing unique quantitative information for answering design questions associated with channel depth, width, geometry, dredging requirements, aids to navigation requirements, and tugboat assistance. Additionally, simulations have also provided a unique, common forum for discussion between design participants and an easily understood context for problem identification, conflict resolution, and decision making.

In some of the applications examined, the construction cost savings stemming from design changes developed using simulation were much greater than the cost of simulation. The committee believes that risks to shipping and the environment can be reduced through design refinements based on simulations, but this reduction is difficult to assess or express in monetary terms. Nevertheless, evidence from the six case studies shows that simulation technology can be effectively applied to the waterway design process with substantial benefits. Simulation models developed for waterway design can also be used in simulations conducted for training.

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WHEN SHOULD SIMULATION BE USED?

Simulation should be used when:

- *Vessel operational risk is a significant design issue.* Incorporation of human pilot skills and reactions in the prediction of the behavior of a vessel in a proposed waterway is unique to shiphandling simulation. Differences in risk resulting from a variety of critical environmental conditions can be identified. Aids to navigation requirements that can further reduce risk can also be assessed.
- *Cost and design optimization is an issue.* The effect on risk resulting from variations in the many design factors that define a waterway can be evaluated. This capability is an important decision aid in the assessment of the components of life-cycle costs. Simulation is particularly useful for assessing operational differences between design alternatives.
- *Competing interests among technical and nontechnical participants in the waterway design process are an issue.* Simulation provides a unique way to bring critical and contentious aspects of the design into focus. Design modifications to accommodate competing interests can be tested and the consequences displayed in formats that do not require technical expertise to assimilate and understand.

Because elements of these three issues are frequently associated with most waterway designs, the committee concluded that shiphandling simulation should be developed as a standard tool available for use in waterway design. The level of sophistication of simulations needed for this process depends on the particular design. However, guidelines for the appropriate level for a given situation are not available within the current state of practice.

HOW CAN SIMULATION BE ENHANCED AS A DESIGN AID?

Simulation is a highly technical art involving the integration of many skills: naval architecture, civil and marine engineering, piloting, computer techniques, and human engineering. In all of these areas, there are substantial unresolved issues. Confidence in the use of shiphandling simulation for waterway design is limited by issues of fidelity and the level of simulation required. Use is inhibited by cost, scheduling, and interpretation of the results. More use of simulation in the waterway design process could be motivated by:

- Reducing the costs of simulation.
- Developing a definitive guide to assist designers in choosing a simulator for specific applications. Although the cost of computer equipment needed for simulation has dropped significantly in recent years, the cost of

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the labor-intensive set up and conduct of the simulation has increased. These latter costs and the duration of the simulation process are sensitive to the level of simulation required, but no guidelines exist for this choice.

- Developing minimum requirements for fidelity and validation of mathematical models of ship dynamics, waterway data bases, and the simulator environment including visual displays and bridge mock-up.
- Developing a better understanding of the behavior of ships in situations unique to waterway design. These situations include operation in the following conditions: with small under-keel clearance, near banks of arbitrary geometry or muddy bottoms, in sheared currents, and in close passage of other ships.
- Developing and validating a mathematical framework for extrapolating the results from a small sample of simulation runs to a prediction of the performance of future traffic in the waterway.
- Establishing a carefully composed, interdisciplinary validation team as a formal element in each simulation validation process.

SUGGESTED RESEARCH

Confidence in simulations can be increased through a systematic research program designed to address the preceding deficiencies. The committee recommends implementation of a research program that

- assesses the need for fidelity in the mathematical models and simulator hardware,
- develops ways to determine, assess and resolve the uncertain elements in mathematic models, and
- provides a capability for interpreting the results.

The research program should be coordinated by the Army Corps of Engineers in cooperation with other interested federal agencies and segments of the maritime community and in consultation with organizations representing the best technical expertise available within the waterway design and simulation community.

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Shiphandling Simulation

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1

Introduction

WATERWAY MODERNIZATION

The nation's ports and 28,000 miles of navigable waterways authorized for improvement under federal programs are vital to national, regional, and local transportation and economies. They provide a critical intermodal link to the global economy while also serving as local and regional employment centers. Over 30 percent of the nation's domestic intercity freight trade and 99 percent of overseas trade by weight (74 percent by volume) pass through this system as waterborne commerce. Although variable from year to year, the flow of cargoes through U.S. ports hit 2.09 billion tons in 1988 (U.S. Maritime Administration, 1990). However, existing ports and waterways do not adequately accommodate the most modern ships in terms of efficiency, safety, and cargo handling capabilities. Thus, there is interest nationwide for modernization of ports and waterways systems to accommodate modern ships and maintain competitive advantage in regional and international trades (Frankel, 1989; *Journal of Commerce*, 1991a; Kagan, 1990; U.S. Maritime Administration, 1990). At the same time, the escalating costs of waterway projects and shift of major funding responsibilities to local sponsors brought attention to a design process that compensates for uncertainty with conservative rules of thumb (Bertsche and Cook, 1980; National Research Council [NRC], 1983).

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Port Development

Development of port infrastructure over the past 2 centuries has evolved through a balance of technological demands required by shipping, urban conditions affecting the port, and public interest in port modernization. Shipping technology has required increasingly deeper and wider channels and waterways (McCallum, 1987; NRC, 1981, 1985). Modern shipping terminals require larger spaces to operate and connectivity to greater and more-efficient intermodal land transport capacity. Larger terminals with higher volumes of cargo are in conflict with the vehicular congestion associated with ports encroached by or developed in urban areas.

Public support for port infrastructure modernization has softened. This decrease is due to competing demands for public investment funds for nonmaritime-related purposes in the port area (for example, residential and commercial developments, recreation sites, marine habitat preservation, restoration) and to heavier emphasis on environmental aspects of proposed waterway projects than in former years, especially the impacts of dredging and the disposal of dredged materials (*Journal of Commerce* , 1991a; Kagan, 1990; Marine Board, 1985; NRC, 1981, 1985, 1987; Rosselli et al., 1990; U.S. Maritime Administration, 1990). Keeping pace with rapid changes in technology while keeping costs manageable and accommodating environmental interests of public policy and public interests groups has become more difficult.

The impact of the factors affecting modernization of the U.S. port infrastructure across the nation is selective. For example, some ports are experiencing extreme congestion on the land side due to differing urban conditions while other ports experience channel limitations on the marine side due to the timing of previous modernization. The overall result has been increasing demands on the local port and a lessening ability to solve port infrastructure problems.

Nevertheless, various modernization projects are in progress. They vary from a $5 billion port development proposed for Los Angeles-Long Beach Harbor to a wider and deeper channel in Miami; from a new container terminal in Tacoma to better rail access in New York. In any one year, over $500 million in port-funded capital improvements for port facilities and waterways is typically under way (*Journal of Commerce* , 1991b)

Water Resources Policy

Although funding development of port facilities is the responsibility of civil authorities and private enterprise, the federal government has historically led development of the port and waterway system (Heine, 1980; National Research Council, 1983, 1985). The major costs of construction,

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WATERWAY TERMS AS USED IN THIS REPORT

BASIN A comparatively large space in a dock, waterway, or canal system, which is configured to permit the turning or other maneuvering of vessels for entering or departing a dock or berth.

BERTH A place where a vessel is moored at a wharf or lies at anchor.

CANAL An excavated, dredged, or constructed watercourse, usually artificial, designed for navigation. Side borders usually extend above the water surface.

CHANNEL Part of a watercourse used as a fairway for the passage of shipping. May be formed totally or in part through dredging.

DOCK The water space between adjacent piers or wharves in which vessels are berthed; an artificial basin or enclosure fitted with lock gates to retain a level of water undisturbed by entering or departing vessels (wet dock); any dock in or on which a vessel can be made to lie completely out of the water (dry dock).

FAIRWAY The main thoroughfare of shipping in a harbor or channel; although generally clear of obstructions, it may include a middle ground (that is, a shoal in a fairway having a channel on either side) suitably indicated by navigation marks (such as buoys).

HARBOR A fully or partially enclosed body of water offering safe anchorage or reasonable shelter to vessels against adverse environmental conditions. May be natural, artificial, or a combination of both.

PORT A place in which vessels load and discharge cargoes or passengers. Facilities in developed ports normally include berths, cargo handling and storage facilities, and land transportation connections. Normally a harbor city, town, or industrial complex.

WATERWAY A water area providing a means of transportation from one place to another, principally a water area providing a regular route for water traffic, such as a bay, channel, passage or canal, and adjacent basins and berthing areas. May be natural, artificial, or a combination of both.

WHARF A waterside structure, also referred to as a pier, at which a vessel may be berthed or at which cargo or passengers can be loaded or discharged.

SOURCES: Bowditch, 1981; McEwen and Lewis, 1953; Rogers, 1984; U.S. Navy Hydrographic Office, 1956.

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operation, and maintenance of federal navigation projects, channels, and waterways used by marine transportation has been funded and built by the U.S. Army Corps of Engineers (USACE).

VESSEL AND OPERATOR TERMS AS USED IN THIS REPORT

BARGE A heavy, non-self-propelled vessel designed for carrying or lightering cargo.

INTEGRATED TOW A flotilla of barges, tightly lashed to act as a unit. Common configuration found on shallow inland waterways.

PILOT The person piloting (directing and controlling the maneuvering of) the vessel. In actual vessel operations, the pilot could be a licensed independent pilot, master or qualified deck officer.

SHIP A self-propelled, decked vessel used in deep-water navigation.

TOW One or more barges or other vessels being pulled, towed alongside, or pushed ahead.

TUG, TUGBOAT, TOWBOAT A strongly built vessel specially designed to pull or push other vessels.

VESSEL A general term referring to all types of watercraft including ships, barges, tugs, yachts, and small boats.

SOURCES: McEwen and Lewis, 1953, Rogers, 1984.

Until the 1970s, the federal government was the major source of funds for basic channel and waterway infrastructure, leaving actual port facility and land-side access up to local ports, other agencies, and private enterprise (especially for petroleum terminals). This redistribution of national resources directly benefitted local ports and their service areas, with indirect benefits accruing to the national interest in assuring the adequacy of the marine transportation system for regional and international commerce.

In the 1980s, federal policy changed. The shifting of more financial responsibility to local sponsors (for example, port authorities) began with the imposition of user fees. Substantially increased requirements for local sponsorship resulted from passage of the Water Resources Development Act of 1986. The act envisioned partnerships between the federal government and nonfederal local project sponsors in which local sponsors would have a significant role in planning, design, and funding. The federal gov

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ernment would continue to bear the major costs of basic waterways infrastructure, but local sponsors would be required to shoulder more of the cost for planning, construction, operations, and maintenance, and perhaps most importantly, responsibility for the disposal of dredged material. For example, local sponsors are required to share 50 percent of the costs of feasibility planning, provide the federal government with any needed real estate and property at 100 percent local sponsor expense, and contribute 50 percent of construction costs for the portion of project depths that exceed 45 feet.

These dramatic changes in federal policy have elevated the attention given by local sponsors to project costs. The changes have prompted interest in scaling down design dimensions to the minimum necessary for safe operations and minimizing the amount of dredging and the volume of dredged materials that must be disposed of. Traditional design methods using rules of thumb increase design dimensions to compensate for uncertainty. They assure adequate margins of safety but provide little comfort to designers charged with achieving maximum cost-effectiveness (Bertsche and Cook, 1980; NRC, 1983).

ROLE OF SIMULATION IN WATERWAY MODERNIZATION

The design of a waterway is as much an art as a science. Design must address many different qualitative as well as quantitative factors affecting its cost and operability. These factors include the engineering, operational, scientific, environmental, economic, and political aspects of a waterway project. Determining the swept paths of the vessels that will ply a waterway, for example, is an essential step in its design. These paths will reveal the relative risks of passage that must be addressed in waterway design. Characteristics such as channel depth, width, and geometry are selected in an attempt to optimize the balance between risk and cost inherent in the design.

A growing number of those involved in waterway design are applying high-technology systems to better determine the most cost-effective waterway configurations. One such technology, shiphandling simulation, has been used for operational training (for example, emergency procedures and maneuvering), analyzing marine casualties, evaluating vessel designs for maneuverability, evaluating bridge equipment, evaluating aids to navigation, and assessing the suitability of a particular vessel for a new port or transit situation. Shiphandling simulation techniques have also been used to select waterway configurations, usually as modifications to segments of an existing system, that accommodate economic, safety, and environmental interests. Additionally, available simulations have been used for multiple purposes of research, training, and waterway design (Ankudinov et al.,

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1989; Burgers and Kok, 1988; Elzinga, 1982; Froese, 1988; Loman and van Maastrigt, 1988; McCallum, 1982; Paffett, 1981; Puglisi, 1987).

Initial shiphandling simulations involved remotely controlled scale models or scale models of sufficient size to accommodate human operators. In recent years, computer-based simulation has benefitted greatly from the advance of computer technology to help determine the swept paths of ships and integrated tows (oceangoing and shallow draft) under a variety of waterway configurations and operating conditions. [This report typically refers to ships, ports, and waterways for convenience of discussion. Integrated tow operating environments (such as found in river systems) are also assessed using computer-based simulations (Miller, 1979)]. Computer simulations can be performed using human pilots in a simulated ship bridge (that is, a functional mock-up) and mathematical models of ship behavior to predict the response of the vessel to commands from the pilot. Simulation is also performed in fast time using computer-based pilot models instead of human pilots.

Although computer simulations of both types have been used increasingly to aid in waterway design worldwide, there are many concerns about the practical application of the technology for this purpose. Widespread application has been hampered by questions of the validity and value of the results. This report assesses the validity of simulation as a design technique to better determine the feasibility, usefulness, and cost-effectiveness of computer simulations for the design process. It describes the waterway design process as it has traditionally been accomplished, the role of simulation in the design process, the components of a simulator, and the present state of practice. The application of simulators in several case studies is presented, and research needs are outlined.

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2

Waterway Design Process

The design of a waterway is a highly complex and demanding exercise. The process involves an amalgam of economics, engineering, environmental and social aspects, political considerations, and historical precedence. Shiphandling simulation plays a role in a small but very important part of this process. This chapter describes the state of practice of waterway design to establish the context in which computer-based shiphandling simulations are applied. Also examined are typical design issues that appear to lend themselves to assessment through shiphandling simulation as well as design elements and data that are critical to successful simulations. The discussion provides a basis for understanding the advantages and limitations of shiphandling simulations and the potential for advances in the underlying technology.

The central role of the U.S. Army Corps of Engineers (USACE) in the waterway design process in the United States has produced a somewhat different institutional process (described in Appendix B) in comparison to the rest of the world. However, the engineering concepts used in waterway design are essentially the same.

A waterway design defines the form and dimensional boundaries required to meet functional objectives consistent with fundamental civil engineering practices and construction options. Construction includes excavation (dredging), manipulation of earth and rock, and the erection of heavy structures. As with other areas of civil engineering, the actual construction

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design is developed by the application of well-known principles of the physical sciences, such as hydraulics, geotechnics, and properties of materials. Most of the effort in waterway design has historically concentrated on these civil engineering aspects. Sedimentation has received particular attention, including the means to reduce or control it and its effects which might result from changing hydraulics within the waterway system relative to the tidal prism (National Research Council [NRC], 1981, 1987; USACE, 1977). However, the true challenge of waterway design is to balance the civil engineering requirements with those of form and function, including environmental considerations.

THE DESIGN CHALLENGE

The distinctive and unique thrust of waterway design is to quantify the factors that are used to determine the form and its dimensions for navigation. The process is difficult and involves complicated hydrodynamic reactions between the waterway and vessels. The difficulty is compounded by the fact that the vessels are independently controlled by human operators and sensitive to the pilots' reactions to varying operational demands. This fact, under any operating conditions, results in a certain lack of precision or certainty in determining vessel paths (Atkins and Bertsche, 1980; McAleer et al., 1965; Norrbin, 1989). Therefore, margins for safety need to be provided in the principal waterway dimensions. Estimation of appropriate margins is a key design function.

Principal design elements of form that are required to be determined and dimensions that must be developed for a given waterway are the following (Atkins and Bertsche, 1980; Dand, 1981; Marine Board, 1985; McAleer et al., 1965; McCartney, 1985; Norrbin, 1986; USACE, 1983):

- location
- orientation or alignment
- depth
- width
- radius of curvature of bends
- tangent distance between bends
- aids to navigation

These elements and their dimensions are primarily a function of the dimensions of the design vessel, its track, and its expected vertical and horizontal movement as it transits the waterway. Additional clearance dimensions to allow for uncertainty of position, operational safety, and hydrodynamic requirements are also required. Depth may also include a preinvestment factor to allow for sedimentation during intervals between intermittent maintenance dredging.

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Vessel motions and path and clearance requirements can be estimated by calculation, physical tests, or semiempirical methods. The operating environment is so variable, and the calculations so complicated, that considerable judgment is usually required for design by traditional guidelines. In practice, it appears that most estimates have been made by applying semiempirical methods and judgment (Atkins and Bertsche, 1980; Dand, 1981; NRC, 1981; Norrbin, 1986).

Closely related to design is the operational analysis of a given waterway to appraise its capacity in terms of vessel size, traffic pattern, or density (Atkins and Bertsche, 1980). Operational analysis is applied to alternate design options, and the results are considered in optimizing design for safety and cost-effectiveness and when designing a navigational aids system. Operational analysis is also used by vessel operators (for example, shipping companies) to appraise the suitability of a waterway for a particular vessel and its loading limitations. A special case is forensic analysis where the conditions for an accident are deduced and re-created.

Much of the same technology is used for operational analysis as for design, but application techniques and methodologies may vary to reflect the somewhat different objectives. Acceptable tolerances for calculated results may also differ (Gress and French, 1980). For this study, operational analysis is considered a special case of design and is not explicitly discussed.

DESIGN ISSUES

The issues to be addressed in waterway design are both technical and institutional (Herbich, 1986; NRC, 1983, 1985; Olson et al., 1986).

Technical Issues

Key technical issues include the following (McCartney, 1985):

- A design vessel or vessels must be selected with dimensions and characteristics around which the design is to be developed. The design vessel may be an existing vessel, a new vessel in planning or under construction, a conceptual ship of the future, or a composite of critical dimensions and properties of several vessels. Selection of the design vessel is a defining decision in the design process, regardless of design aids used (USACE, 1983).
- Dynamic behavioral characteristics must be determined for the design vessel (or vessels) as the vessel transits the waterway subject to various external forces and its own hydrodynamic and inertial properties. Related is the question of whether the vessel is to be maneuvered with or

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without the assistance of tugs (Armstrong, 1980; Brady, 1967; Crenshaw, 1975; Reid, 1975, 1986).

- The actions of a vessel's pilot must be determined relevant to dynamic behavioral characteristics (Armstrong, 1980; Crenshaw, 1975; Hooyer, 1983; Norrbin, 1989). Piloting skills resident in a local pool of pilots are not necessarily a critical factor in channel design studies. If a ship can be proved to be adequately handled by an experienced pilot, and thus the physics of the transit problem are not critical, then it follows that other pilots may be trained to operate the vessel safely, although better navigational aids might be required.
- Operating requirements must be noted, including the required speed of vessel in transit, density of vessel traffic in the waterway, traffic mix, special safety requirements, and degree of tolerance for risk of operating interruption (such as a grounding or collision).
- Assumptions for environmental conditions and limits must be assessed including oceanographic, hydrological (for example, tidal prism, currents, water levels), atmospheric, meteorological, and ecological factors, as well as time of day as it affects visibility.
- Costs must be determined for construction, maintenance, environmental and social impacts, and for vessel operations, together with their allocation and the assignment of benefits.
- Levels of risk that are acceptable must be determined.

Acceptable Levels of Risk

A special technical issue is risk. Tradeoffs made in design result in channel and waterway configurations that can be characterized as achieving an acceptable level of risk. There are no guidelines about what the acceptable risk level should be; thus the determination is highly subjective. During the assessment and based on its collective experience, the committee observed that port and public officials are reluctant to concede that some level of risk is an element in any port and waterway design. Reasons for this include concern over liability, project permitting, and interport competition. This general attitude has impeded the use of risk analysis with or without shiphandling simulation. Insight on risk can potentially be addressed by using simulation to identify maneuvering problems that may be associated with design alternatives or may be induced by certain physical conditions in the waterway environment. Moreover, the use of simulation has the potential to reduce the extra margins traditionally used to overcome uncertainty, thereby reducing construction and maintenance costs. Although this benefit may appeal to the project sponsor, it is the significant design refinement opportunities afforded by simulation that lead directly to the question of whether the fidelity of the technique justifies reliance on it over

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or in addition to traditional design practices to achieve adequate margins of safety.

Institutional Issues

Institutional issues are more difficult to define. Although they influence and are influenced by the technical issues, institutional issues are often the overriding and decisive factor in many waterway designs. They are usually associated with methods of finance, special environmental or social concerns, litigation, or legislation (Kagan, 1990; McCartney, 1985; NRC, 1987; Olson et al., 1986; Rosselli et al., 1990). Within the past several decades, competition for use of coastal areas has greatly increased. Competition exists between residential, industrial, recreational, and conservation uses. As a result, waterway development processes have come under much greater scrutiny by local interest groups, resulting in a lengthening of the already long approval process (Kagan, 1990; NRC, 1987).

In the United States, for example, the time interval between design study and construction for a federal waterway project is frequently more than 20 years (NRC, 1985), which means that the assumed technical issues will likely have changed greatly by the time construction is completed. Typically, the original design vessel becomes obsolete (and may no longer be in service), shipping practices change, new supportive technology is developed, and cost relationships are altered. There is no reliable methodology for projecting future vessel design or operational trends when planning waterways or for adequately accommodating changes that occur. Thus, original technical issues can be quickly overtaken by events.

Although an extreme, this situation in the United States is merely an exaggeration of global historical trends. Technological development in ships and in shipping operations have repeatedly stretched the technical limits and dimensional margins of waterways and harbors (McAleer et al., 1965; McCallum, 1987; Permanent International Association of Navigation Congresses [PIANC], 1980). The trend has been magnified during the past century and a half in response to the industrial revolution and expansive trends in world economic activity.

The dilemma for waterway designers is to balance the costs and benefits. Shipowners are the direct beneficiaries of increased efficiencies gained from larger vessels. Others may receive direct or indirect benefits but may also bear the costs of providing facilities (NRC, 1985), which affects the resources available for a project.

Institutional pressures and counter pressures (NRC, 1985) affect the designers' ability to implement a design of maximum utility and overall economic benefit. Ports and harbors are one element and represent a small share of the overall investment in the worldwide seaborne transportation

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system. However, construction, operation and maintenance cost are usually a major issue for local and national authorities responsible for funding. This fact, coupled with environmental and social concerns that have potentially significant cost implications, means that waterway development will inevitably remain under pressure for provision of minimal facilities or deferment (Kagan, 1990; NRC, 1985, 1987).

As a consequence, economic pressure to use ships larger than design ships into existing waterways will continue (Jensen and Kieslich, 1986). Because the United States has few natural deep-water harbors, waterway designers have had to continually reappraise vessel size and operating limits for existing waterways and have developed minimal incremental improvements for extending those limits, usually for economic purposes (Atkins and Bertsche, 1980). However, there has been no impetus for use of simulation for project-specific design reevaluation or safety appraisal. Assessing the effectiveness of waterway design once a project is constructed, the adequacy of the design for use by vessels exceeding design vessel characteristics, and the accuracy of simulation predictions are not elements of current practice. Furthermore, no one, including the Army Corps of Engineers, Coast Guard, or project sponsors, appears to be overseeing operations to assure that vessels using a waterway remain within the vessel operating characteristics for which the waterway was designed. In fact, there is an economic incentive for shippers and port authorities to exceed the design parameters of the waterway in order to accommodate the latest generation ships, thereby maintaining a competitive advantage relative to other ports and maximizing the amount of cargo that can be accommodated.

DESIGN PROCEDURES

The classic full-effort design procedure consists of the following steps (Dand, 1981; McAleer et al., 1965; Norrbin, 1986; Sjoberg, 1984):

- establishing various trial design alternatives to meet both civil engineering and navigation requirements;
- comparing their estimated capital and maintenance costs, benefits, and other factors; and
- selecting a best alternative.

Further incremental improvements to the selected alternative are usually considered and made by an iterative process until the design team is satisfied. By weighing tradeoffs in the cost-benefit analysis, the process approaches optimization (Burgers and Loman, 1985; Olson et al., 1986). True optimization of waterway design is seldom achieved or even attempted because of the lack of data, particularly data that are reliable and accurate and relating to accidents.

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DESIGN PARTICIPANTS

CONGRESS Legislates project authorizations and appropriations for federal share of project funding.

U.S. ARMY CORPS OF ENGINEERS (USACE) Plans, constructs, and maintains federal projects in navigable waterways. Conducts technical research in waterway design and construction techniques.

U.S. COAST GUARD (USCG) Plans, constructs, maintains, and operates federal aids to navigation in navigable waterways; administers federal regulations pertaining to marine safety, security, and marine environmental protection.

U.S. MARITIME ADMINISTRATION (MARAD) Shiphandling simulation research and development; steering and maneuvering properties of ships. Provides advisory support in the design process.

PROJECT SPONSORS The local or regional organizations or authorities who contribute nonfederal funding to a specific waterway project. May include state, port, and local authorities.

LOCAL INTERESTS Segments of the local community with interests in waterway construction, operation, and maintenance who may act as petitioners or advisers for waterway projects. May include state and port authorities, terminal operators, shipping companies, and pilot associations.

PUBLIC INTEREST GROUPS Organized representatives from the public sector who have a direct or indirect interest in waterway projects. Interests include social, political, and environmental issues.

DESIGN ENGINEERS Technical design consultants to the USACE, sponsors, and other interested parties on a contractual basis. Principally involved in providing full technical support for waterway projects outside of the United States because most countries do not have the equivalent of the USACE and many foreign ports—especially in developing countries—are owned by private companies.

For public waterway projects in the United States, there is some attempt to follow this classic procedure, but with significant variations. The design process prescribed by the USACE has six phases:

- reconnaissance
- feasibility

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SOME TECHNICAL TERMS USED IN THIS REPORT

DRIFT The sideways motion of a vessel from its track as it makes its transit.

DRIFT ANGLE The angular between a vessel's heading and its track.

SWEPT PATH A trace of the paths of the extremities of the vessel plan form as it makes its track while it transits the waterway. Account is taken of drift, drift angle, and yaw.

SWEPT PATH ENVELOPE The outer boundaries of the swept paths with the most extreme deviations from target track that encompass all of the swept paths of the vessels that transited the waterway.

TRACK A trace of the path of a vessel as it makes its transit of a waterway.

TRANSIT A passage of vessel from point to point in a waterway.

YAW The angular rotation of a vessel's longitudinal axis from the desired line of track.

- preconstruction engineering and design
- real estate acquisition
- construction
- operation and maintenance

The first two phases listed are theoretically where the waterway form and dimensions are determined (Olson et al., 1986). In practice, form and dimensions are fixed in the construction phase because of actual or perceived inadequate consideration of the interests of participants in earlier phases. In some cases, considerable delays in project approvals and implementation have occurred, resulting in a range of both constructive and detrimental effects (Kagan, 1990; NRC, 1985). A brief description of USACE design process mechanics is provided in Appendix B.

Developing a reasoned and sound technical design (which accommodates engineering, operational, safety, and environmental factors) as early in the process as possible establishes a solid basis for subsequent refinements. An issue is whether existing design tools are adequate to the challenge.

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DESIGN TOOLS AND TECHNIQUES

The tools available to the waterway designer for technical solutions have improved markedly in recent years (Gress and French, 1980; McCartney, 1985; Norrbin, 1986; Olson et al., 1986). Before the ready availability of computers, designers were limited to carrying forward previous experience by judgment alone—with the aid of experiments with physical scale models—or by laborious mathematical calculations. Graphical methods with paper plots of position were often used to help visualize the pilot's task, the interaction of the forces on the vessels, and the vessel's resulting path. For practical reasons—usually monetary and time constraints—the number of model tests that were run and the variations that could be tested were usually limited. Similarly, the complexity of the mathematical solutions and applied formulae limited their number and required major simplifications to be usable. The calculations typically were used to check and verify previous assumptions rather than as a primary determinant.

The capacity and speed of the modern computer has changed the designer's task dramatically. Mathematical solutions are now practical from the initial stages of design. The relative ease of changing input conditions has broadened the feasible alternatives to be considered (Burgers and Loman, 1985; Gress and French, 1980).

Even with the modern tools available, the waterway designer must carefully input parameters and interpret results. To assist the designer, various groups, including USACE, PIANC, and International Association of Ports and Harbors (IAPH), have developed guidelines for design dimensions (PIANC, 1980, 1985; USACE, 1983). Although these guidelines are often helpful for visualizing a new waterway for initial studies, they are too general to assure an optimum design for a given condition. There are many examples of workable waterways that do not meet the guidelines by wide margins (Jensen and Kieslich, 1986; NRC, 1985). No substitute has been developed to replace intelligent and skillful analysis by a qualified, experienced waterway design engineer (Dand, 1981; Norrbin, 1986; Sjoberg, 1984).

Not all of the elements of a waterway are equally amenable to analysis by modern tools and technology. Basic data gaps and incomplete theories still exist. Although the technical press reports some study of the subject in recent years, considerable approximation and applied judgment are required for some elements and conditions. It is beyond the scope of this study to examine design factors in detail. However, several elements are important in considering the appropriateness of design tools and techniques, of which computer-based shiphandling simulation is one option. The elements are depth, width, aids to navigation, environmental data and civil engineering, and design vessel.

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Depth

Depth is the key waterway dimension. It usually results in the greatest cost impact, establishes the character of the port and its traffic, establishes the initial and maintenance dredging requirements, and affects the horizontal controllability and resultant swept paths of the vessels that use the waterway. In the United States, project depth is determined by some technical analysis, but primarily by political and administrative means. Technical requirements for depth include allowances for (NRC, 1983; USACE, 1983)

- the vessel's expected draft;
- the vessel's vertical motion from squat or sinkage as it moves through the water and from pitch, roll, and heave caused by waves and other external forces;
- an under-keel clearance for hydrodynamic reasons; and
- an extra clearance to account for errors in measuring channel depth and vessel draft and for dredging tolerances. For new projects, an extra depth allowance may be included to allow for sedimentation to occur between intermittent maintenance dredging.

The primary technical tool for estimating depth requirements is designer judgment. Calculation of depth requirements involves the determination of critical sea and meteorological conditions, vessel operations, and other factors that affect the vertical motions and chance dimension errors. Because it is unlikely that maximum conditions for all factors will occur simultaneously, some designers have attempted to determine depth requirements by probabilistic forecasts. For example, studies for the Panama Canal Company in 1975 involved a special probabilistic approach related to pilot variance in compressed-time simulations (Norrbin et al., 1978). However, in practice, probabilistic forecasting has had mixed acceptance by designers. Even where practiced, considerable human judgment is still required for both input and evaluation.

Guidelines help, but in actual practice in many waterways, ship drafts consistently exceed those indicated as allowable by guidelines published by USACE, PIANC, and IAPH. Ships are routinely brought into ports with drafts that exceed project depths by taking advantage of daily tides and river stages (MacElrevey, 1988; NRC, 1983, 1985; Plummer, 1966). In practice, the only consistent, albeit informal, control over maximum draft on port entry or departure seems to be exercised by local pilots who make expert judgment calls on under-keel clearances that will permit safe movement of each vessel. Although the published guidelines offer a reasonable if imprecise gauge for safe under-keel clearances, economic criteria are applied by shipping interests.

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Width

The required design width includes one or more vessel maneuvering lanes plus allowances for side clearances from the design vessel to the edge of the channel, other vessels, banks, structures, or natural features of the waterway. Width of the maneuvering lane is determined by the horizontal dimensions of the design vessel, its varying orientation in the waterway, and its deviations or drift from the desired track (Marine Board, 1985; USACE, 1983). A trace of the design vessel's extremities outlines and defines its swept path. The maneuvering lane is intended to provide an envelope of all the expected swept paths of the vessels that will transit the waterway under the various assumed design conditions. It is desirable that the lane's alignment is as close to a straight line as possible. Deviations in path alignment to avoid obstructions, take advantage of natural features, reduce dredging and sedimentation, or improve vessel operations are made with allowance for the design vessel's turning ability.

The side clearance dimension from an obstruction or bank provides a minimum path for the return flow of water displaced by a vessel as it moves along the edge of the maneuvering lane. It also provides a safety allowance for potential errors in the vessel's position. Deviations from desired orientation and vessel track are caused by a vessel's inherent stability or instability, the effects of external forces from wind, wave, current, and hydrodynamic reactions, and the applied control efforts by the pilot.

The degree of vessel control applied by the pilot is a major variable assumed by the designer. Unlike vertical motions, a vessel's horizontal motions and deviations can be anticipated and compensated for by pilot action. The effectiveness of this action is dependent on the pilot's level of skill, perception, and reactions, and following execution, on the inherent controllability and responsiveness of the vessel. Determining the degree of vessel control is a difficult challenge for the designer.

As with depth, actual practice has indicated that widths of much narrower dimensions than those recommended by traditional guidelines are both feasible and practicable. Some waterways such as the Houston Ship Channel fall into this category and are operated successfully (Jensen and Kieslich, 1986), although not without risk (Gates, 1989). Although technological gaps in the science still exist, there has been considerably more work done regarding width in recent years than there has been on the vertical phenomena. Calculation is feasible with a reasonable level of confidence.

Special cases, such as basins where low speed maneuvers are planned, bends and turns in channels, and passages through bridges, require special study. However, the design tools are generally the same and are available.

Weaknesses in the technological base include a lack of definitive data

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on maneuvering of vessels with very small under-keel clearances, especially in confined waterways. Also, quantitative guidance on the effects of different bottom material and contour forms and the effects of pitch, roll, and heave on track keeping in shallow water are scanty. Designer judgment and the transfer of prior experience are the principal tools to account for these conditions at present.

Navigational Aids

Aids to navigation systems are an important but frequently overlooked element of waterway design (Atkins and Bertsche, 1980). By integrating aids to navigation into the waterway design, the effectiveness and possible precision of vessel position fixing is improved and the designer can allow for tighter margins in waterway dimensions if they are validated by some means.

Available navigational aids range from traditional aids to navigation, such as buoys and ranges, to electronic position fixing devices, such as loran and differential GPS (global positioning system). All aids require human perception and reactions for maneuvering the vessel. Quantifying and evaluating behavioral modifications associated with use of aids to navigation is a particularly difficult challenge to the waterway designer.

Normal design procedure is to solicit the opinions and judgment of experienced mariners as a guide. Although this method frequently is satisfactory, it does not fully evaluate navigational systems in the context of a new or modified design. Shiphandling simulation has been applied and demonstrated to be of value for assessing aids to navigation (Atkins and Bertsche, 1980).

The waterway designer must carefully allow accuracy tolerances for behavioral modifications relevant to maneuvering strategies that may result from the type and placement of aids to navigation. Because unbroken delineation of channel boundaries and traffic lanes is typically not feasible in a waterway or fairway, the relationship of the vessel to its intended track is determined either by electronic or visual fixes (with some lag behind actual positions due to human and electronic processing time) or by expert estimations based on all information available. The pilot's strategy is therefore based on the perception of position and the onward track. Any lack of precision widens the track requirements.

Environmental Data and Civil Engineering

Navigational and civil engineering (including construction) aspects of waterway design require considerable data relating to the environment, both above and below the surface. Ideally, the data would be drawn from analy

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sis of meteorological and hydrographic measurement records coupled with up-to-date physical surveys. Such records are not always available with the detail required for a specific project site.

Physical scale and mathematical hydraulic models have sometimes been used to interpolate general data regarding site-specific estimates of currents, sedimentation, and wave patterns. Similarly, mathematical models have been used with general synoptic charts for estimating meteorological conditions (Seymour and Vadus, 1986; USACE, 1977). Random or selective field measurements are usually advisable for verifying such estimates. As with all other aspects of waterway design, the engineering skill of the designer, together with clear and complete analytical reasoning, are prerequisites for success.

Design Vessel

Selection of the design vessel, or vessels, is one of the most critical decisions in waterway design (Dand, 1981; McAleer et al., 1965; USACE, 1983). Vessel dimensions and maneuvering characteristics are key to the required waterway geometry and dimensions, no matter what design method is used. The design vessel might be an actual vessel based on proposed operations or a hypothetical vessel. In accepted practice, the design vessel is selected to represent a combination of the largest ship with the least controllability that will require the greatest depth and largest width of the waterway, considering both swept path and clearances. It may not necessarily represent either the largest specific ship or the least controllable ship, although both are normally considered before a selection is made.

Ideally, vessel size and characteristics are based on forecasts of operations, considering world trends in shipping, and on forecasts of trade and traffic for the port. In actual practice, vessels used in most waterways differ substantially from what the designer had forecast 20 or more years earlier. In the committee's view, major reasons for this discrepancy include:

- dramatic changes in the form and composition of the national and worldwide merchant fleets made available through modern technologies;
- the time scale of the waterway development process, which is longer than the working life of a typical ship; and
- the absence of a waterways management regimen that restricts vessel access only to vessels that do not exceed design vessel characteristics (which could have the potential side effect of impeding development of maritime technologies).

Because of the inexact forecasts of future actual ships or vessels and the wide degree of variation in handling characteristics even of similar

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ships due to such factors as loading, the exact modeling of a particular design vessel is excessive. A reasonable approximation is sufficient. The objective is to model a representative vessel with typical behavior under the control of typical pilots under the conditions being studied.

Dimensions and other particulars for existing and new designs can be gleaned from naval architecture journals and publications from the classification societies. Estimates of the far future can be based on interviews with shipping interests and on deductive reasoning. In all cases, verification of handling characteristics by experienced mariners is of great assistance.

SUMMARY

Waterway design, whether for new construction, improvement of an existing waterway, or appraisal of the capacity of a waterway, involves estimating the navigation requirements of an assumed vessel or vessels, coupled with estimates of the civil engineering factors. Present technology allows calculation and mathematical modeling of the factors that affect waterway width and form in the horizontal plane, but considerable judgment still needs to be applied. Depth and other elements, including the need for aids to navigation, are still estimated and based primarily on human judgment. Human reactions by vessel pilots are an important ingredient, and their assessment and accommodation present a particularly difficult challenge to the designer.

Optimization of design, wherein all elements are appraised in terms of the others and alternate solutions are compared for maximum cost effectiveness, is not usually practical because of insufficient data and imperfect technology. Optimized designs in the United States are difficult to achieve because of institutional factors, such as increased emphasis on social and environmental objectives in design and the long lead times before implementation of a project after planning. Design tools or techniques are needed that can give reasonably correct technical solutions quickly and early in the process to provide a more scientific and technical basis for accommodating competing objectives that affect the waterway development process.

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3

Use of Simulation in Waterway Design

Waterway design, which is reviewed in Chapter 2, is a complicated process. Some elements of the design process present opportunities for the application of computer-aided design techniques, including shiphandling simulation.

The use of shiphandling simulators to support the training of merchant mariners is generally well-known, and a number of ship simulators exist worldwide for training vessel operators and engineers. The emphasis of these simulators is more on reproducing the "feel" and behavior of the vessel rather than on predicting a vessel's trajectory with the accuracy needed for waterway design. Some simulators provide sufficient accuracy to accommodate both objectives. This chapter introduces the practice of using simulators to generate data that can replace or supplement "experience-based data" and rules of thumb, which have formed the basis for waterway design in the past. Simulation estimates the trajectory of design vessels that will use, or are projected to use, the waterway during its design life. Carefully designed simulator runs are used to gather the data that are then analyzed to draw conclusions about optimum or required minimum waterway dimensions and orientation, as well as ship operating procedures.

This chapter identifies the basic features of shiphandling simulators and simulation, the questions that simulation attempts to answer, and the basic assumptions that are made in simulation studies.

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RELATIONSHIP OF PILOTING TO SIMULATION

A simplified block diagram of the full-scale piloting system is shown in Figure 3-1. The central component is the closed-loop feedback system consisting of the pilot, the display being used for navigation, and the response of the ship (those elements within the dotted box). The display represents the physical depiction of the present environment that affects piloting. The display can vary from a 360° visual view of the surrounding area on a clear, sunny day to just a radar image of the surroundings. The pilot interprets the situation and reacts by, for example, changing the rudder angle or increasing or decreasing thrust. Any changes in the heading and speed of the ship are discernable in the display. The behavior of this closed-loop feedback system is referred to as the behavior of a piloted ship.

Two other principal components in Figure 3-1 are the external environmental forces and the external visual environment. These blocks represent all of the external influences on the ship and on pilot behavior that are unique to the waterway, including channel topography, atmospheric visibility, tide, waves, currents, and wind, as well as the geographic features, such as aids to navigation, buildings, and bridges, that constitute the waterway

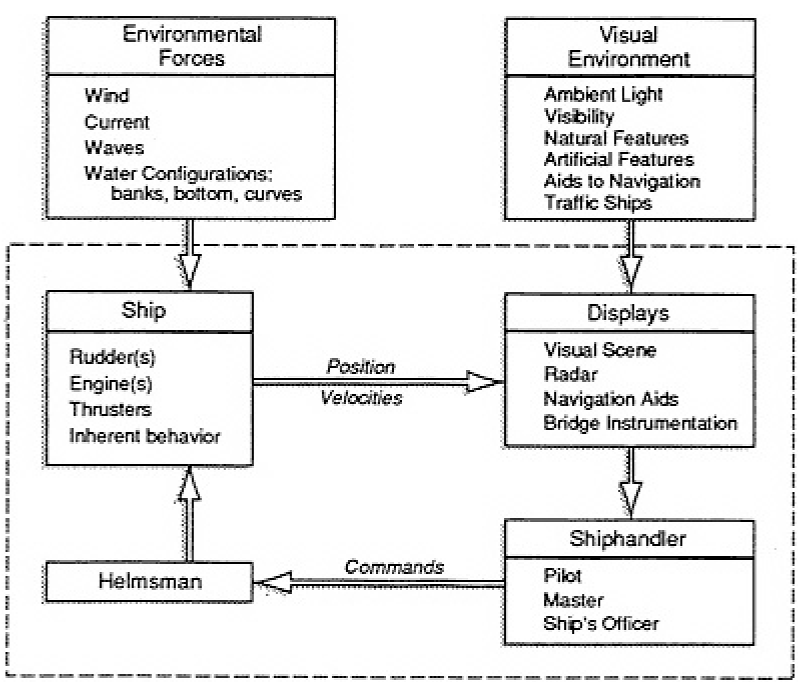

FIGURE 3-1 Block diagram of piloting.

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environment. Some of these aspects are not fixed and can vary according to the moment (such as other ships in the waterway), the time of day (such as tide), from day to day (such as visibility, wind, and waves), or from season to season (such as flow in the waterway). The impact of many of these waterway features are generally known to the pilot only implicitly, that is, from the ship's reaction to them. Pilot ability to anticipate their effects is directly related to a pilot's familiarity with the vessel's operating characteristics and with the waterway.

The purpose of a simulator run for waterway design is to predict the track of a ship piloted by a mariner who is experienced in piloting in the existing waterway. Accordingly, a shiphandling simulator models the components of the full-scale piloting problem discussed above. The fundamental difference is that a simulator replaces the inherent behavior of the ship with an approximation of the behavior of a full-scale ship. This model of inherent ship behavior is a computer-based, mathematical model of the ship's dynamics. When possible, track plots of the simulated ship and the full-scale ship for the same maneuver are compared. The results are simulated trajectories of ship passages through a prospective waterway configuration in the same manner that the ship would be piloted under a variety of operational and environmental conditions if the configuration actually existed. Simulation can be accomplished using human pilots (real-time simulation) or using a computer-based pilot simulation (fast-time simulation). The mathematical pilot model used in fast-time simulation is often referred to as an autopilot, a term that can also refer to automatic equipment used to steer a ship on programmed courses or tracks.

Shiphandling simulators also include the other components shown in the simplified block diagram (Figure 3-1). Because the behavior of the ship is now represented by a computer model, the waterway must also be represented in a compatible (that is, numerical) fashion. Most shiphandling simulators include more extensive means of recording the results of pilotage than exist on an actual ship because the tracks and other information generated during the simulation are to be used in the waterway evaluation and design process.

Although modeling of ship behavior usually consists of a computer-based, mathematical model of the ship's dynamics, simulation facilities using physical scale models of vessels and waterways are also in operation. They have been used to aid in waterway design and results have been considered beneficial, particularly for addressing hydrodynamic factors. Physical model systems are generally constrained by physical and operating characteristics of vessel models on hand (or specially constructed for the simulation), waterway configurations that can be modeled at the facility, and if an outdoor facility, lack of control over external forces such as wind. Furthermore, the reaction times on reduced scale physical models are much faster

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than on the full-scale prototype. With regard to time scales, the pilot would in theory respond as if in real life but at an accelerated pace. However, artificial behavior could be induced through the ability to see quickly the results of maneuvering commands. The actual effects of all these differences on the faithful reproduction of ship maneuvering behavior by the pilot and resulting simulated trajectories are not known. As a result, most simulators developed in the last decade have been computer-based, which permits mathematical alternation of vessels and waterway configurations. These simulators are the subject of this report.

RELATIONSHIP BETWEEN SIMULATORS AND THE DESIGN PROCESS

The many factors involved in designing a waterway, including civil engineering aspects, navigational aspects, and sociopolitical aspects, are discussed in Chapter 2. Indeed, a considerable history exists of designing waterways by design codes rather than by a detailed analysis. However, design codes are usually quite generous in their dimensions and undergo considerable refinement (and thus cost reduction) if credible analyses of the alternatives can be performed.

Fundamental to assessing how simulation can contribute to the design process is understanding the type of information that simulation attempts to provide. Fast-time simulation (also referred to as compressed-time simulation) provides the designer with many swept paths for the design vessels under a wide variety of conditions within the waterway (tide, current, wind, speed limits, and so on) in a compressed time frame. This information corresponds to, and replaces some of, the graphical constructions used in the simplified approach to channel design. Fast-time simulation can also be helpful in determining maneuvering lane width and overall waterway geometry early in the design process. Fast-time simulations are sometimes used to screen various design configurations for those that will be assessed through the more time-intensive real-time simulations. Real-time simulation (also referred to as full-mission simulation) uses qualified pilots to maneuver the simulated vessel through the modeled waterway using a true-to-life time scale. These simulations can be used in calibrating the pilot model for fast-time simulations, answering questions concerning navigational aids, and assessing piloting under difficult situations (complex bathymetry or environmental conditions, passing bridges or other marine traffic, and so on) where human decisions are critical.

The thrust of simulation in waterway design is to assess the risk to life, property, and environment of passage either for a new waterway or for an existing waterway (perhaps with new ships) without incurring either those risks or the costs of obtaining this information from real-life experience.

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For convenience of discussion, assume that it is possible to make a simulator predict exactly the path of a given vessel in a given waterway with a given pilot. A program of simulated passages designed to provide a detailed assessment of risk of passage for the given waterway could, for example, involve simulating the voyage of every conceivable ship that would ply the waterway during its lifetime, under every conceivable state of the environment and traffic, and under the pilotage of all manner of pilots. Even if one could afford the cost of mounting such a program, the time required would be comparable to the lifetime of the waterway. Although this time would be significantly reduced if the real-time runs were mostly replaced by fast-time simulation, such a program would still be impractical.

The committee believes that applying simulation in waterway design relies on the following inherent working assumption:

> *A limited number of simulations using a less-than-perfect simulator, a few select (design) ship types, a few select environmental conditions over extreme ranges characteristic of the local area, and a few pilots with representative local expertise and shiphandling proficiency are sufficient to obtain a useful appraisal of waterway design.*

Evaluations of such simulations rely heavily on professional judgments and experience to identify or clarify design deficiencies, detect unforeseen problems, and determine areas where refinements would optimize the design to reduce costs without compromising safety. It may be possible to relax this assumption through the combination of real-time and fast-time simulations.

The validity of this assumption is critical to the efficacy of simulations as a design tool. Similar engineering assumptions are made in other fields with satisfactory results. For example, the design of an offshore platform requires the estimation of the worst loads that will be exerted on it during its lifetime (for example, loads experienced in a storm with a return period of 100 years). Statistical methods have been developed to estimate these loads from a limited environmental history and from limited model test results or analytical computations.

Conceptually, the undertaking of a limited program of simulations to appraise designs falls within accepted engineering practices. If a limited program is used, the relative accuracy or detail of each of the four elements (simulator, type of ships, waterway environment including vessel traffic, and pilots) must in some sense be balanced. The cost of a simulation program increases almost linearly with the scope of the program after the simulation model is set up. The design of a simulation program is therefore generally focused on determining the minimum scope of the simulation program necessary to make a meaningful risk assessment for a given design (or set of design alternatives). To accomplish this goal, the program is usually biased toward combinations of elements that will strain a waterway

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the most. The assumption is that if the waterway is satisfactory for these combinations, it certainly will be for other combinations that do not strain the waterway as much. Interpretation of the results must reflect the biases inherent in these choices. For instance, for many waterways the designer can anticipate traffic composed of a wide variety of ship types, some of which are not yet in existence. Some of the anticipated traffic may include small, maneuverable vessels that will ply the waterway with ease no matter what the waterway design; other traffic consisting of very large ships with limited maneuverability in restricted waters may strain the waterway depth limits, the maneuvering lane widths, or both. These latter ship types and cargoes carried often have potential for significant consequences (typically channel blockage or pollution) should accidents involving them occur.

Typically, research is directed toward the application of a specific ship to an existing waterway or a waterway to be constructed. In other cases, when many different ship types are involved, the selection of the ship or ships to be used in simulation is subjective, relying heavily on experience. Ideally, the selection is based on the input of pilots who are familiar with the area of the proposed waterway and who are qualified to pilot the types of ships to be simulated. If local pilots do not have experience with the simulated vessel, pilots from other areas with the necessary ship maneuvering expertise could be included in the study. Ship selection must also involve some description of the loading conditions of the ships, because the behavior of a fully loaded ship with small under-keel clearance will likely be very different from that of the same ship, lightly loaded, with a large under-keel clearance and more subject to wind loadings.

Designers may also anticipate and design for increased risk of an accident during severe environmental conditions (for example, storms, high currents), which could severely strain the skills of even the most experienced pilot. Like the selection of ships for simulation, selection of these additional factors ultimately is made subjectively. In the past, many questions and some controversy have arisen about what can be reasonably assumed for pilot control and skill in the selection of weather conditions, aids to navigation, and dimensions of waterways. This uncertainty is especially true when estimated ship trajectories are developed by simplified analytical schemes that do not put qualified pilots in the simulation process. The same controversy also applies to trajectories estimated from fast-time simulations. By using experienced ship handlers in a real-time simulation and presenting them with an adequately realistic situation, the question of applied skill level of the pilot is addressed, if not fully answered.

Real-time simulation with human control is gaining acceptance throughout the world as a useful aid in harbor and waterway design. Some of the many applications to date are discussed in Appendix C. Although its acceptance has been slowly and steadily increasing, there is no consensus amongst

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designers concerning its usefulness, even though it has been used as a tool in early development stages of some waterway designs (Norrbin et al., 1978; Ottosson and van Berlekom, 1985; Puglisi, 1988; Simoen et al., 1980). Reasons for the apparent reluctance to use simulation for concept development include:

- cost and time requirements;
- the validity of the modeling; and
- interpretation of results.

In addition, some waterway designers may not be comfortable with changes from traditional techniques with which they are very familiar to a process that not only may not be familiar to them but also would expand participation beyond the traditional design community.

Because real-time simulation is human resource intensive, the capability for quickly modifying inputs to the mathematical model which describe the waterway and its environment is desirable to facilitate assessment of design alternatives. There sometimes is difficulty in achieving this objective depending on the waterway under examination. From an examination of several case histories where simulation was used (see Chapter 7; Appendix C), it appears that these objections are not exaggerated, although the difficulties did not prevent project sponsors from acquiring valuable technical and design data. In time, as users become more familiar with the tool and its use is refined, simulation may play a more important role in design, particularly much earlier in the process.

Special design problems for which real-time, human-controlled simulation appears particularly suitable are the following:

- determining a pilot's ability to assess the vessel's position in relation to horizontal dimension requirements, including the value and placement of navigation aids;
- evaluating traffic density limitations;
- optimizing side clearance dimensions for a vessel of a given size;
- maneuvering actions, including docking and undocking; and
- optimizing bend and turn dimensions for a vessel of a given size.

All of the above considerations are important in waterway design, and all are almost totally dependent on applied pilot skill. Heretofore these problems have been addressed mostly on the basis of opinion without a means of quantification other than full-scale testing.

Sometimes the resolution of design problems has been as much political as technical, necessitating extensive efforts to achieve a consensus between parties with conflicting views. The committee found that where used (see Chapter 7; Appendix C), simulation has been a unique way to test opinions on specific designs in a focused and clearly visual way. Further

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more, real-time simulation has in some cases helped to build consensus in the design process by providing a realistic presentation of problems that is understandable to all interested parties.

SUMMARY

Simulation is a technology used for predicting the track of a ship in a waterway either by using qualified pilots (real-time simulation) or a pilot model (fast-time simulation). Typically, simulation runs primarily reflect situations that will most stress the waterway and the number of these runs that can be made is limited. Nonetheless, useful technical information concerning the vessel track can be obtained, and consensus building among the conflicting parties in the waterway design can be achieved.

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4

Shiphandling Simulators

Shiphandling simulators encompass a wide range of capabilities, facilities, and man-machine interfaces. They can be divided into two major classifications: real-time simulators, which have a human controller (referred to as a *man-in-the-loop*), and fast-time simulators, in which the human is replaced by a computer-based pilot model (often referred to as an autopilot). Because there is no human involved in fast-time simulation, the speed of the simulation is limited only by the speed of the host computer. With modern computers, these simulations can be performed at much greater speed than real time.

Simulation allows examination of proposed waterway designs before they are selected or implemented. The primary contribution of simulation is quantitative performance data characterizing the design and operational alternatives being considered. A number of methods furnish data that can be used in the design process: physical models, fast-time mathematical models, and man-in-the-loop simulation. The latter provides data on the entire navigational system, including the variability of the shiphandler, and thus it is referred to as *full-mission* simulation. This method provides subjective evaluations as well as quantitative assessments that can be used to guide the selection process and acceptance of a proposed design.

Both fast-time and real-time simulations are available offering various levels of sophistication. The phenomenal growth in computing power and its low-cost availability relative to the total cost of a simulator program has

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eliminated simulator hardware as an important limiting factor in applying simulation to waterway design. Instead, the cost of obtaining data for the mathematical models (called *identifying* the model), processing of these data, and developing the visual scene are emerging as the dominant costs in marine simulation.

COMPUTER-BASED MODEL FOR SHIP BEHAVIOR

A simulation model for ship behavior is a computer-resident mathematical model of the waterway and of the dynamic properties of the ship. The waterway model includes not only the bottom topography, but also the winds and the currents below the water surface. This model is usually a combined data base and interpolation scheme where model details can be determined for an arbitrary location in the waterway.

The core of the ship dynamic model is the set of equations of motion of a rigid body (the flexibility of the ship is inconsequential for these problems). The equations of motion are usually referred to a coordinate system fixed in the ship, and the result is called Euler's equations of motion. These equations are six-coupled, nonlinear, ordinary differential equations that relate the motions of the ship to arbitrary external forces acting on the ship.

The force system that acts on the ship is a result of hydrostatics, hydrodynamics, and aerodynamics. Hydrostatic forces can be computed by Archimedes' principle. Techniques for numerically modelling the exact flow of air or water around a ship hull do not exist, even in the open ocean where the topography of either land or ocean bottom is not an influence. In a waterway, these local topographical details are very important and strongly influence the hydrodynamic and aerodynamic forces acting on the ship. As a result, a combination of theory, experimental results, and heuristic approximations is used to determine mathematical expressions for the force system on a ship in a waterway.

In addition to the ship's dynamics, mathematical models are developed for several other dynamical systems. These include the main propulsion system; steering machinery; thruster machinery, if available; and assistance of tugboats.

The success of the computer model in reproducing a vessel's behavior depends on the ability to describe the waterway and its environment numerically, to predict the instantaneous force system on the ship, and to integrate the mathematical expressions or algorithms of the ship and other mechanical components that contribute to the vessel's trajectory. Each of these elements involves approximations, and in the end, each is reduced to a set of equations. A detailed discussion of this process is given in Chapter 5.

In recent years, digital computers have been used exclusively for these problems. Inputs to the simulator computer are the commands issued by the

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pilot, and output is the position and velocity of the ship and the visual presentation. Because the size (and cost) of modern digital computers of high capability is so low, the limitations on speed and memory capacity that were important considerations 20 years ago no longer exist. Therefore, the quality of the module for the vessel's behavior rests solely on the expressions, algorithms, and data bases that are programmed into the computer. In practice, these algorithms, hull and model scale data, and expressions are usually proprietary to the individual simulation facility, and as a result, comparisons of these aspects among facilities are limited.

Specific Components of Fast-Time Simulations

Fast-time simulation is closed loop, with a pilot model rather than an actual pilot in the loop. The pilot model, or autopilot, is computer software that simulates, to some level, the human performance of a shiphandler. It is not to be confused with the autopilot hardware found aboard ships that steers set courses or predefined turns. Pilot model software provides dynamic access to the necessary vessel motion and waterway data base parameters and algorithms to evaluate the vessel's track and to generate appropriate control commands for the vessel.

The typical autopilot for fast-time simulation is part of the software in the computer-based simulation and is defined in terms of the algorithms it uses to evaluate the vessel's track and to generate control commands. In typical fast-time simulation, the simulator operator supplies additional information in the form of a preferred track for a point on the ship (usually at midships centerline). The track may also include desired speeds for various parts of the transit that are used to trigger engine commands. This track therefore represents a predetermined strategy for negotiating the passage and is presumably geometrically feasible (that is, if the ship follows the path exactly, no portion of the ship should extend beyond the bounds of the waterway). The pilot model in this situation performs as a track follower, because this approach roughly approximates what happens when a human pilot starts a passage with a set strategy and adjusts the transit when deviations from the planned route occur. In practice, the programmed track for the pilot model is usually selected after consultation with experienced pilots about appropriate transit strategies.

Autopilot designs can vary in sophistication depending on their needs. At one end of the spectrum, a simple autopilot is used. This autopilot, using the exact location of the ship (as computed by the mathematical model) as datum, generates simple rudder and engine commands as specified by the associated transit strategy in an attempt to minimize any deviation between the current location and the prescribed track.

The simulation obtained by simple pilot models are useful because dynamically feasible swept paths can be defined. For example, results can

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include deviations from the desired path resulting from such factors as inertia of the vessel, hydrodynamic effects, and lags in the power plant and steering gear.

Attempts are often made to make the pilot model behave more like a real pilot, including one or more of the following refinements:

- making the position error zero until a certain detection threshold is met,
- not executing a command until it is a significant one (for instance, waiting until a rudder command of at least 5° or 10° can be given),
- providing for anticipated course changes,
- introducing delays in decision making, and
- introducing noise (random error) into the position information.

Each refinement generally leads to a different swept path, which is in theory reflective of the swept paths that would be experienced with human pilots whose performance varies due to many factors such as professional skills, experience, and stress (including fatigue, boredom, and other physical condition factors). A virtue of the pilot model is that its performance can be made consistent (that is, human variations are screened out) so that the actual effects of physical forces on the design vessel for various tracks can be assessed through sensitivity analysis. Data from each approach can also provide a comparative basis for accommodating operational factors in the design.

Although the measures for representing human behavior introduce some variability into the pilot model, they do not achieve any semblance of the full complexity of human pilot behavior that reflects many different styles and levels of effectiveness in shiphandling. To represent the underlying perceptual and cognitive processes involved in detecting and interpreting aids to navigation and vessel traffic, decisions about maneuvering actions, and other operational decisions, much more sophisticated pilot models than exist today would be needed. Only then could true transit strategies be programmed into the simulation without taking the vessel into some predefined track. Potentially, developments in piloting expert systems (that is, computer-aided, knowledge-based decision making including use of neural networks) could be incorporated into pilot models to reproduce some of the more cognitive aspects of piloting behavior (Grabowski, 1989).

Fast-time simulations are usually used for sensitivity analyses because they do have consistency. One typical use is determining the effects of current variations and tidal stages on maneuvering. Because many runs can be performed in a reasonably short time, many different hydraulic conditions can be used. Another use of fast-time simulators is to evaluate a select number of alternate waterway designs. In either case, detailed records of the commands and resulting trajectories must be kept for analysis. This record-keeping requirement applies to real-time simulations as well.

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Specific Components of Real-Time Simulators

Real-time simulation involves a number of large and often expensive physical components that are not used in fast-time simulation. These simulations must be run in real time because they involve the participation of the human pilot to interpret the progress of the transit and to issue commands. Paths of communication must be provided between the pilot and the computer, including a means of displaying the location of the ship to the pilot (visual display) and a means of communicating pilot commands to the computer (controls).

Visual presentation

Two different types of visual presentation of the vessel's situation in the waterway are common. One corresponds to a *bird'-eye* (plan) view, such as a radar screen; the other corresponds to a bridge-view display that resembles what the pilot might see looking out from the vessel's bridge. Of the two display systems, the bird's-eye view is by far the simpler one to develop and requires only modest computational capacity. The bird's-eye or situation display is often more detailed than the corresponding radar scene and may include an accurate depiction of the vessel, geographical landmarks, aids to navigation, and other waterway features. Simulation of the corresponding radar image can be effected by eliminating or reducing much of this detail. When coupled with information equivalent to what would normally be available on the vessel being simulated, this display can create a simulated operating environment corresponding to restricted visibility atmospheric conditions. Regardless of the display format, research has determined that if a simulation system provides more information to the pilot than available in real operating scenarios, the results of simulation may not be representative or useful (Norrbin, 1972). The results can also be biased if important information is missing.

Bridge-view displays are intended to be viewed and interpreted by the pilot as a representation of what would be seen during vessel transits when the atmosphere does not completely obscure the view of landmarks and aids to navigation. This display could simply be one monitor (corresponding to what might be seen out of one bridge window) or an array of screens presenting the pilot with a rendering of an actual 180° or a full 360° view. When using these displays, the following interdependent physical factors limit perceived realism:

- display size,
- physical field of view,
- viewing distance (from the eye), and

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- display quality (for example, color resolution, spatial resolution, brightness, and contrast ratio).

Bridge-view and bird's-eye displays are usually computer generated and are presented using either cathode-ray tube (CRT) monitors or large-screen, television-like projectors. When projection systems are used, the display size can be made fairly large with increased eye-to-screen distance for realism. However, the resolution does not improve, and the brightness decreases in inverse proportion to the area of the display. A compromise between brightness, screen size, resolution, and eye-to-screen distance can be made to present reasonable visual cues to the pilot.

The physical field of view refers to the angle subtended by the display as seen by the person performing as pilot during the simulation. Usually this angle is measured in the horizontal (azimuth) plane for ship maneuvering problems. A small television-size monitor can have a large field of view if it is placed close to the observer. However, viewing such displays can be uncomfortable, and they do not impart the feeling of a view from the vessel's bridge or pilothouse due to eye-to-screen distance. For realism, it is important that the field of view being represented in the simulation scene be approximately matched by the observer's field of view of the simulation display. Both the observer's and the simulation scene's fields of view from a single monitor or projector are inherently limited. Large display systems are often composed of three, five, or more display screens arrayed in roughly a circle around a mock-up of the bridge. Coordinating the projectors for multiple displays is not difficult with today's technology; it is possible to obtain displays with up to 360° of azimuthal field of view, although a somewhat smaller field of view, about 240°, is more common. Vertical fields of view vary depending on the simulator application, 20° to 24° being typical. Docking simulators generally require a larger vertical field than those applied to maneuvering or channel design work. Reasonable depth perception and reduction of parallax error for the simulation scene in relation to a simulator's bridge typically require a screen-to-eye distance greater than 10 feet. The closer this distance is to real-life conditions, the smaller the parallax error.

Display quality can be measured by a number of factors, including resolution, update rate, and texture. Spatial resolution refers to the fineness of detail that can be displayed. For computer-generated displays, the smallest unit of display is called a pixel. Individual computer displays are generally rated by the two dimensions of the array of pixels forming the display. However, what is more important for a simulator display is the visual angle a pixel subtends for a pilot located on the simulator's bridge relative to the angular visual acuity of the pilot's eye. Depending on the sophistication of the computer display generation, the appearance of any pixel can be chosen

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from a limited number of colors or greys, or from millions of different colors to reproduce natural shading and texture.

Update rate is the frequency with which new scene information is displayed. A slow update rate makes the scene "jump," whereas a fast update rate (greater than 15 hertz) yields a movie-like smoothness of motion. This rate depends critically on the computer supplying the graphical information and is often significantly slower than the refresh rate, the rate at which the screen is "repainted" by the electronics. Higher refresh rates eliminate screen "flicker" which contributes to viewer fatigue. The computer determines what is displayed by computing a two-dimensional perspective view of the scene as observed from the pilot's station. The computer derives this view from a three-dimensional description of the modeled environment stored in its memory. The speed of the process depends on the computer's ability to form the elemental shapes comprising its two-dimensional picture, to eliminate hidden lines or surfaces, and to determine the color of each pixel. Special, dedicated computer systems have been developed to perform this type of calculation with great efficiency. Because the update rate varies inversely with the number and type of objects arrayed in the three-dimensional space that will be visible or bounded within the scene, simple scenes can be updated at a faster rate than complicated scenes.

An elemental shape formed in the perspective view (e.g., a polygon representing a buoy) can be filled uniformly with the same color or filled with different colors which form a pattern reflecting its "texture" or shading (where, for example, the smooth texture and shading of a buoy may differ from that of the surrounding water surface). Many newer graphical computers have the capability to produce such texture, which can contribute significantly to the apparent realism of the display. A special use of texture is the "greying" of distant objects to enhance the observer's feeling of distance.

Controls

Another aspect of the physical setup of a real-time simulator is the realism of the controls and the navigation instruments used in the mocked-up ship's bridge. There is a wide range of mock-up realism in common use for simulators. In the most modest facilities, the only display may be a single CRT monitor for radar and visuals; the controls may be simply "radio" knobs that can be turned to give commands to the engines or rudders; and the navigational instrumentation readout may be simply a printer or portion of the CRT that shows the current readings. In the most elaborate facilities, the complete bridge of a ship is duplicated including all standard, commercial instrumentation and controls. The equipment, furnishings, and bridge windows are arranged to conform to traditional bridge layouts or

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layouts specific to the design vessel under study. Some facilities mount the bridge on a motion platform and include loudspeakers. The objective is to enhance the *fidelity* of the simulation by providing an approximation of the sound and feel associated with vessel response to environmental factors (for example, pitch and roll in a seaway) and maneuvering commands.

Fidelity

The word *fidelity* in this report refers particularly to the appearance and functionality of the simulator as experienced by the pilot. In the literature, the concept of fidelity often includes separate measures for various other components of simulation (for example, the mathematical model).

Ideally, the pilots are provided an environment that so closely resembles a ship's bridge (or pilothouse) that they are unable to detect that they are not aboard ship. In other words, the ideal is a bridge that looks, smells, feels, moves, and sounds like a real ship's bridge and has views through the windows and ports that are absolutely lifelike. Such an environment would be referred to as having "perfect" fidelity. These environments are, in fact, almost achieved for the training of aircraft pilots. The quality of the display and the realism of the mock-up contributing to fidelity are directly related to their costs, although the costs of the display hardware have dropped dramatically with advances in computer technology.

The actual environment presented to pilots in a simulator inevitably falls short of perfect fidelity, varying considerably from facility to facility. Most simulator facilities attempt to include appropriate displays that either mimic those on board an actual ship or at least evoke their presence. Some simulators incorporate the angular motions resulting from seaway and maneuvering by tilting the bridge and display systems. These motion systems can be extremely costly. Although one might naturally assume that higher fidelity is better, evidence is lacking that correlates the influence of fidelity to the results of the simulation. Consequently, no consensus exists among simulation practitioners regarding what levels of fidelity are required to achieve reliable simulation outcomes, or how the requirement might vary with the simulation study objectives.

There is considerable interest in the potential of technical representations such as electronic charts and real-time positioning displays to substantially augment and perhaps become more important than visual observations. A large number of performance and application issues are being researched, including the effectiveness of integrated displays for use in piloting waters (Astle and van Opstal, 1990; Clarke, 1990; DeLoach, 1990; Eaton et al., 1990; Grabowski, 1989; Graham, 1990; Kristiansen et al., 1989; Maconachie, 1990; Russell, 1987; Sandvik, 1990). However, there

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are many national and international policy issues requiring resolution. Thus, adoption of advanced systems cannot be reliably forecast.

The eventual use of integrated bridge displays and the subsequent changes these may have on piloting, will need to be reflected in future real-time simulations. Since it is less expensive to emulate a high technology bridge than to produce a high fidelity visual scene, it is likely that the cost of these changes would not become an issue. For waterway design, it would be prudent to equip real-time simulators with display systems of appropriate fidelity and bridge equipment that reflect the probable state of practice for merchant shipping. Improved performance by ships with advanced positioning and control systems could be expected to provide additional margins of safety relative to simulation results.

Man-in-the-loop

Pilots as shiphandlers represent the most complicated element in the behavior of ship maneuvering through a waterway (see Figure 3.1). Pilots must integrate diverse information acquired via the human senses on all aspects of own ship, environment, and other vessel traffic, as well as navigational conventions and other factors (Armstrong, 1980; Crenshaw, 1975; Plummer, 1966). Because pilots are integral to shiphandling in confined waterways, inclusion of pilots with knowledge of the design vessel, local conditions, and tug assistance is essential to the simulation process, if the simulation is to have complete credibility with prospective users of the waterway.

The pilot views the waterway scene from the bridge directly or, especially in the case of obscured vision, through electronic means including VHF communications, radar, and electronic aids to navigation. The pilot gains immediate information about the vessel from the readouts of the vessel control instruments. Based on the pilot's experience on the waterway and interpretation of the situation, rudder and engine commands are given. The pilot's skill involves the ability to determine the vessel's position and motion within the waterway based on observation, to predict change in the vessel's track resulting from the local environment, and to initiate required maneuvering commands in anticipation of the vessel's progress so that it will remain on the desired track.

Selecting appropriate pilots to participate in a simulation involves considerations of piloting skills, local waterway operating practices, and statistical sampling factors. Even when pilots for a simulation study are selected as a representative sample of the local pool of pilots, significant variability among pilots and their piloting performance is inevitable. Piloting different types and sizes of ships in waterways is a skill that takes many years to learn. Piloting skills vary with the nature of service (that is, coastal, bar,

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river, harbor, or docking pilotage, or a combination of pilotage services), experience, and personal capabilities. Also, a pilot's skill level may vary from day to day depending on human and external factors.

Piloting in a shiphandling simulation is somewhat different from real piloting. During the design stage of either a new waterway or an extensive modification of an existing waterway, no pilots have had experience with the design. The generic skills required to pilot a simulated ship through the waterway are, however, identical to those required if the waterway design is executed. Thus, it appears sufficient to use capable pilots for real-time simulation, with the understanding that these pilots will probably need to become familiar through simulation with the new or modified waterway. It is equally important that these pilots are familiar with the local operating environment and incorporate local knowledge into the simulation. Often, this can be assured by using pilots certified by the Coast Guard or appropriate state or local authority for the pilotage route.

If simulation runs are performed by pilots whose ability far exceeds the expected average for the waterway under examination, the results of the simulation may be overly optimistic. The converse may apply for simulations run with very capable pilots who lack the knowledge of local conditions. The fact that pilots know they are only performing a simulation and that the consequences of failure will not include vessel damage, lawsuits, or personal injury, may make their performance quite different from real-life pilotage.

Some simulator facilities always use a few select pilots in rotation. In these circumstances, peer pressure to excel and the simulator's sophistication may affect performance. This may be an advantage for simulation training but not for waterway design where duplication of real life performance is needed. Because there are no universally accepted measures of piloting skill or knowledge, assessment of these dimensions is subjective. It is difficult to evaluate whether or not pilots chosen to participate in a given simulation reflect the average capabilities of local pilots or how their performance may have been affected by simulation conditions or the pilots' sophistication with simulation techniques.

LEVEL OF SIMULATION

Each simulation facility conducting port and waterway design work uses different simulator components. These facilities are often compared by characterizing their components using a subjective measure called the *level of simulation*.

To indicate how this subjective measure might be arrived at, Figure 4-1 shows the various components that make up a real-time simulator and further subdivides these into the characteristics of the components. A profile

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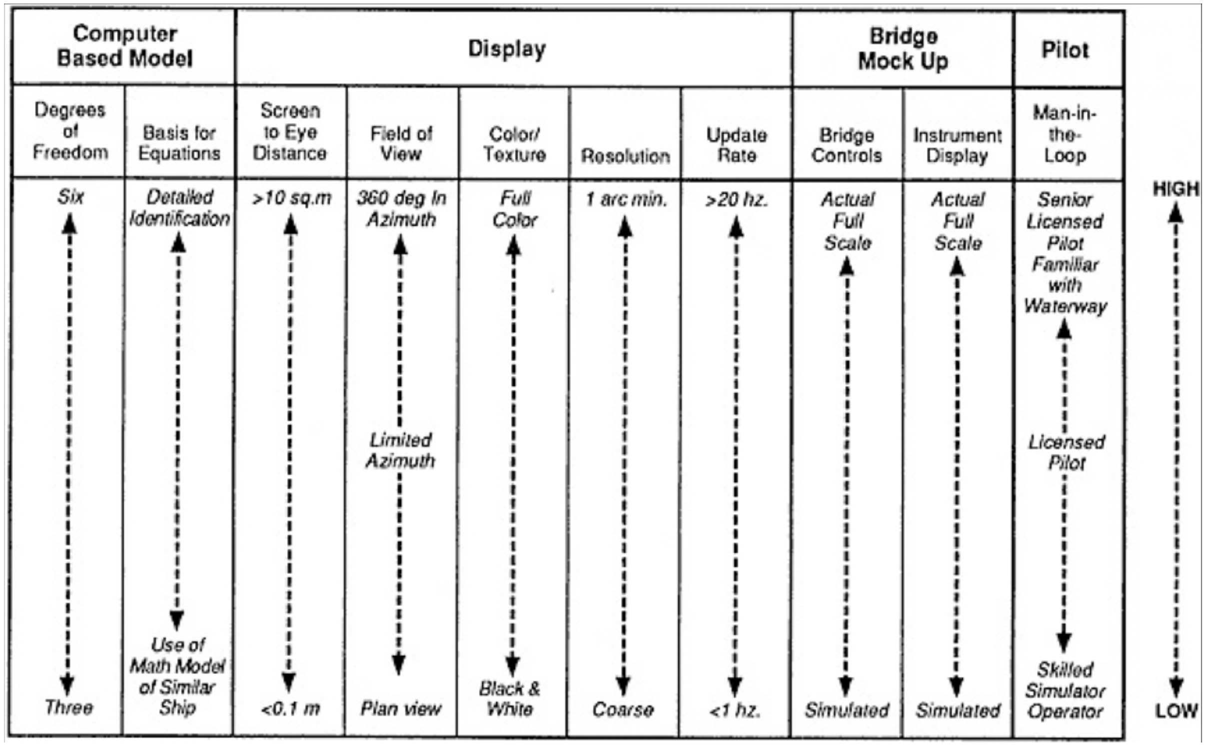

FIGURE 4-1 Levels of shiphandling simulation for evaluating real-time simulation facilities. Each column represents a scale for an individual characteristic of the simulation facility. The most desirable characteristics are at the top of each column, and characteristics of decreasing complexity (and generally decreasing cost) are listed down each column.

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of any facility can be made by placing a horizontal mark in the figure at a height for each component that approximately reflects that facility. If the marks generally lie near the bottom of the columns, the facility is referred to as having a low level of simulation; if the characteristics generally lie near the top of the columns, the facility is referred to as offering a high level of simulation.

Practitioners of simulation generally accept that various levels of simulation are appropriate for different design situations. No definitive guidance is available to assist prospective users in determining the level of simulation needed for a particular problem. There is a dearth of quantitative information relative to selecting the level of simulation appropriate to a particular waterway design study. Nevertheless, if the level of simulation is not sufficient to capture an essential feature of the waterway, ship dynamics, or other key aspect of the real system, then the results of the simulation may be suspect. In practice, a higher level of simulation than what appears necessary is often used simply because the consequences of overlooking some subtle feature may have an important impact on vessel transit results. For example, the presence of a full bridge team to provide navigational support to the pilot would add to the face (that is, apparent) validity but would not necessarily add to the level of simulation. The actual contribution would depend on the capability of the bridge team to assess the operational situation and communicate this effectively. Thus, as with waterway design generally, the tendency in simulation is toward conservatism.

After the vessel (or vessels), environmental conditions, and appropriate simulator hardware are selected and installed, the simulation process occurs in three steps. In the preliminary phase, mathematical models of each simulation component are collected, and the various constants are identified (see Chapter 5). In the simulation phase, the model is exercised in either real time, fast time, or both. In the interpretation phase, the simulation results are assessed in terms of the risks posed by the channel design and potential alternative designs. However, because the simulation program is biased toward the most accident-prone situations, results must be carefully interpreted (see Chapter 6).

SUMMARY

The prospective user of shiphandling simulators for waterway design is confronted by several factors that complicate the decision to use a simulator. Given the range of technical considerations, careful examination of the capabilities, research methodologies, and results of available simulations is needed to assess simulator suitability for each individual waterway design project. Of equal importance is the selection of pilots for real-time simulations because they are critical to both the validity and credibility of results.

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5

Mathematical Models

Many components of shiphandling simulators are substantial physical pieces of hardware. Some components can be evaluated easily from their appearance (the bridge and its equipment) or performance (the size, resolution, or update rate of the display). The mathematical model, which is embedded in the simulation computer and invisible to the user, is difficult to generate and even more difficult to validate. This section describes the state of practice of the development of the computer-based model for a shiphandling simulator. Validation of the model is presented in Chapter 6.

SELECTING AND IDENTIFYING THE SIMULATION MODEL

Before a simulation can be performed, it is necessary to develop quantitative computer-based models for the waterway, ship, and various components of the traffic. Each of these models consists of two kinds of information:

- a *framework* (or structure) for the data (which describe the generic component), and
- a set of *numerical constants* associated with the framework.

The framework is a widely applicable mathematical procedure or algorithm that embodies the relationships between the various factors involved. Numerical constants or coefficients quantify these relationships for the spe

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cific case under consideration. Selection of a particular framework for a specific component varies from facility to facility, is usually based on theoretical developments associated with that component, and is usually proprietary. Determination of the numerical constants associated with the framework is called *identification*. A discussion of both the selection of a framework and identification of its constants for each major component of the computer model is presented in the following sections.

WATERWAY BATHYMETRY

In order to determine the forces that act on a ship, it is necessary to determine the bathymetry (depths, contours) of the waterway in the neighborhood of any position the ship might assume during its passage. The framework typically consists of a data base that stores the waterway depth at specific locations and an interpolation scheme for these data that allows estimation of the water depth at an arbitrary point in the waterway. The structure of these data bases varies considerably. No clear advantage has been demonstrated for any particular scheme. Usually selection is a tradeoff between size of the database and ease of interpolation, which translates into a tradeoff between the storage capacity and computational speed of the computer used for the simulation. The presentation of the data in the original source is a strong influence on the selection of framework.

A typical framework for the data base is a grid on a chart of the waterway (either a rectangular grid or curvilinear grid fitted to the channel). Entries in this matrix correspond to water depth at each node of the gird. Data points must be specified with sufficient density to capture the underwater geometry of the waterway. Of the various choices, the rectangular grid (normally based on latitude and longitude) requires the largest number of data points but is simplest for interpolation. Data bases that use a waterway-fitted grid (for instance, one that uses the channel centerline as one coordinate) are much smaller but require more complex interpolation.

In any of the grid data base systems, different levels of interpolation can be used. Linear interpolation is the easiest and has the advantage of being most computationally robust. However, linear interpolation is also the least accurate because the interpolated values always lie within those data base values used as input to the interpolation. Higher order schemes, such as parabolic interpolation or cubic spline interpolation, require fewer data base points. However, if the data base points do not correspond to a smooth surface, anomalous interpolations can occur. Consequently, linear interpolation is most often used.

Some facilities use a different system altogether, one in which the numbers stored in the waterway data base correspond to polygonal contours of equal draft. Although this scheme results in an extremely compact repre

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sentation of the bathymetry of the channel, it also results in the most computationally demanding interpolation scheme. The bathymetry of very complicated waterways can be described to the degrees of accuracy necessary with either the grid system or the contour system. Increases in accuracy require corresponding increases in the amount of stored data in the data base regardless of the interpolation scheme used.

Identifying actual data for the data base is not always easy or straightforward. Typical proposed waterway modifications usually involve some widening and deepening of existing channels or perhaps changing the channel path. Some projects involve dredging channels where none had existed before. In cases where the channel dimensions of a new design are specified, the bathymetry can be read directly from the plans for the waterway.

Much of the overall project area may be in a natural state or may be the result of previous dredging. Many available charts of waterways are not recent, and few of these include information on water depth that is dense enough for an adequate data base. Most field survey records provide discrete soundings at specific data points rather than a continuous bottom profile. About 60 percent of field surveys conducted by the National Oceanographic and Atmospheric Administration (NOAA) were done prior to 1940 with lead lines (NOAA, unpublished data).

Waterways are not static; they are constantly changing. Some bathymetric changes are due to seasonal variations of flow, others may be part of variations resulting from singular events that occur every few years (for example, floods), and still others represent long-term trends that may span decades, if not centuries. Investigation and correction of chart discrepancies reported by various sources are backlogged, with about 20 thousand discrepancies remaining unresolved in backlog during early 1991. NOAA can field investigate about 20 percent of chart corrections, which leaves major areas with unresolved discrepancies. As a result, reliable continuous bottom profiles are available for only some of the important shipping routes along the coasts and in ports and waterways (NOAA, unpublished data). Therefore, developing a bathymetric data base requires careful research and may well require the supplementation of information on available charts with in situ measurements. It should be noted that the density of bathymetry data points required for determining channel flow and grounding is more demanding than that required for determining of the forces on a ship (Norrbin, 1978; Norrbin et al., 1978).

WATERWAY ENVIRONMENT

Because of the efficiency that results in the computer programming, the data base framework selected for the waterway environment is usually identical, or at least corresponds quite closely, to that for the waterway bathym

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etry. In this way, similar interpolation schemes can be used for both. However, determining the waterway environment data base is fundamentally more complicated than for waterway bathymetry. Those quantities that describe the environment, such as wind, current, and density, often vary with time of day or season or with altitude or depth in the waterway. For existing waterways, information on existing charts regarding currents is typically even less detailed than that for bathymetry, and information on other quantities is even more sketchy. For waterway designs involving changes in existing bathymetry, information on current variations needs to be developed.

The waterway environment can reflect some unique problems. In some cases, a density stratification may exist (for instance, at a river mouth where fresh water may override a saltwater wedge). In such cases, the variation of current with water depth can even include a reversal of the flow. Similarly, air characteristics, such as velocity, turbulence, and temperature, can vary with weather or with altitude above the waterway and can be significantly different in the shadow of buildings or bridges than elsewhere. Design-related bathymetric changes relative to the tidal prism in coastal ports may also affect sedimentation rates and, consequently, waterway operations and maintenance. Data on such effects are generally not available, but depths could be changed in the simulation to obtain a rough estimate of behavioral changes in the design ship when sedimentation modifies the bottom profile. However, there is no indication that maintenance factors have been incorporated into most simulations.

The database for the environment can be formed in several ways. For an existing waterway, a field survey can be conducted to determine the values in situ, but the cost of such a survey may be high. Hydraulically scaled models are traditionally used either as a less-expensive alternative to in situ measurements in existing waterways or as a way to determine the flow in waterways not yet built. These models usually predict reliably the gross characteristics of horizontal flow. However, due to difficulties in scaling viscous effects, predictions of vertical variation of fluid velocity at any given point are less reliable.

Computational fluid dynamics (CFD) schemes have been developed in the past decade to predict currents in waterways with complicated bathymetry. Already these methods are less expensive to use than physical models. As with physical models, CFD schemes yield better results for the average horizontal fluid velocity than they do for the vertical fluid velocity distribution at a given point. However, both hydraulic models and CFD schemes can benefit from comparison with in situ measurements.

It is very difficult to determine the variations of the waterway environment that occur with depth or altitude. More importantly, no validated means exist for predicting the effect of these variations on the forces acting

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on the ship. Therefore, it is typical to replace the variation of current with depth or the variation of wind velocity with altitude by a single, uniform current or wind vector that will produce approximately the same force distribution on the vessel. In this case, the actual value of the current that is not depth dependent may be entered into the data base and is chosen carefully to reflect the more complicated character of the actual flow. In particular, the value appropriate for one ship loading and draft may not be appropriate for the same ship at a different loading and draft.

Some facilities retain the vertical variation of the current with depth in their data bases and estimate the effective value of the current as a value of current averaged over the actual ship draft at the given location. This scheme requires a much bigger data base and more computation, but it has the advantage of not requiring revision if a different ship or ship loading is used for the simulation. Finally, there is usually not one but a collection of environmental data bases, each reflecting a given state (phase of the tide, current distribution, and weather).

MATHEMATICAL MODEL OF SHIP DYNAMICS

The framework for the theoretical model of ship dynamics was described in general terms in Chapter 3. It involves two separate pieces: Newton's equations of motion (as modified by Euler for moving bodies) and a representation of the forces acting on the ship as a function of its orientation in the waterway and with respect to environmental conditions. The Euler equations of motion have a sound scientific base. The coefficients associated with these equations are easily identified and are therefore not discussed further in this report. Essentially there is no variation in this part of the framework from one facility to another.

Because Euler's equations are not in question, the accuracy of the mathematical model of ship dynamics is governed by the ability to predict the instantaneous force system on the ship. (For brevity of discussion, this report does not distinguish between forces and moments, referring to both simply as *forces*). The forces acting on the ship arise primarily from the combined effects of water surrounding the ship, wind, waterway geometry, and other external forces such as tug boat assistance and riding on anchor (Abkowitz, 1964; Bernitsas and Kekridis, 1985; Eda and Crane, 1965; Norrbin, 1970). Most of the complexity (and uncertainty) of a mathematical model for the behavior of a ship stems from the estimates made for this force system. Considerable variation exists from one facility to another because representations of the forces that act on the ship are complicated and do not have the firm scientific basis of Euler's equations.

The dynamic framework is usually separated into several manageable constituent parts (or modules), which are dealt with relatively independent

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ly as shown in Figure 5-1. The separation of the ship hydrodynamic forces into those in unrestricted shallow water and corrections to account for restrictions, such as banks, reflects the historical development of mathematical modeling of maneuvering ships over the last 100 years. Figure 5-1 depicts three threads of information (represented as thick horizontal lines) that affect several modules within the ship model. Two of these, the commands from the pilot and the position and velocities resulting from the ship's behavior, are available outside the ship model. The third, which is the sum of instantaneous forces on the ship, is part of the necessary internal bookkeeping for computing the ship's motion.

In many simulators, only three degrees of freedom are used (surge, sway, and yaw—the so-called horizontal motions) because the vertical motions interact little with the steering and maneuvering characteristics of the ship. In a severe turn, the ship roll angle may become large for ships with small inherent roll stability. The angle of roll changes the wetted hull shape. This can substantially increase the turn radius. Where the underkeel clearance is small, the vertical motions (heave, pitch, and roll) can

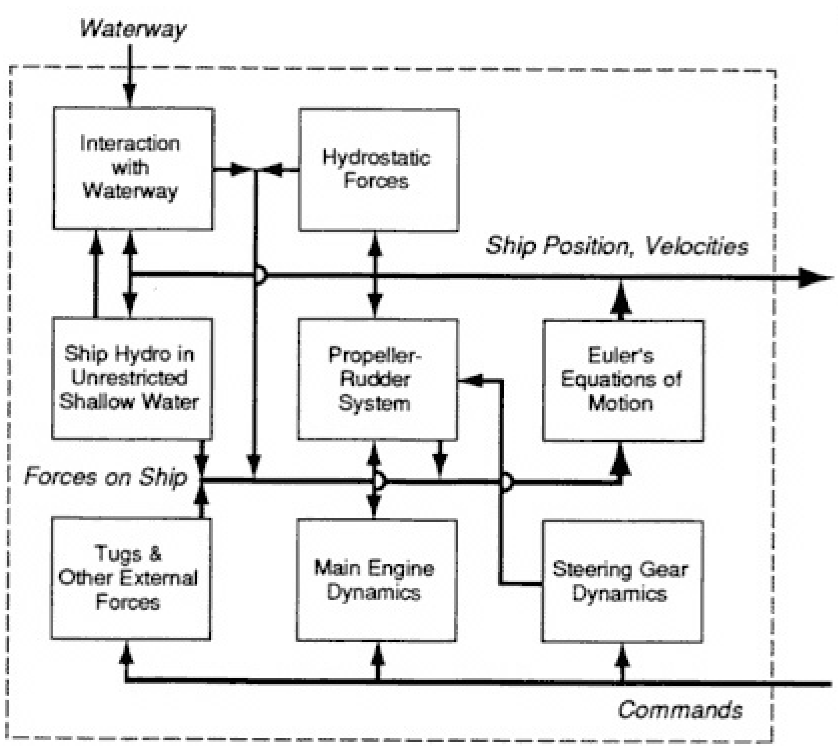

FIGURE 5-1 Schematic diagram of modules in simulated ship behavior.

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have an important effect due to the combined effects of squat and the response to waves, currents, or wind. In these circumstances, all six degrees of freedom are used.

COMPONENTS OF THE FORCES SYSTEM

In the following sections, various components of the forces system acting on the ship are discussed in general terms, including approximations used for application in a simulator and the identification of numerical parameters. Characterization of the hydrodynamic forces on the ship is usually treated as a variation and expansion of the classical treatment of steering and maneuvering in deep water. Therefore, the deepwater problem is discussed first, even though it is not applicable to typical waterway design. Components are also discussed in relation to unrestricted shallow water, restricted shallow water, rudder-propeller systems, and propulsion and steering systems.

Specific equations are not introduced in the following sections. The mathematical presentation of any of these models is algebraically intensive, as demonstrated by a mathematical model for the *Esso Osaka* in unrestricted shallow water (for further information on *Esso Osaka,* see Abkowitz, 1984; Ankudinov and Miller, 1977; Crane, 1979a,b; Dand and Hood, 1983; Eda, 1979b; Fujino, 1982; Gronarz, 1988; Miller, 1980; Report of the Maneuvering Committee, 1987).

Deepwater Factors

Measurement of the steering and maneuvering characteristics of ships in deep water is a well-understood and highly developed technology. Most facilities use a history-independent formulation where the forces are assumed to be approximately the same as those that would exist on a ship that has been in the same situation for a long time. Forces acting on the ship are assumed to depend only on the instantaneous attitude velocities and accelerations of the ship (referred to simply as the instantaneous *state* of the ship). It is assumed that these forces do not depend on the motions of the ship or its attitude at previous times. Indeed, *memory effects* are a well-known phenomenon resulting from the wave system and viscous flow created by the ship's forward way and by wave-induced motions, and these effects are important in predicting the oscillatory motions of a ship due to a seaway. However, time scales for the steering and maneuvering problem are so large that these memory effects are unimportant in this context.

The framework usually consists of a polynomial representation of the forces in terms of the instantaneous displacements, velocities and accelerations of the ship, propeller, and rudder (and various products of these mo

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tions). This polynomial can be viewed as a truncated, multivariate Taylor's expansion about the state of the ship, which corresponds to straight-line travel at a constant forward speed. This representation does not embody any physics per se, but simply reflects an implicit assumption that these forces vary smoothly with the state of the ship. The expansion is truncated to include only those higher-order terms that appear to yield significant forces. Quantification of the framework is obtained by identifying the coefficients of each term in this polynomial. In fact, many different mathematical frameworks are used at simulation facilities around the world, and each facility appears to have its favorite. Most of these frameworks are identical in their linear terms and in many of their nonlinear terms. Differences occur in the number and type of higher-order (that is, nonlinear) terms that are retained. However, it should be noted that the numerical values of the coefficients associated with the linear terms depend on which nonlinear terms are retained in the framework.

The coefficients that relate instantaneous motions to forces acting on the ship are most often determined experimentally by captive model tests using either an apparatus called the Planar Motion Mechanism (PMM) or a special facility called a rotating arm basin. These tests are performed by oscillating a laterally restrained scale model of the ship in question in sway and yaw at Froude-scaled test conditions. It is assumed that viscous effects (which are not scaled in the model tests) can either be ignored or corrected for. Analysis of the time histories of the forces acting on the ship model resulting from many captive model tests is used to determine both linear and nonlinear coefficients in a mathematical model for these terms. These coefficients are obtained by a multivariate regression or by curve fitting, depending on the conduct of the captive model test. In addition, tests are performed with the rudder at various angles and the propeller at various rotational speeds. Changes in forces and moments resulting therefrom are also identified by coefficients in polynomial framework.

The mathematical model for hydrodynamic forces and moments is joined with Euler's equations of motion and a model for the dynamics of the propulsion system (discussed separately below) to form a simulation model for deep water. This model can be used for simulating steering and maneuvering exercises in deep water and for training of a ship's bridge team. Such models have been used by Japanese shipbuilders, for instance, to select the size and location of rudders in new tanker designs.

Because captive model tests are expensive and time consuming, many facilities have built up libraries of dynamic data on previously tested models. These data have been used by some of these facilities as a data base from which the coefficients in the mathematical model for ships can be estimated by regression (that is, without a physical model test). Presumably, if the data base were large enough, this approach would be successful.

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However, most facilities do not release their data, and thus, it is difficult to judge the success of this process.

In recent years, an alternative scheme called *systems identification* has been devised for determining the coefficients in the mathematical framework for all the hydrodynamic forces, including the propeller and rudder (Abkowitz, 1980; Aström et al., 1975). In this scheme, a free-running model (or full-scale ship) is instrumented to record both the motions and inputs (for example, rudder angle, propeller revolutions per minute [RPM], speed, heading). This information together with a proposed framework is used to "identify" the numerical value of the coefficients and to give a measure of "goodness of fit." The mathematics are too involved to attempt to describe in this report. If these data are taken on a model, then some correction for the viscous effects may be called for; if these data are taken on the full-scale ship, then the coefficients may be used directly. Some indications suggest that this approach can be as successful as using captive model tests, although the systems identification approach typically identifies fewer coefficients than are used in the traditional approach.

Interestingly, neither analytical hydrodynamic analysis nor computer-based algorithms (CFD codes) are sufficiently mature to predict coefficients for use in steering and maneuvering models from the underwater geometry of the ship, even for this simplest case of deep water. The difficulty lies in the fact that viscosity has important effects and cannot be ignored. Advances are being made in developing computer-based programs for treating viscous free-surface flows. However, these programs may be as expensive to run as physical model tests, and their ability to reproduce physical model test results has not been demonstrated.

The simulation of steering and maneuvering in deep water appears to be satisfactory for engineering applications, as long as the coefficients of the mathematical model are identified by a properly conducted physical model test. Using a data base of test results to predict the coefficients of a ship without a model test may be acceptable for most waterway work (Clarke, 1972; Kijima et al., 1990).

Unrestricted Shallow Water

The maneuvering of ships in unrestricted shallow water (water of a depth less than 2.5 times the vessel draft of infinite lateral extent) has been investigated much less than that of deep water. The flow around a ship becomes dependent on the water depth, and this additional parameter makes both theoretical developments and experiments much more difficult. Nonetheless, nothing about these experiments makes the interpretation of the results more complicated or more difficult than the deepwater case, except in the instance of extremely shallow water where the viscous flow under the

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ship's bottom may not be modeled well in small-scale experiments. In particular, the same mathematical framework typically is adopted for the force model, with perhaps a few more nonlinear terms included to capture forces that are important in shallow water but are inconsequential in deep water.

Several experimental studies have been performed in moderately shallow water, and their results are surprising. Whereas the force coefficients in the mathematical framework vary smoothly with water depth, some of the handling characteristics do not. For instance, several researchers using model tests found that ship turning performance first improves upon entering shallow water and then degrades rapidly as the under-keel clearance becomes very small (Crane, 1979a; Fujino, 1968, 1970). This finding suggests that the effect of very low under-keel clearance can be dramatic and cannot be ignored. No measurements, full or model scale, have been made in the range of 10 percent under-keel clearance or less, a range commonplace in U.S. ports (National Research Council, 1985).

To obtain experimental data for use in the mathematical framework, it is necessary to run the same type of PMM tests or systems identification study for deepwater cases, but at several finite water depths as well. This approach requires a test basin where the bottom is extremely flat; few such basins exist worldwide. As a result, very few ship models have actually gone through extensive shallow water maneuvering testing, and the data are sparse. Available data have been referred to extensively.

The situation in unrestricted shallow water is similar to that in deep water. However, not all the phenomena are clear. To perform either physical model tests or full-scale trials would require addressing significant modeling questions concerning the viscous flow in the gap between the ship and bottom and concerning the deformation of the mud bottom by the ship. The cost of performing the required tests is high because a new test parameter (water depth) must be varied. The lack of a flat bottom at most facilities has inhibited the testing of ship models with under-keel clearances comparable to current ship traffic. With the help of some theoretical developments, most ship model testing facilities have developed proprietary, semiheuristic schemes to modify deepwater maneuvering coefficients so that they are approximately correct for shallow water.

Restricted Shallow Water

The preceding discussion of the ship model focused on maneuvering a ship in unrestricted, quiescent water of finite depth. However, many other interactions need to be considered if the simulator is to be useful in waterway design. Interactions include the force system on a ship maneuvering in a channel with geometric complexity (turns, banks, uneven bottom, and so

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on), with hydrodynamic complexity (complex current patterns, tidal variations, and so on), and with atmospheric disturbances. It is convenient to separate differences in these areas into two force systems: one resulting from the atmospheric environment and the other resulting from the water environment. Interactions due to other vessel traffic and the use of auxiliary help, such as tug boats, also need to be considered.

The effect of wind, resulting from both the average velocity and gusts, can be important in some waterways. Wind forces become relatively more important when the vessel has small forward movement, when the vessel has a large "sail area," or when it has a shallow draft. Sail area is affected by hull and superstructure configurations, freeboard, and deck cargo such as containers. With loading, the sail area of a tanker decreases, and its draft increases, making a fully loaded tanker less susceptible to wind effects. A containership loaded with empty containers that are stacked high on deck may have both a large sail area and a small draft, and thus it is very vulnerable to wind effects. When the wind is parallel to the channel and in the same direction of travel as the ship, controlling the forward movement can be difficult, especially for diesel-powered ships where the minimum sustainable RPM corresponds to a significant speed and where the number of air starts may be limited.

Significant wind forces usually arise when the wind velocity is much greater than the ship velocity, and as a result, a simple framework for these forces is usually adopted. Aerodynamic forces are estimated using an empirical drag coefficient dependent on the relative wind direction. The effects of gusty conditions are usually included as an increment to the average wind velocity.

The framework for the hydrodynamic forces is a set of equations used to predict the *changes* between the force system resulting from these interactions and the force system that would exist in unrestricted shallow water of the same depth. This framework usually has the same general polynomial format as that used for hydrodynamic forces in unrestricted shallow water. The coefficients now depend, however, on the distance to, and the character of, the bank and other obstacles.

This force system consists of steady forces and unsteady forces. Steady forces are typically due to an interaction with a bank. When the ship is travelling parallel to the bank, force is directed toward the bank (so-called bank suction forces), and the moment results in a bow out movement. However, at other angles, changes in these forces can be either toward or away from the bank. Propeller revolutions can also affect these forces in the presence of a bank. A considerable body of literature on these steady forces exists where the results of experiments are reported (Norrbin, 1970, 1978). Empirical formulas have been developed that are successful for predicting them.

Unsteady forces are usually separated into two types. The first or

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quasisteady force system represents a modification of the steady force system due to the instantaneous motions of the ship due to the proximity of restrictions. The second or fundamentally unsteady force system represents the transient forces that result from the ship approaching a bank or obstruction, passing by a discontinuous bank, passing another ship (either on reciprocal courses or overtaking), or passing into an area where the water depth changes suddenly or the water current varies dramatically in speed or direction (see Armstrong, 1980; Crenshaw, 1975; Plummer, 1966).

The quasisteady force system arises when the ship is traveling, on the average, parallel to a continuous bank of uniform geometry in a region and where the depth changes are very gradual and the current is nearly constant in speed and direction. In this case, motions arising from course keeping can be considered as small perturbations about an otherwise steady flow. The quasisteady force system is usually characterized by the same framework as that for unrestricted shallow waters, except that the coefficients must include an additional parameter: the distance from the bank. Coefficients in this framework depend not only on water depth and ship geometry, but on current in the waterway and geometry of the bank as well (Abkowitz, 1964). For this situation, it is also possible to perform PMM testing at several different water depths and, at each of these depths, perform additional testing at several different distances from the bank. However, the number of variables involved make the cost of this type of model test program high. Thus, such tests are almost never conducted to identify these coefficients. Nevertheless, some tests of this type have been performed, and results are available in the literature (Abkowitz, 1980; Eda et al., 1986; Norrbin, 1978).

When the ship is not traveling approximately parallel to the channel or is oriented to other traffic so that the flow is fundamentally unsteady, it is impossible either to eliminate time (that is, history) from the problem or to reduce the transient force system to simple time-independent coefficients. The most studied of these fundamentally unsteady phenomena are cases of ships passing interrupted banks, ships approaching banks, and ships passing one another (Dand, 1984). The literature in this area is very limited, and most of the data that are available are for the passing ship case.

Experimental studies have been conducted on the effect of interrupted bank systems where the interruptions are in a straight line (Norrbin, 1974, 1978). Reducing these data to numerical formulas appears to have been accomplished by various facilities using proprietary techniques. The effect on the force system due to sudden changes in waterway depth, to a waterway bathymetry that is truly three-dimensional, or to currents that vary significantly along the length of the ship apparently have not been systematically studied. However, mathematical simulation models typically ignore or only crudely approximate the effects from this kind of temporal or spatial

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dependence. The computation of this representative value from the instantaneous state of the ship and its position in the waterway is heuristic and varies considerably from facility to facility.

Model tests to determine the force and moment history of two ships passing one another have been conducted in several contexts and particularly for the Panama Canal study (see Appendix C). The overtaking configuration is, in general, the most severe because the time during which the interaction between vessels may be strong is far longer, although studies of meeting situations are more common. Interaction forces between the two hulls will cause perturbations in the trajectory of both ships, particularly if the waterway is narrow (Gates, 1989; Hooyer, 1983; Plummer, 1966).

Potential parameters in such a study are numerous and include the description of the two ships, each of their speeds, initial passing distance, passing angle, water depth, and distance to a bank. Parametric tests to investigate each of these variables appears feasible, but such tests probably would be prohibitively expensive. The usual practice (when passing tests are conducted at all) is to measure the force system when passing ships are constrained to straight-line motion. Fundamentally unsteady forces and moments are measured, but deviations of the ships' tracks in response to these forces are not allowed. These responses may be significant, especially when the passage is a close one or when ships are in an overtaking configuration (where the exposure time is long). Typically, constrained model test data are used, together with empirical or heuristic corrections, to predict the force and moment history for the actual passing condition.

A body of theoretical literature also exists based on a linear (small motion) analysis of a ship passing a bank or other objects (Yeung, 1978). These theoretical developments often are used to establish framework elements of the unsteady waterway interaction framework. Coefficients associated with this framework are usually identified using the above-mentioned experimental results available in the literature, modified to account for differences between the ship under consideration and the ship that was tested. These semiheuristic methods are almost always proprietary to the individual facility.

Finally, there are other possible important interactions that may be required for certain simulations. Tug boat assistance is a feature of many maneuvering situations. The presence of tugs alongside a larger ship is, like the passage of ships, a situation where a strong interaction is expected in principle. However, because these tugs are typically much smaller than the simulated ship, their principal interaction is through the thrust (both size and direction) generated by the propeller-rudder combination (Brady, 1967; Dand, 1975; Reid, 1975, 1986). In general, this interaction is directed by the pilot or master of the simulated ship, and the modeling of this interaction is typically treated in a quite simple fashion.

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Rudder-Propeller System

This force system module represents the combined effects of the propeller and rudder, which are usually treated together because they are the primary actuators for steering and maneuvering. Rudder angle, propeller RPM, and propeller pitch (if the propeller is variable pitch) are introduced as new variables, and the forces resulting from the interaction of propeller, rudder, and hull typically are characterized by them. Because these forces also depend strongly on the flow about the basic ship, formulas for these forces also involve the state of the ship and its geometry (particularly the after body).

The force and flow field produced by a propeller driving a ship at constant speed are relatively well known, and means for its prediction are available. The force and flow field created by a propeller spinning at a speed different from these equilibrium conditions is less well known, especially when the ship is maneuvering and the propeller may be spinning with a rotation that would ultimately cause the ship to reverse its present direction. Four separate situations with regard to propeller operation can be identified, depending on the sign of the velocity of the ship (either ahead or astern) and the sign of the propeller rotation (either in the ahead direction or the astern direction). These four situations are usually called quadrants, because they appear on a graph of ship speed along one axis, and propeller RPM appears along the other. Characterizing the effect of the propeller for all possibilities of ahead and reverse propeller rotation, and forward and astern ship's velocity (the so-called four quadrant problem) is difficult. Most simulators do, however, include an approximate model for these conditions.

The side forces on a rudder are usually proportional to rudder angle when small rudder angles are used, but depend in a more nonlinear fashion for large rudder angles. Side forces on a rudder also depend approximately quadratically on the flow velocity over the rudder, and thus, the hydrodynamic effects of the propeller and rudder are fundamentally linked. When the ship is proceeding ahead and the propeller is rotating to maintain this motion, flow over the rudder is typically at a somewhat higher velocity than the ship's velocity. However, if the pilot decides to execute a full-astern maneuver (or the pitch of the propeller is reversed), then flow through the propeller is ultimately reversed, and the rudder may experience little or no flow over it. This situation is often referred to as *blanketing the rudder* and results in the rudder being almost ineffective. A characterization of these effects using elementary hydrodynamic analysis and empirical results is usually included in a semiempirical model for the propeller-rudder system.

Various facilities differ in their approach to quantifying propeller-rudder interactions. Because a Froude-scaled ship model does not reproduce

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the viscous effects properly, a self-propelled ship model cannot behave as the full-scale ship would. That is, the propeller in a self-propelled ship model has to produce considerably more thrust to overcome the relatively greater viscous drag of the model. The propeller-rudder interaction forces are often measured on a captive, towed model with the propeller spinning at a range of RPMs and at various rudder angles. The results are scaled up to full scale using the information from separate propeller tests using larger models, performed in a facility called a propeller tunnel. This type of facility models the atmosphere so that important effects of cavitation can also be modeled and observed.

The cost of experimentally determining influences of the propeller and rudder is high. Many facilities use empirical formulas based on previous model tests to estimate the four-quadrant behavior of the propeller and its interaction with the rudder.

Additional modules are often added to account for other maneuvering devices, such as thrusters, if they are installed. Characterizing these devices and their interaction with the hull is in principal very complicated. As a result, a semiempirical approach is usually adopted.

Model of Propulsion and Steering Systems

The propulsion and steering systems are also critical to maneuvering a ship, because the propeller RPM and rudder angle are determined by them. They are also mechanical devices with their own dynamics. These devices cannot respond instantly when commanded because of their own inertias and other limitations. A detailed characterization of these maneuvering elements would involve developing equations of motion that reflect the physical properties or response of many individual components. Steering gears and thrusters have relatively straightforward mechanisms, and they apparently do not require great sophistication in the mathematical model to capture their behavior.

Characterizing the main propulsion system behavior is, however, more difficult because typical systems are large, have substantial inertias, and involve many components, particularly for diesel systems. The propulsion model (usually referred to as the engine model) also requires characterization of the torque characteristics of the propeller as a function of its RPM. Two choices are typical for main propulsion: steam turbines and diesel engines.

Steam turbines have few moving parts in the main drive train to model. These include the rotary inertia and friction of the turbine rotors, gear system, line shafting, and propeller. Because these elements are geared together, they are dynamically equivalent to a single rotating mass. These characteristics result from the thrust the propeller produces and its hydrodynamic

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losses. In addition, dynamics involving the steam valves and associated equipment may be important. Models for complete steam turbine power plants are somewhat complex, but reliable models have been constructed by several different facilities (van Berlekom and Goddard, 1972).

In today's fleet of merchant ships, diesel engines are much more popular choices for the main propulsion plant and are, unfortunately, much more difficult to characterize. Large, direct-connected diesel engines typically have 6 to 12 cylinders and are equipped with many auxiliary mechanical components, such as turbosuperchargers. The sheer number of moving parts in such an engine and the associated degrees of freedom preclude direct modeling of the intercoupled mechanics of each component. Rather, an indirect, behavioral model is usually adopted, where the engine in toto is replaced by an equivalent dynamic system with only a few degrees of freedom and with inertias and damping chosen to mimic the behavior of the diesel engine.

In addition to the mechanical modeling of the main elements of a diesel engine, other modeling problems exist. Starting and reversing these machines are achieved by injecting compressed air into some of the cylinders. Although this process is fairly reliable, failure to restart is not uncommon, especially in cold weather. Thus, a random delay may occur in the reversal of the engine. Further, some diesel engines have a finite reserve of starting air, and the reversal-restart cycle may become compromised if many such maneuvers must be performed in close succession. During changes in power level for some configurations of diesel engines, a significant lag may also occur in the air boost pressure due to the dynamics of the turbosupercharger-air plenum system. Thus, modeling the dynamic performance of a diesel engine during maneuvering is a significantly greater challenge than modeling a steam turbine, and the state of the art is not as well developed (Eskola, 1986).

SUMMARY

The mathematical model used for shiphandling simulation consists of not one model, but a series of many models, each representing a particular piece of hardware or important physics. These models are interconnected inside the computer that runs the simulator to reflect the physical interactions among the elements they represent. Each of these component mathematical models has its own set of uncertainties resulting from the modeling process, and it is difficult to assign an uncertainty for the overall model. The model that predicts the hydrodynamic forces on a ship as a result of its motions and proximity to the bottom, banks, and other waterway features is perhaps the most difficult to develop, and its uncertainty is greatest in the case of shallow, restricted channels.

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Assessment of Simulator Technology and Results

As described in the previous two sections, simulation involves an array of physical and mathematical components, each with their own limitations and inaccuracies. In addition, real-time simulation uses a pilot who introduces human variations into the simulation. If the results of the simulation are to be interpreted sensibly in the waterway design process, it is important to determine how well this array will predict the track of a ship in a given situation. Discussion in the preceding chapters shows that it is difficult, if not impossible, to treat the question quantitatively and scientifically. With this caveat, the following discussion assesses simulator technology from an engineering point of view, that is, in the context of its application to waterway design.

ACCURACY

Simulation has only recently become a feature of some waterway design initiatives, although use of the technology is increasing. Interpretation of the simulated vessel tracks provides insight into the various navigation factors (principally turn characteristics, channel width, and depth). The assessment presented here addresses the related concepts of accuracy and validity of simulation in the context of the waterway design process. For this discussion, a simulation will be considered accurate if it can produce piloted track predictions that are useful as a basis for a design decision

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concerning navigation and risk. Accepted guidelines for this accuracy apparently do not exist, and the accuracy requirement varies depending on the exact nature of the design problem. Construction tolerance for horizontal dimensions of the waterway is about 10 feet for fairways. Therefore, comparable accuracy for simulation is a reasonable goal for channels or approaches to berths involving dredging; greater accuracy is only of academic interest. However, for berthing or lock operations with very tight maneuvering tolerances, the level of precision required for the simulation is correspondingly higher.

Validity of a simulation can be expressed in the form of two narrow but scientific assessments. First, does the predicted track of a given ship accurately reproduce the real ship track when the pilot or autopilot performs at the simulator exactly as either would perform on a real ship? More scientifically, is the output of the simulator the same as that of the ship when the input to both is identical. If the simulator meets this criterion, then, will the pilot (or autopilot) make the same maneuvers at the same times in the simulator environment as would be made in the shipboard environment given the same transit conditions?

If the answers to both questions are affirmative, then the simulation can clearly be considered valid. That is, the predicted tracks will compare well with the full-scale results for a piloted ship. For discussion purposes, the first of these is identified as the mathematical modeling problem and the second as the pilotage modeling problem. In the past, these two very different aspects of model validation have often been intermingled.

Assessing the validity of a simulation in terms of the separate accuracies of the mathematical model and of the pilot model is used here for convenience of discussion. The mathematical modeling described above is the *open loop* response of the ship (that is, without the use of corrective steering measures). A mathematical model that is accurate by these terms can perform *dead reckoning*, a computation of the track, given only the history of the commands. This significantly more sensitive problem poses a particularly severe demand on accuracy.

In either the full-scale or simulated transit, the pilot takes corrective action when the ship appears to deviate from the strategy for transit, no matter what the cause. Thus, the pilot in a simulator will attempt to correct any deviation from the planned track resulting from an error in the mathematical model, just as if some real deviation was caused by the proximity of a bank, vessel, or other waterway feature. As a result, the tracks of all types of ships tend to be close to one another, independent of their inherent maneuvering behavior. The pilot's skill enables anticipation of the ship's behavior and its interaction with the environment so that commands are given expeditiously. This result is achieved, even for ships that are difficult to steer. Thus, the errors in the mathematical modeling are particularly

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difficult to discover from an analysis of piloted tracks. On the other hand, the accuracy demand for the mathematical model used in a shiphandling simulation can be less than that required fo dead-reckoning simulation. That is, feedback provided by the pilot may minimize the effects of inaccuracy. During this study, no research was identified that can provide guidance for relating these two accuracies. In the sections below, a critique is presented for the state of practice of the two aspects: the mathematical modeling problem and the pilotage modeling problem. These discussions, however, remain rather general because, as the above discussion reveals, the accuracy required of these components cannot be specified within the current state of practice.

CRITIQUE OF MATHEMATICAL MODELING TECHNOLOGY

The discussion in Chapter 5 demonstrates that many acceptable data base frameworks for the waterway and its environment are possible. Identification of the constants for the data base is direct for bathymetry, but may require either physical or computational fluid dynamics (CFD) modeling for the currents or winds. Thus, tools are available for developing these data bases, but the cost of determining the appropriate input data and of exercising these tools limits their use.

Mathematical models for ship behavior are well known in the case of steering and maneuvering in deep water. The measurement of turning performance in deep water is usually included in the trials of new ships. As a result, many comparisons with actual ship data have been made between simulator predictions for deep-water maneuvering and full-scale gross measures of maneuvering performance (for example, advance, transfer, tactical diameter, directional stability). The state of practice is such that theoretical predictions of deep-water turning performance are typically within 10 to 20 percent for these measures when the coefficients in the particular mathematical framework are identified using scaled physical experiments (captive model tests and extensive propeller-rudder interaction model tests).

Unfortunately, the performance of physical model maneuvering tests on new ship designs is not common. The identification of coefficients in the mathematical framework for new ships is often performed by interpolating within a data base of coefficients for similar ships (that is, without using physical experiments). This approach appears to be successful if the new ship is indeed similar to those in the data base, and the degree of success depends critically on both the size and quality of the database and on a careful review of the resulting coefficients by a knowledgeable practitioner.

The frameworks and coefficient identification process in use for both unrestricted and restricted shallow water vary from simulation facility to simulation facility. Almost all of these mathematical models are considered

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proprietary to the individual facilities and were not available for scrutiny or detailed comments in this report. As discussed in Chapter 5, the technology to identify coefficients in any such framework is available if the under-keel clearance is greater than 10 percent. Only a small part of this technology is ever involved in any simulation because of the extremely high cost of the required experimental setup and of the data collection. For very small under-keel clearances, the physical phenomena remain unclear.

In the current state of practice, many frameworks and associated coefficients for models that deal with details specific to waterway design (shallow water, banks, passing ships, variable currents, and so on) are constructed heuristically by using an amalgam of available theoretical developments, by using results of the limited available model tests of ship performance in idealized waterway configurations, and by bold assumption. In addition, there appears to be little scientific basis for the usual, quasi-steady treatment of highly time-dependent events, yet these are critical situations in many simulations.

Scientific verification of the accuracy of available models by comparison with full-scale results generally is also missing. Full-scale measurement of maneuvering tracks in unrestricted shallow water is limited. The most extensive set of tests appears to be those conducted on the *Esso Osaka* 10 years ago (Abkowitz, 1984; Ankudinov and Miller, 1977; Bogdonov et al., 1987; Dand and Hood, 1983; Eda, 1979b; Fujino, 1982; Gronarz, 1988; Miller, 1980). Even so, these tests were performed at under-keel clearances that are still large compared to those tolerated in many waterways.

Thus, the parts of the mathematical modeling process that are critical to simulation results but lack scientific precision are precisely those aspects that differentiate simulation for waterway design from simulation for deepwater maneuvering. These include:

- modeling of the hydrodynamic forces and moments for situations where the under-keel clearance is small;
- determination of the forces on a ship passing near waterway sides (banks);
- determination of the forces on a ship in essentially unsteady conditions (approaching banks, approaching and passing other ships, moving into regions with sharp current or bathymetric gradients); and
- the implicit assumption in most frameworks that the forces resulting from the various phenomena (for example, bank effects, propulsion, rudder effects) can be superimposed without considering their interaction.

Because of all the additional assumptions, it is unreasonable to expect that state-of-the-art mathematical models for maneuvering in restricted shallow water will be as accurate as those for deepwater maneuvering. However, as discussed above, the accuracy required for the mathematical model (open

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loop) may be considerably less than the accuracy needed for the waterway design (closed-loop). This consideration, together with the significant costs involved, has inhibited the development of more accurate mathematical models.

In practice, the validity of the mathematical model is established by comparing it with one or more of the following:

- real-world measurements or data, such as ship test trials;
- results from tests conducted using measurements deived from scale-model tank testing;
- performance estimates derived through mathematical extrapolation or interpolation using accepted theoretical models;
- the performance expected and evaluated by experts on the system the simulation has been designed to model; and
- the performance expected and evaluated by an interdisciplinary team of participants in the design process, including sponsors, planners, designers, and pilots, for the system the simulation has been designed to model.

CRITIQUE OF PILOTAGE MODELING TECHNOLOGY

A properly developed mathematical model will predict with acceptable accuracy the motions performance of a ship plying a waterway in response to commands from its pilot. The pilotage problem is this: Will the pilot perform on the simulator as if on board an actual ship? This question is much different from, and more difficult than, the mathematical modeling aspect because it is, to a major extent, a physiological and psychological question. If the pilot is a human pilot, then one can anticipate that slightly different commands will be given during each transit, even if the conditions during the passage are exactly the same. Thus, the sets of commands for a series of like passages by a single human pilot will be only approximately alike. Variations of this type are not encountered in standard fast-time simulation. If wide variations in shiphandling do result from man-in-the-loop simulations, the implications for waterway design may be important. If it can be determined that a particular waterway configuration is highly sensitive to pilot performance, then it would be prudent to search for and consider an alignment that is less sensitive: for example, a more desirable alternative would show little variation in swept path amongst different pilots.

The bridge, visual scene, and radar contribute to an observer's judgment of the *face validity* (also referred to as apparent validity) or realism of a simulation. A full-size ship's bridge, a high-fidelity visual scene, and a "stimulated" real radar set have high face validity. In turn, such a judgment contributes to the observer's acceptance of the simulator, design study, and eventual implementation of the findings. Physical surroundings may also

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contribute indirectly to pilot-ship-environment system performance by affecting the shiphandler's motivation.

Thus, a relationship exists between fidelity of the simulator and pilotage accuracy, but the relationship is difficult to pin down. The omission of real-world elements may influence the pilot to make a command that would not be made on board ship, or vice versa. Such an omission may be a major element (for example, the absence of a compass repeater in a place where it can easily be referred to) or the omission of a seemingly small item (for example, a distant church steeple that the pilot normally uses as a navigational reference). Because it is difficult to know a priori what is important to portray in a simulation and what is not, designers and pilots generally have more confidence in a high-fidelity, real-time simulator than in a low-fidelity one.

Whether or not fidelity adds to the accuracy of the pilotage modeling, it certainly adds considerably to the cost of simulation. For example, including a prominent water tower next to the church steeple in the visual scene mentioned above may only contribute to face validity, the immediate impression of realism. However, face validity can contribute to user acceptance of the simulator and its results. If the steeple is not used by local pilots as a visual cue in the piloting process, however, its inclusion may add little or nothing to the accuracy or fidelity of the simulated pilotage.

The question of how much fidelity is needed to achieve accurate simulation is different from how much fidelity is needed to make the pilot perform realistically in the simulator. Pilots, by the nature of their profession, need to be quick learners and exceedingly adaptable. For instance, pilot skill includes the safe piloting of vessels from the pilot's very first pilotage on vessels of that class. This flexibility helps pilots interpret and use modest simulation that can only be called low fidelity. A typical low-fidelity simulator may have, for instance, only one crude television-sized display that can be switched from a synthetic radar view to a low-resolution, dead-ahead view. In these situations, pilots with experience in operating ships and knowledge of the waterway in question may be able to fill in the missing information and produce a track similar to that achieved on a high-fidelity simulator. Moreover, it is possible, even in a low-level simulation, to provide the pilot with a much more accurate view of the situation than will be available on board ship (for instance, with an accurate bird's-eye view). In this case, the results of the simulation may underplay the safety factors (Perdok and Elzinga, 1984; Schuffel, 1984). Because a high-fidelity simulation can be quite costly, the demonstration of validity and user acceptance for a low-fidelity simulation could lead to increased use of the latter.

The accuracy of pilotage modeling in a real-time simulator is much more difficult to ascertain than that with mathematical modeling of the

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basic ship behavior. No objective measure was found for it during the study. The accuracy of pilotage modeling of fast-time simulation is an issue that is separate from that of real-time simulation, and it is most often accomplished either by comparison with man-in-the-loop results or by simply presenting results to pilots familiar with the area in question and eliciting their comments and criticism. If the mathematical model of the ship track is known to be accurate, then the focus of the comparison is on the command sequence and timing produced by the autopilot. However, in the typical uses of fast-time simulation (that is, sensitivity studies to determine effects of changes in the waterway environment), a high degree of accuracy may not be needed.

VALIDATION

Because it is not possible to assess scientifically the accuracy of either the mathematical model (for fast-time or man-in-the-loop simulation) or the pilotage performance of individuals relative to the simulation, an overall validation of the simulation is typically conducted instead. Currently, a simulation is considered valid if pilots conclude that it accurately reproduces the modeled ship's behavior in a particular waterway (Eda et al., 1986; Hwang, 1985; Moraal, 1980; Puglisi et al., 1985b; U.S. Maritime Administration (MARAD), 1979; van de Beek, 1987; Williams et al., 1982). The idea is that if several pilots familiar with the waterway, the modeled ship, or both are all satisfied with the simulation, then there is reasonable confidence in the results. However, since this process is highly subjective, great care must be exercised to assure that preconceived views and experience with vessel behavior do not bias the evaluation of simulation results (J. P. Hooft, personal communication, 1992).

The process for developing a valid simulation (mathematical model plus pilotage model) is iterative. Various procedures are used to screen out unintended bias that might result from "ownership" in simulation runs, preconceived views about vessel behavior, and other performance and technical factors. Typically, simulator facilities use an interdisciplinary team approach for validation although the process is often not made formal in facility procedures. Pilots participating in preliminary simulations to validate simulator performance are either part of the validation team or provide information for the validation process. Other pilots, qualified facility staff or other experts are sometimes used to observe and evaluate simulation runs to guard against bias (J. P. Hooft, personal communication, 1992; Puglisi, 1985; Puglisi and D'Amico, 1985). The mathematical model of vessel behavior, the physical representation of the visual scene, and for fast-time simulation, the autopilot model, are modified until the validation team is satisfied that the simulator performs realistically. Modifications that are

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made represent an acceptable balance between theoretical considerations and practical experience. Considering the subjectivity that is involved in this process, the validation team must be carefully composed to include expertise for key governing factors in the simulation. Guidelines for validation team composition have not been established. The committee believes that for waterway design, expertise in vessel operations, hydrodynamics, mathematical modeling (of the physical environment and vessel behavior), and waterway design would be prudent.

As part of the iterative validation process, simulation facilities typically conduct interviews with pilots participating in real-time simulation before any simulations are performed and after each simulated transit. These interviews serve several purposes. The pilots' knowledge of subtle aspects of a waterway is especially important because these pilots may be the only source from which these features can be detected, as evident from simulation case studies (Appendix C). The interview agenda is structured to obtain the pilot's subjective interpretation of how the simulated vessel behaved under the conditions tested, such as realism of vessel response to wind. Their broad experience in shiphandling helps identify flaws in the mathematical model but, according to many simulation facilities, is less useful for identifying the cause of these flaws. Pilots also have individual general strategies for making a transit and use their critical visual cues to navigate according to these strategies. Omission of pilot-specific cues can lead to less than satisfactory simulations. Interviews help uncover omissions so that they can be corrected.

Finally, when analyzing a modification to an existing waterway, many facilities will first use a model of the existing waterway together with a model of a ship that currently uses the waterway. This simulates a situation familiar to the pilots and is useful for determining how much fidelity is needed to uncover errors in the basic mathematical model and to gain pilot confidence. This process also establishes a baseline from which to measure the effect of proposed changes. Introduction of either new ships or waterway configurations can then be made with greater confidence.

In developing a new harbor or waterway, rather than modifying or upgrading an existing one, it is more difficult to determine simulation validity, even subjectively. For new waterways, pilots (as well as others participating in the design process) have no local knowledge as a reference for assessing the simulator's performance. Similarly, pilots confronted with unfamiliar hull forms or vessel sizes would be constrained in their assessment of validity. When similar waterway configurations or ships are used elsewhere, experts familiar with them are sometimes invited to work with regional experts to determine simulation validity.

Considering the highly subjective nature of simulator validation in the maritime sector, can validation procedures be adapted from the aviation

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sector where simulation is widely used for design and training? The committee found substantial differences between simulation in the aviation and maritime sectors that make transfer of technology and procedures highly problematic. Aircraft flight simulators are an integral element of the aircraft design and evaluation process. They are used to support design decisions, assess the design validity, train pilots (initial and proficiency training), and support mission planning and analysis. For commercial aviation, both aircraft and flight simulators are certificated by the Federal Aviation Administration (FAA). Military operational flight trainers and weapon system trainers are accepted by the using organizations for new designs as the new aircraft enters flight operations. Attention to fine detail is integral to designing high fidelity simulation mathematical models and recreating the aircraft's cockpit. Very good simulation fidelity is obtained by using proper models of the aircraft's aerodynamics, propulsion system, control system, weight and inertias, and by including a high fidelity cockpit. The aircraft design process is structured to provide this information that concurrently supports development of flight simulators, including their validation (Appendix F). Pilots are brought into the airframe development process early to provide operational perspectives for airframe design, and participate in final testing of flight simulators, primarily adjustments to the mathematical model to gain pilot approval.

Unlike the aviation sector, shiphandling simulations are not developed as an integral part of vessel design. The design process for ships provides limited quantitative information for developing mathematical models for commercial ship behavior. Commercial ships are often one-of-a-kind or constructed in limited classes. Even if a class vessel, ship behavior varies significantly relative to other ships in the class with loading (which can radically change ship hydrodynamics) and other operational factors. Hydrodynamic testing is not performed extensively and aerodynamic testing is rarely conducted for commercial vessels. Ship trials data are available for certain vessels, but the operating envelope for testing is almost exclusively unrestricted deep water, providing no insight on variations (usually substantial) between ship behavior in deep and shallow water.

Substantial differences also exist between the aviation and maritime sectors relative to modeling the operating environment, particularly the effect of external boundaries. In particular, the forces on a ship are strongly affected by the details of waterway geometry. Modeling the aviation operating environment (such as the atmosphere and atmospheric disturbances) is more straightforward. Aircraft are mostly operated out of ground effect. Even if operated in ground effect for longer periods of time, modeling change in ground effect is much easier to predict than what is required to model the forces in relation to other vessels, shore structures, and bathymetry (which can vary dramatically in contour). Marine simulations also in

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volve the effects of aerodynamic forces on a vessel that vary with draft and deck loads. Data on these effects are often insufficient or not available. Consequently, marine simulations for training and channel design lack the quantitative data that forms the basis for developing and validating aircraft flight simulators.

Characterizing ship-operating environment interactions remains a challenge in applying marine simulation technology to waterway design. Until a firm quantitative basis is developed, validation of marine simulations will continue to rely on subjective evaluations by expert marine pilots and other parties involved.

INTERPRETING THE RESULTS

As discussed in Chapter 3, the current state of practice in waterway design is to focus on ships and situations that will strain the safety of a waterway the most. Interpreting such results remains problematic. No formal basis was found to relate the results of simulation to a numerical measure of risk for the waterway. In other contexts, similar estimates are made for engineering projects by summing the products of probabilities of each possible accident in the project's lifetime and the cost of the consequence of the particular accident. This computation yields an estimate (expectation) of the risk exposure during the lifetime. Performing such a computation from the results of shiphandling simulation seems difficult, because only a few ships, pilots, waterway environments, and traffic situations are studied. The lack of objective validation of the simulation further compounds this analysis.

As a result, the current practice is limited to a subjective judgment that the waterway design is or is not satisfactory based on the limited simulations. Many facilities indicated to the committee that the judgments formed on this basis predict a much greater accident rate than is seen in practice. Whether this anomaly is due to mathematical model inaccuracy, lack of personal consequences to the pilot (including absence of liability and discipline that could result from mistakes in real life), or some other cause is not known. Often, simulation studies will be carried out on several alternative designs for the selected ship. Clearly, the judgments resulting from these comparisons may have more value, because fewer variables are introduced. That is, the trends of these comparisons may be more correct than their absolute tracks and may provide sufficient information for selecting one alternative over another.

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SUMMARY

The accuracy of simulation for restricted shallow water almost certainly is lower than that obtained for deepwater maneuvering, because the latter situation has a much larger research base and does not require the use of so many heuristic models. Currently, no guidelines are available for assessing the accuracy required from the mathematical model to develop results useful for waterway design. Likewise, there is no numerical measure available for determining the accuracy of pilotage modeling. In particular, no guidelines are available for determining the level of simulation required for a particular situation or for an appropriate analysis of its results.

The state of practice is to use subjective measures (for example, interviews with pilots) to validate the overall simulation and subjective interpretations of the simulation results in terms of overall risk corresponding to the waterway design. Although questions about accuracy, validation, and interpretation cannot be resolved objectively, simulation has proven extremely useful in some applications (see Chapter 7).

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Simulator Application in Harbor and Waterway Design

Shiphandling simulators have gained considerable acceptance worldwide as a useful aid in harbor and waterway design, albeit slowly and not yet universally. Detailed examination of representative simulation applications is useful to

- evaluate overall simulation usefulness,
- determine how simulation results were applied to the design process,
- develop an understanding of some of the problems encountered and how they were addressed,
- understand how simulation validity was verified, and
- assess the impact of different levels of simulator sophistication on simulation results.

Six simulation projects were selected for examination. These simulations were performed for projects at

- Oakland Harbor, California;
- Upper San Francisco Bay (Richmond Long Wharf), California;
- Grays Harbor, Washington;
- Norfolk-Hampton Roads, Virginia;
- Coatzacoalcos, Mexico; and
- Gaillard Cut of the Panama Canal.

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The projects were selected for several reasons, including

- the variety of navigational-harbor design problems that the simulations addressed,
- the different levels of sophistication applied in several of the applications, and
- the firsthand knowledge of many of the simulations by the committee.

A summary of each of the six case studies is included in Appendix C. Each was reviewed with particular attention given to specific lessons learned that might be generalized for application to other simulations. These lessons, both technical and administrative, are included in the descriptions in Appendix C and are consolidated into the five findings that follow.

CASE STUDY RESULTS

Simulation results were used to reduce costs, increase ship safety, and reduce environmental risks.

In each of the six applications of simulators that were examined, the project sponsors were able to modify the waterway design and/or operation to achieve: significant cost savings, improvements in ship safety, and/or reduction in environmental risk. Cost savings were generally the result of reduced dredging or shifting of dredging activity to less costly sites. In one case, Coatzacoalcos, the cost savings resulted from being able to use larger ships safely without additional dredging.

Increased ship safety was achieved by identifying critical navigational areas during the simulation process. For example, in Oakland, significant safety benefits were derived by widening the bar channel and the entrance channel beyond the width initially proposed. Although this widening required an extra cost for additional dredging, it was offset by reduced dredging in other areas where the simulation had indicated it was not necessary. (Although the simulation was successful, port-sponsored project construction on an accelerated schedule has been discontinued because of legal constraints and the inability of the sponsor to develop a plan for disposal of dredged material that was acceptable to all parties [Appendix C]).

Environmental risks may be reduced by simulations in two ways. Improved ship safety contributes to a reduction in environmental risk because it reduces the probability of spillage of oil or other toxic substance that might result from ship groundings or collisions. Simulation can also reveal channel configurations that have smaller dredging requirements and which therefore minimize the environmental impact.

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The committee cannot say with certainty that the cost, safety, and environmental benefits observed in these case studies would not have been achieved without the use of simulations, that is, if more intensive design reviews and audits had been conducted in the base case. However, it was observed that these benefits were not forthcoming before undertaking the simulations. Therefore, the committee finds it appropriate to credit the simulations for these benefits.

Simulation facilitated communication among the parties involved ina particular harbor and/or waterway project. These enhanced communications significantly affected the development of a successful, cost-effective design.

Successful harbor and waterway design involves the effective interaction of many different parties, including officials from federal and local governments, community and public interest (including environmental) groups, port operators, shipowners, hydraulic and civil engineers, naval architects and hydrodynamicists, environmental engineers, and pilots.

In the projects reviewed, simulation effectively focused the attention of these various parties on the harbor and waterway project. It provided a common framework for describing the project and the related problems as perceived by the various groups involved. In essence, it permitted these groups to communicate with each other with a common language and understanding that might not have been otherwise possible.

The use of simulation to focus communications demonstrated the potential of simulation to contribute measurably to successful, cost-effective harbor and waterway design and development. This benefit is separate from the research or engineering contributions that are usually expected of simulation.

Local pilots were regularly used by simulator facilities as the primary means of verifying simulation validity.

The issue of simulation validity received considerable attention throughout the study. During initial assessments, it was determined that an accurate mathematical modeling of the ship-channel interactive process was not possible, given current knowledge. The broad mathematical principles underlying the physical situation are generally well defined. However, a valid simulation in the strict engineering or scientific sense requires the measurement of environmental forces, their interaction, and the response of the ship to a degree that has never been attempted because of the great technical difficulty and costs involved.

In each of the six projects, local pilots were extensively used, not only as participants in the simulation process, but also, in essence, as the final arbiters of the validity of the simulation. Although the use of local pilots in

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this manner is not ideal because of the subjectivity involved, this limitation was recognized in the six projects and was addressed by incorporating greater safety margins than might have been necessary if the simulation validity could have been objectively measured. The risk exposure when applying simulation results, even with current knowledge, is considered less (at times significantly less) than that without simulation. Application of appropriate safety margins appears to be a reasonable way to deal with the current inability to measure objectively the validity of simulation.

Different levels of simulation were appropriate for different projects. Complex problems required sophisticated simulations. Sufficient information to resolve uncomplicated problems was obtained from lowlevel simulations.

Different levels of simulation were used in many of the case studies or, often, even within a single case study. Significant differences in the sophistication of the displays used for real-time simulation were noted between the various facilities. For example, some facilities had greater than 270° fields of vision, while others had only a straight-ahead display. Some facilities complemented the simulated radar screen with a bird's-eye presentation of the ship's position in the harbor, while others did not. Meaningful results were obtained from less-sophisticated simulations for certain problems. For example, fast-time simulations (no person in the loop) were used extensively for the Thimble Shoal Channel and Atlantic Ocean Channel simulations during the Norfolk-Hampton Roads project conducted at the Computer Aided Operations Research Facility (CAORF) for the State of Virginia and the U.S. Army Corps of Engineers. Navigation in these entrance channels does not require the use of any visual references from landmarks. Therefore, a real-time simulation with sophisticated displays was deemed unnecessary and costly. In other studies, high-quality visual displays were felt to be extremely important. This was the case for Grays Harbor, Washington, where it is necessary to navigate through two bridges that are offset from one another immediately after the vessel completes a sweeping turn in the river.

No comprehensive methodology was in place for assessing risk when interpreting and applying simulation results.

Simulation was demonstrated in application to be a source of guidance for the designer or user of a harbor and waterway. Simulation results must be interpreted and applied with care because their accuracy cannot be objectively verified. Although this limitation seemed to have been recognized by participants in each of the six projects, no comprehensive methodology was found to be in place for guiding designers on the establishment of safety

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margins or dealing with the uncertainties inherent in simulator results. This is a significant gap in the state of practice.

Simulations usually were not used in the early stages of the design process.

Simulations typically were used more often for design verification and refinement rather than for developing basic design parameters and limitations. This situation may change as harbor and waterway designers become more familiar with the usefulness of simulations and more skilled in their application. Some movement in this direction by designers seems to be taking place.

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Research Needs

Shiphandling simulation is a high-level technology that is emerging as an important tool in waterway design. Previous chapters identified that many aspects of the present state of practice in the development, use, and interpretation of results for shiphandling simulations are, however, less than rigorous and scientific. As reflected in the case studies, the benefits of shiphandling simulation for visualization of waterway design problems and of consensus building are nonetheless great.

GAPS IN THE STATE OF PRACTICE

The committee's review of the use of shiphandling simulators for waterway design revealed an overall concern for validity and five specific technology areas that could benefit from substantial research. These areas, which are dependent on one another in an approximately sequential fashion, are the following:

- the level of accuracy required for the mathematical model,
- procedures for identifying and validating the mathematical model for ship behavior in restricted and unrestricted shallow water,
- information and procedures for determining the effect of fidelity of the pilot's visual and physical interface with the simulator on results of real-time simulations,

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- a framework and standards for interpreting the results of simulation, and
- guidelines for the level and scope of simulation required in relation to the type of waterway design process.

A research program to fill these gaps is not presently being undertaken in the United States. Moreover, from a review of the state of practice of shiphandling simulation for waterway design in foreign countries, the committee found no evidence that such a comprehensive research program is being conducted abroad. Apparently, fundamental research on shiphandling simulation is rather moribund worldwide (for example, the privatizing of the Computer Aided Operations Research Facility (CAORF) at Kings Point, New York, has resulted in a shift in focus from fundamental research to contracted applied research and shiphandling training), although practical use of simulators for waterway design is growing. It is not clear whether or not congressional interest in research of marine simulation for operator training (generated by major tanker disasters) will result in a resurgence of basic operations research.

An original goal of this study was to develop guidelines regarding the appropriate level of simulation. Because substantial gaps remain in the five research areas necessary for developing such guidelines, the committee could not attain this goal.

Substantial improvement in knowledge and capabilities in each of the preceding areas holds promise for improving the confidence of practitioners and waterway designers in the results of simulations and, ultimately, for achieving the full potential of simulation. Although this study does not address use of shiphandling simulation for operator training, the basic questions concerning fidelity of simulation also apply where port-specific ship behavior is an element of the training regimen.

FUTURE RESEARCH

The committee has identified five specific areas for further research that would address the five technology areas defined above: 1) accuracy requirements for mathematical models, (2) identification and validation of the mathematical models, (3) effect of fidelity (visual and behavioral) on real-time simulation results, (4) interpretation of the results of simulation, and (5) guidelines for the required level and scope of simulation.

Fidelity Requirements for Mathematical Models

As discussed in Chapter 6, shiphandling involves intelligent feedback to available cues (either in real time using a human pilot or in fast time

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using a sophisticated pilot model). In either case, the pilot or autopilot corrects for errors, whether they are due to real effects or errors in the mathematical model. This situation appears to reduce the demands for accuracy on the mathematical model for ship behavior (over that required for an open-loop, dead-reckoning model), but there is little or no information in the literature to document this conjecture or to indicate what level of model accuracy is required. Research could be conducted to determine the sensitivity of the results of simulation for waterway design to either the framework for the mathematical model or the accuracy of the coefficients used in conjunction with this framework.

The mathematical model frameworks in typical use differ little, if at all, in their linear terms. The differences, where they occur, exist in the number and arrangement of higher order terms. A better understanding is needed about the requirement for accuracy of the various coefficients in typical mathematical frameworks, in particular, the coefficients that characterize the effects of small under-keel clearances and the interactions with varying banks and currents. Identification of these coefficients is exceedingly difficult and therefore expensive.

Sensitivity studies constitute a necessary preliminary for the remainder of research opportunities, but need not represent a significant investment. Fast-time simulation is ideal for this purpose because it is repeatable and does not include the variability inherent in human pilots. Examples exist of complete mathematical models for ships in restricted waterways. Investigations of the adequacy of the framework can be based on the use of different known models for one ship type and models for several representative waterways. Investigations of the accuracy of the coefficients probably will involve systematic perturbations of the mathematical models for several different ship types and for several representative waterways.

Identification and Validation of the Mathematical Models

If, presumably, the above-mentioned research determined the level of accuracy needed in coefficients of a mathematical model, the problem would remain of identifying these coefficients. Chapter 5 revealed that considerable weaknesses exist in the identification of hydrodynamic coefficients for use in a mathematical model. Although scientific means are available for performing accurate identification, the expense would be prohibitive for tests to characterize the behavior of just one ship in all possible small under-keel clearance and bank situations. New, less costly approaches are needed to overcome this gap.

Developing this information by computational fluid dynamics (CFD) is beyond present capabilities, although the use of CFD methods is rapidly expanding. Physical modeling techniques and the scaling relations neces

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sary for their performance exist and have been known for some time. However, physical modeling is limited in three ways. First, the number of tests necessary to characterize the hydrodynamic forces on a single ship in a restricted waterway with a shallow bottom and banks is very large, and as a result, the costs would be large. Second, only a few facilities in the world have flat-enough bottoms to perform model tests in shallow water comparable to realistic under-keel clearances. None of these facilities are in the United States. Finally, it is impossible to scale viscous effects in smallscale model tests, and there is reason to believe that this factor is important in the case of small under-keel clearances.

Even if extensive model tests were performed, validating the resultant mathematical model would be even more challenging. To date, validation by comparison with full-scale measurements of ship trajectories in restricted waterways has been limited to only a few cases. Even so, the most extensive and most scientific of these (the *Esso Osaka* trials) did not involve small under-keel clearances comparable to typical waterway situations or the influence of banks.

Validation methods of deepwater maneuvering predictions that are based on full-scale maneuvering trials have often been incorporated in the delivery trials of new ships. However, these trials usually have been aimed at simple turning performance and steering stability. Similar trials in shallow or restricted waters common in waterway design have not been performed for reasons of safety. This constitutes a significant gap in the validation tools for waterway design. Associated research opportunities include

- the development of new, efficient techniques that could reasonably be expected to identify numerical coefficients for a mathematical maneuvering model for restricted waterways to the level of accuracy required, and
- the development of techniques for safely conducting full-scale tests in typical waterway situations and for analyzing the results to calibrate and validate the mathematical models.

The committee anticipates that these techniques would be tailored specifically to the needs of waterway design. In particular, it is anticipated that the required accuracy of the coefficients may be less than that achievable by classical model tests, and that new, innovative, and more economical techniques would result from exploiting this requirement. The committee further anticipates that the identification and validation would likely be a combination of theoretical results and model tests (perhaps involving systems identification methods or CFD approaches).

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Effect of Visual and Behavioral Fidelity on Real-Time Simulation Results

Conventional wisdom states that the higher the visual fidelity of the simulator, the more useful will be the results of real-time simulation. Although some studies have addressed individual aspects of fidelity, proof of this conjecture does not exist. The importance of developing more information concerning visual fidelity is driven by two considerations. First, with the cost of computation now decreasing dramatically, visual fidelity is no longer the principal determinant of the cost of a simulator facility. Second, new shipboard instrumentation is developing at such a pace that some existing studies of fidelity may no longer be relevant.

Bird's-eye view displays have often been the only displays available in low-fidelity simulators, a feature that is considered by some to be a defect because the displays provide the pilot with more information than would be available on a real bridge. The development of differential GPS (global positioning system), digital chart data, and inexpensive on-board computer graphics equipment (relative to the cost of the ship and cargo) have made accurate bird's-eye view displays a reality. Electronic chart systems can include all the aids to navigation and other waterway information. In the future, integrated bridges, some with piloting expert systems (that is, artificial intelligence decision aids), together with normal shipboard sensors may produce other displays that communicate real-time decision-making information to the pilot. Integrated bridges are presently available on only a small number of vessels worldwide. An associated research opportunity is to determine the presence and fidelity of such systems on real-time simulations used for waterway design. The effort would investigate the potential role and efficacy of new instrumentation available to pilots and the extent to which this needs to be represented in marine simulations.

Interpretation of Simulation Results

Chapter 3 stated that shiphandling simulation is based on the assumption that a small sample of simulations using one or two ships, a few environmental conditions, and a few pilots will provide meaningful information for use in waterway design. Because the accuracy of the mathematical models of ship behavior is in question, the setup of a simulator facility is so costly, and the collateral benefits of simulation (for example, consensus building) are often an important objective, less emphasis has been placed on developing a formal framework for interpreting marine simulation results than on simulation in other industries.

Elaborate frameworks (usually statistical measures) have been developed for quantifying the performance of many engineering simulations in

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other disciplines and for use in design. Typical among these are simulations of the behavior of telephone networks, traffic congestion on highways, and flow of products in oil refineries. In these fields, the characteristics of the system elements are well known, but the system is subjected to random demands that stress it in complicated ways. Statistical measures are used to relate the design parameters (which reflect construction costs of the system) to risk of failure and its consequences (the contingent costs of the system).

Other types of simulations use quite different frameworks for analyzing performance. For instance, simulators designed to train personnel in the art of aircraft handling include both objective measures, for instance calibration against measured performance characteristics (such as turning circles) and subjective measures, such as pilot confidence, that the simulator behaves like a real airplane (Appendix F).

Unfortunately, the use of shiphandling simulators for waterway design does not fit comfortably in any of these molds. Shiphandling simulation is in many ways more difficult and complicated than the examples cited. As with aircraft simulators, marine pilots must feel confident that the "feel" of the simulated ship is like a real ship. However, information to calibrate the model, such as performance in very shallow water or near banks, is not known with scientific accuracy for any commercial ship. As with road traffic simulations, the quality of pilots and the number of different ship types and their performance vary greatly. However, an equivalent to the considerable data that characterize vehicle behavior on a highway does not exist for ships. The highway problem is also simpler in another way: there is no analog for the changes in steering performance needed in ships due to changes in under-keel clearance or banks. The basic problem in shiphandling simulation arises because the sample size in the simulation is so small restricting the application of classical inferential statistics.

Needs for future research include the following:

- The development of a framework to interpret results of a small sampling of simulator runs in terms of the quantities that affect waterway design. This framework could include, for example, a numerical estimate of the significance of results and confidence bounds on the predictions of swept paths measured in the simulation.
- The development of a procedure for estimating risk of accident associated in a particular waterway design and for estimating the consequences resulting from potential accidents.

Guidelines for the Required Level and Scope of Simulation

A synthesis of the results of research suggested above could yield considerable insight into the level and scope of simulation required for the

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waterway designer. However, simulation is a sophisticated technical discipline that relates to only one aspect of waterway design, and it is outside the typical focus and training of the waterway designer. The planning representatives of local project sponsors who must approve the expense of simulation are even further removed from this expertise. Therefore, an associated research opportunity exists for synthesizing information from the previously mentioned research and transforming it into a set of guidelines that could be used by the waterway designer and the sponsor to select appropriate simulation studies for a particular waterway design.

The committee found that such guidelines do not exist. As a result, waterway designers and their sponsors have little basis for selecting one simulator over another and for selecting the scope of simulation studies to be performed. Further, a set of guidelines based on a firm scientific footing could permit more rational decisions regarding when and to what extent simulations should be performed for given waterway projects.

STRATEGIES FOR IMPLEMENTING A RESEARCH PROGRAM

Support for basic research on shiphandling simulation has withered within the past decade. Only the U.S. Army Corps of Engineers (USACE) has a modest, project-oriented program in this area. As a consequence, the number of persons within the interested federal agencies experienced with shiphandling simulations has declined. However, the services of a substantial number of ship hydrodynamicists, both internal and external to the federal government, might be applied to fundamental research. Several experimental facilities exist worldwide that could be used to conduct elements of the research. (A facility catalog of ship hydrodynamic facilities is maintained by the International Towing Tank Conference.) One notable limitation is the inability of existing facilities to scientifically validate the scaling of mud behavior from model scale to full-scale (that is, reproducing on a model scale a material that would emulate behavior of bottom sediment) when testing ship maneuverability in situations with very small under-keel clearances.

The research program necessary to put shiphandling simulation for waterway design on a firmer scientific basis, thereby greatly increasing the confidence of the entire maritime community in the usefulness of the technique, would be ambitious, expensive, and long range. The committee believes such a program would require about 10 years of dedicated effort and about $15-30 million in research funds. However, costs in this range are modest relative to the annual investment in port facility capital improvements and in waterway construction, operations, and maintenance. Developing a strategy for the research program would entail addressing sponsorship as well as the resources necessary to conduct the research, including skills and facilities.

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The USACE is the government agency charged with primary responsibility for waterways development, including waterway design, permitting, dredging, and disposal of dredged materials. With this leadership role comes implied responsibility for organizing and coordinating research needed for waterways development in the United States. USACE operates a modest computer-based simulator, has a small pool of technical expertise, and has used these resources in about 40 waterway design studies. With regard to basic simulation research, a technically broad scope of effort would be required. USACE, by practice, principally conducts and has good experience with limited-term, project-oriented research for civil works. Present USACE technical resources do not appear sufficient to undertake or guide the multi-year research program that is needed to improve the scientific basis of simulation technology. In the committee's opinion, USACE would need to augment its technical base with experts from industry, especially in the areas of ship hydrodynamics simulation-based research, and human factors.

Other entities that have interest in waterway design (and in some cases operator training) and are potential beneficiaries of improvements in the national simulation capability include the U.S. Coast Guard (USCG) and U.S. Maritime Administration (MARAD) (both of which have previously been involved in simulation research), project sponsors, shipping companies, and operators of port facilities. Resources of these entities vary widely. The committee found that none of the non-federal entities appeared to have either sufficient focus or in-house capability to independently direct even a small part of the research program.

Two implementation strategies appear feasible. The federal government could fund the research in support of a national interest in maintaining competitiveness in international commerce. USACE could undertake, plan, and coordinate a government research program, which includes participation (and perhaps cost sharing) by other involved government agencies such as MARAD, the USCG, and perhaps the U.S. Navy (USN), in a supporting role.

An alternative would be to establish a government-industry research consortium that included key components of the U.S. maritime industry in both sponsorship and technical support capacities. Nongovernmental participants could include waterway designers, port operators, shipowners and operators, and pilot associations. This approach would have the advantage of involving all the direct beneficiaries to support the research, although coordination of such a body could prove cumbersome.

This research program could take full advantage of available expertise and capabilities at existing simulation and research facilities throughout the United States to ensure that the selected research plan is focused on the areas of greatest need, is sufficiently comprehensive, and is cost-effective.

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In an environment in which available funding is likely to remain limited, it is essential to ensure the maximum cost-benefit ratio of all research conducted.

SUMMARY

The development of meaningful guidance for waterway designers and sponsors on the use and applicability of shiphandling simulators for waterway design is inhibited by gaps in knowledge and capabilities in several critical areas. Because of the complex scientific basis for simulation and the hardware associated with it, the research required to fill those gaps is essential for full utility and acceptability of the technique, albeit its expense. Currently, no government agency, commercial enterprise, or research organization has undertaken or appears ready to undertake a dedicated research program on shiphandling simulation. Such a program could be a joint government-industry initiative, perhaps dovetailed with research that may be needed to establish shiphandling simulation as a fully accredited shiphandling training aid. USACE would be an appropriate organization to coordinate needed research because of that agency's primary role in waterway development.

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Conclusions and Recommendations

The design of waterways affects the nation's economy, the safety of ships and their crews, the inhabitants near waterways, and the natural environment of waterways. Over the past two decades, the use of shiphandling simulation to achieve refinements in waterway design not verifiable with other design tools has significantly increased. However, use of simulation in this way has been incorporated in only a small portion of the total number of waterway projects.

DOES SIMULATION WORK?

Shiphandling simulation has been used effectively as a design tool by planners and engineers to aid substantially in waterway design. The committee found the following:

- Simulation can be and is used during early and later stages of the design process to answer critical design questions, including those raised during permitting. Early use of simulation is especially important in cases where it can be used on a recurring basis throughout the design process.
- Pilot acceptance of simulations during validation and study trial phases indicates reasonable success in re-creating a realistic piloting experience.
- Simulation offers a systematic means for capturing the complexity

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of a waterway layout, the physical environment, and operational factors of a waterway design in an integrated and visible fashion.

- Simulation enhances communication between design participants. It brings together various constituencies with interests in waterway design, thereby providing a unique, common forum and framework for discussion and decision making.

WHEN SHOULD SIMULATION BE USED?

RECOMMENDATION: ***Practitioners should use simulations in all waterway design problems where ship operational risk is important. Furthermore, it is advisable to use simulation where optimization is an objective.***

Although cost, significant gaps in knowledge and capabilities, and lack of confidence inhibit wider use of simulation, the efficacy of applying shiphandling simulators as a design aid has been proven in practice. In spite of all the uncertainties that exist in terms of modeling and interpreting simulation results, the demonstrated benefits of simulation for a wide variety of projects more than adequately justifies its use as a standard practice in waterway design.

Simulation should be used in the following situations:

- When vessel operational risk is a significant design issue. Representation of human pilot skills and reactions in the prediction of vessel behavior in a proposed waterway is unique to shiphandling simulation. Differences in risk under various critical environmental conditions can be identified. Requirements for aids to navigation to further reduce risk can also be assessed.
- When cost and design optimization is an issue. The effect on risk resulting from variations in many design factors that define a waterway can be evaluated. This capability is important for assessing the components of life cycle costs. Simulation is particularly useful for assessing operational differences between design alternatives.
- When competing interests among technical and nontechnical participants in the waterway design process are an issue. Simulation provides a unique way to bring critical and contentious aspects of the design into sharp focus. The consequences of what participating parties are interested in can be acquired and displayed in formats that do not require technical expertise to assimilate and understand.

Because elements of these three issues are frequently associated with most waterway designs, shiphandling simulation should be developed as a

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standard tool for use in the waterway design process. The level of sophistication of simulations needed for this process depends on the particular design. However, guidelines for what level is appropriate for a given situation are not available within the current state of practice.

HOW CAN SIMULATION BE ENHANCED AS A DESIGN AID?

RECOMMENDATION: ***Simulation facility operators should establish a formal validation process that uses a carefully composed, interdisciplinary validation team to assure that key governing factors are adequately addressed and to provide consistency in the validation process.***

Simulation is not used more often by designers for three principal reasons: costs and schedule of simulation, lack of confidence in the results, and lack of awareness of simulation as a design tool.

Costs of conducting simulation studies presently inhibit the use of simulators in the design effort. The cost of the simulator itself, because of advances in computer technology, is no longer the limitation it was just a few years ago.

The state of practice of shiphandling simulation for waterway design varies widely. No agreement exists among practitioners on the minimum requirements for simulator fidelity for a given application. From examination of previous applications to waterway design, it is evident that a significant level of confidence in the application of shiphandling simulation to waterway design is not uniformly shared by all waterway design participants.

This lack of confidence revolves about questions of overall fidelity and validation. The components where fidelity is questioned are mathematical models of ship dynamics, waterway data bases, and visual displays. The behavior of ships with small under-keel clearances is especially not well understood nor well represented in existing models. Increasing the level of user confidence and acceptance will require development and validation of more robust mathematical models. Other factors that inhibit simulation include:

- the lack of a formal, objective method to validate the model and
- the lack of an accepted scientific framework for interpreting simulator results for waterway design. No consistent means exist for extrapolating results from the small sample of real-time runs to a prediction of the performance of the design over the life of the waterway.

To make simulation a more attractive design option, basic research should be conducted to resolve confidence issues and provide the capability

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for more effective simulation. A single, cohesive research program, focused on identified research needs, should be defined and managed as a coordinated effort that draws on the best technical expertise available within the waterway design and simulation community. Multi-disciplinary involvement in improving simulation capabilities would help increase confidence by the port and maritime transportation communities in simulation as a design and evaluation tool for waterways. Multi-disciplinary participation can be improved immediately by establishing formal validation processes that include essential operational and technical expertise in carefully composed interdisciplinary validation teams.

ESTABLISHING A RESEARCH PROGRAM

RECOMMENDATION: ***A systematic program of research designed to put simulation on a firmer scientific footing and to develop means for guiding its use and interpretation should be undertaken as a joint government-industry initiative. It should be coordinated by the U.S. Army Corps of Engineers and should include participation by pertinent federal agencies and the port and marine transportation communities. The research needs identified in Chapter 8 should be the central elements of the research program designed to***

- **assess the need for fidelity in mathematical models and simulator hardware,**
- **develop accurate means to identify the elements in the mathematical model, and**
- **develop means to interpret the results of simulation.**

The research program should improve the design tools needed to develop safe and cost-effective waterways. The program would be expensive and would require long-term funding. The size and scope of the research program is beyond the budget allocations from government agencies with responsibilities for waterway design and operation. Such a program would also have a cost and time frame that would be beyond incremental improvements of current programs. Implementation will require recognition of these research needs by Congress and the Departments of the Army and Transportation as a national priority to assure competitiveness with national research needs in other fields.

The U.S. Army Corps of Engineers, in view of its designated responsibility for waterway design, should take the lead in coordinating the research program. Such a research program should be carried out on a cooperative basis by all interested parties and beneficiaries. Program participants should include the U.S. Coast Guard, the U.S. Maritime Administration, and other

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organizations within the marine transportation and port communities. Funding support should be provided by the federal government because of national interests in ports and waterways and by beneficiaries in the port and marine transportation communities. Development and execution of the research program should take advantage of available expertise and capabilities of the existing research and simulation facilities across the country.

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Appendixes

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A

Committee Member Biographies

WILLIAM C. WEBSTER, *Chairman*, is full professor of naval architecture and associate dean of engineering for student affairs at the University of California at Berkeley. He is a leading national authority on ship maneuvering and has been heavily involved in the hydrodynamic aspects of ship model testing and in the mathematical developments underlying shiphandling computer simulation. Dr. Webster has published on both the hydrodynamic and operational aspects of ship maneuvering, has served as member and chairman of the Marine Board, and currently is a member of the Commission on Engineering and Technical Systems. He received his B.S. degree in naval architecture and marine engineering from Webb Institute of Naval Architecture and his M.S. and Ph.D. degrees in engineering science/naval architecture from the University of California at Berkeley.

WILLIAM A. ARATA is a state and federally licensed pilot with Biscayne Bay Pilots in the Port of Miami, Florida. Prior experience includes 20 years in the U.S. Navy where he served primarily in the submarine fleet in capacities from watch officer to commanding officer. He also directed naval analysis programs of the Office of Naval Research and submarine electronic programs for the deputy chief of Naval Operations, Submarines. Captain Arata received a B.S. degree from the U.S. Naval Academy, a B.S. degree in mechanical engineering from the U.S. Naval Postgraduate School, and a M.S. degree in business administration from the George Washington University.

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RODERICK A. BARR is a principal in Hydronautics Research, Inc. He has 30 years experience in marine hydrodynamic research and development, analysis, and design. Previously, he was a principal in Tracor Hydronautics. His experience includes development of theoretical methods; computer-based, time-domain simulation studies; model testing; and design studies. Dr. Barr has lectured on ship hydrodynamics at the Catholic University, and authored numerous technical papers and reports. He received a B.S. degree in naval architecture and marine engineering from Webb Institute of Naval Architecture, a M.S. degree in mechanical engineering from the University of Maryland, and a Ph.D. degree in naval architecture from the University of California at Berkeley.

PAUL CHILCOTE is senior director for planning, budget, and environmental affairs at the Port of Tacoma. He is responsible for coordinating port development into long-range planning, management of the port's Capital Improvement Program, and environmental management. Previously, Mr. Chilcote was a consultant for the State of Washington, specializing in port, rail, and marine transportation; manager, Intermodal Market Planning-International with the Southern Pacific Transportation Company; and senior trade analyst and senior long-range planner with the Port of Seattle. Mr. Chilcote received a B.S. degree in international/urban geography and history from Long Beach State University and a M.S. degree in economics/transportation geography from Oregon State University.

MICHAEL DENNY is president of ShipSim Corporation. During the study, he was systems architect with the Data Systems Division, Grumman Corporation, where he managed the technical development program, concentrating on systems architecture, expert systems, and artificial intelligence. Earlier, Dr. Denny was program manager with Ship Analytics, Inc., where he managed port and waterway design, vessel navigation bridge procedures, and human performance experiments at the Computer Aided Operations Research Facility, Kings Point, New York. His work has spanned both shiphandling simulation for waterway studies and leading edge computer simulation developments with human interaction. Dr. Denny has also served as assistant professor in the psychology department at Michigan State University. Dr. Denny received his B.S., M.A., and Ph.D, degrees in experimental psychology from Michigan State University.

FRANCIS X. NICASTRO is coordinator, industry affairs, with the Transportation Department, Exxon Company International. Previously as manager, Chartered Ship Operations and Port Services, he was responsible for the Exxon-sponsored simulation study of the navigability of tankers in the oil port of Coatzacoalcos, Mexico, which was conducted at the Computer Aided Operations Research Facility. Other technical and managerial service with Exxon Company International have included chartering manager, commercial support manager, and vice president and manager, New Con

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struction Office, Kobe, Japan. Mr. Nicastro has served on various technical panels of the Society of Naval Architects and Marine Engineers. He received a B.S. degree in naval architecture from Webb Institute of Naval Architecture.

NILS H. NORRBIN is internationally known for his work in ship hydrodynamics, maneuvering, and shiphandling simulation. Dr. Norrbin retired from the Swedish State Shipbuilding Experimental Tank (SSPA) in 1991 as senior scientific advisor and project manager. Previous positions with SSPA included head, Dynamics Division, and head, Ship Dynamics Division, of the Research Department. Dr. Norrbin is a fellow of the Royal Institution of Naval Architects and a member of Fachmitglied, Schiftbautechnische Gesellschaft. He has served on many international committees concerned with ship maneuvering, has pioneered research in the effects of realistic ship channel boundary effects on navigation, and was visiting professor of naval architecture, Department of Ocean Engineering, Massachusetts Institute of Technology. Earlier work included naval design with the Royal Swedish Naval Administration. Dr. Norrbin received a M.Sc. degree in naval architecture from the Chalmers University of Technology, a Technical License in Ship Hydraulics and Mathematics, and the Dr. Technology degree from the Royal Institute of Technology, Stockholm.

JOSEPH J. PUGLISI is associate director, Office of Computer Resource, the U.S. Merchant Marine Academy. He is responsible for all academic and administrative computing at the academy including integration of computers into the curriculum. Previously, Mr. Puglisi was managing director, Computer Aided Operations Research Facility (CAORF), where he was responsible for over 100 shiphandling simulation studies leading to formal reports. He directed the development of upgrade plans for CAORF, including marketing, research, system expansion, design and engineering, manpower, and funding. He subsequently coordinated field-level components of the privatization of CAORF. Mr. Puglisi received a B.S. degree in electrical engineering from the City College, City University of New York, and a M.S. degree in electrical engineering from New York University. He is pursuing advanced studies at the University of Wales.

LEONARD E. VAN HOUTEN is a consulting engineer with over 35 years experience worldwide in charge of planning, design, and construction of industrial facilities for marine transportation, oil and gas production, mining, heavy manufacturing, and defense-related activities. He has led development of waterway improvement projects in 45 countries representing all continents and a complete range of climatological conditions. Mr. Van Houten previously was a member of the Marine Board's Committee on Sedimentation Control to Reduce Maintenance Dredging of Navigation Facilities in Estuaries and is active in a number of technical and professional

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societies. He received B.S. and M.S. degrees in civil engineering from Rensselaer Polytechnic Institute.

JAMES A. VINCENT manages the Aeronautical and Marine Systems Department with Systems Control Technology. His experience is in flight mechanics, with specialization in system identification air vehicle mathematical modeling, control system design, simulation testing, handling qualities analysis, and wind tunnel testing and aerodynamic configuration development. Previously, Mr. Vincent served with the Boeing Company where he validated flight simulation by actual flight tests. He received B.S. and M.S. degrees in aeronautical engineering from the University of Colorado.

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B

Design Elements of Waterway Development

The waterway development process in the United States follows procedures prescribed by the U.S. Army Corps of Engineers (USACE). Six phases are organized in a logical progression:

- reconnaissance,
- feasibility,
- preconstruction engineering and design,
- real estate acquisition,
- construction, and
- operation and maintenance.

Although a progression is indicated, considerable overlap occurs at various stages, particularly if a project or its design is challenged after the reconnaissance phase is completed.

Prior to the reconnaissance phase, local interests determine whether a project is needed, what the project should entail, and for which elements interested parties are willing or able to become project sponsors. The usual procedure is for the local sponsor to petition the U.S. Congress and USACE for authority and funds to conduct a study. If the petition is successful, studies constituting the reconnaissance phase are conducted by USACE at full government expense. The objectives are to define the opportunity for the project; assess support; determine apparent costs, benefits, environmental impacts, and potential solutions; and estimate cost and time for the next

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phase. USACE usually brings others into the process, but not necessarily all parties that subsequently may be determined to have an interest.

The project may or may not proceed into the feasibility phase. Feasibility phase costs are shared equally by the sponsor or sponsors and the federal government. In this phase, alternate plans are identified and evaluated, leading to a full description of the project. All aspects of the project are supposed to be examined and all potential participants brought into the process. The desired product from this phase is a final project form, based on consensus insofar as practical, that is acceptable to all interested parties.

If the logical progression were followed exactly, a design would be fixed by the end of the feasibility phase after consideration and analysis of all reasonable alternatives, benefits, and impacts (Olson et al., 1986). This design would then be used as the basis for necessary permits and other following elements in the process.

In practice, the selected design may be challenged, for technical, social, or environmental reasons up to and including the construction phase, to address unrecognized flaws or further address competing objectives. Resolution of challenges may result in accommodations affecting the technical integrity of the original design solution, which necessitates further studies, data collection, and design work. Delays in completing the process may affect the availability of options selected and resources available (see Kagan, 1990).

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C

Practical Application of Shiphandling Simulators to Waterway Design

CASE STUDY COATZACOALCOS, MEXICO COMPUTER AIDED OPERATIONS RESEARCH FACILITY, 1980-1981

PROJECT DESCRIPTION

Exxon Corporation sponsored a simulation study at the Computer Aided Operations Research Facility (CAORF) to determine the maximum size oil tanker that could safely load at Coatzacoalcos, Mexico. The exit from the loading docks requires passage through a narrow, 330 foot wide channel cutting obliquely across the Coatzacoalcos River. Very high river currents were reported during the rainy season. The harbor chart is shown in Figure C-1.

SIMULATION DESCRIPTION

CAORF, a government-owned but privately operated facility located on the grounds of the U.S. Merchant Marine Academy, Kings Point, New York, was selected to conduct the simulation study. Real-time simulations were conducted using local pilots. Simulations compared the performance of the larger ships proposed for this service with that of ships actually using the

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port. Generalized mathematical models were used in the simulations based on material available for similar ships.

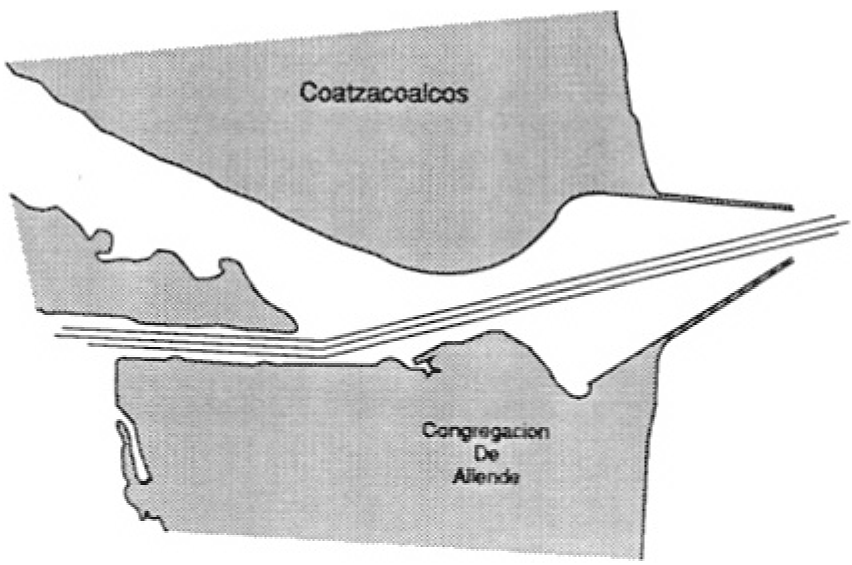

FIGURE C-1 Coatzacoalcos Harbor.

Field visits were made to develop visual effects for the simulation, to observe the performance of ships using the port, and to measure environmental effects (river currents). Measured river current velocities were found to be significantly less than those reported by local pilots and harbor authorities. As a result, a considerable amount of additional testing and interpolation of results was necessary.

SIMULATION RESULTS

The simulation indicated that tankers about 10 percent larger (70,000 deadweight tons [DWT]) than those currently used could be safely loaded at this port. The larger tankers required a slightly greater under-keel clearance than the smaller tankers during the rainy season (U.S. Maritime Administration, 1980, 1981).

PROJECT IMPLEMENTATION

Larger tankers regularly began using this port in late 1981. The cost of simulation was recovered in less than 2 months of operation of the larger ships.

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LESSONS LEARNED

Design Team

A shiphandling simulation is not a simple engineering project. Success depends on assembling a team of qualified and imaginative professionals (hydrologists, hydrodynamicists, pilots, simulator operators, and end users) and managing that team in a way that encourages each member's full contribution.

Pilot Participation

Local pilot participation was important to verify qualitatively the accuracy of the simulation. In this study, changes in the treatment of bank effects were made as a result of pilot advice.

Operating Parameters and Costs

Significant economic savings may be gained from relatively modest changes in permissible operating parameters.

Data Validation

Assessments of environmental data that are not supported by accurate field measurements should be carefully weighed before they are accepted.

CASE STUDY NORFOLK/HAMPTON ROADS, VIRGINIA COMPUTER AIDED OPERATIONS RESEARCH FACILITY, 1980-1986

PROJECT DESCRIPTION

The State of Virginia sponsored a simulation study to improve existing channel designs so as to permit deep-draft coal colliers of 225,000 DWT and 55-foot draft. The objective of the project was to make Hampton Roads ports (Figure C-2) more competitive in the world coal market.

SIMULATION DESCRIPTION

This project was the first large-scale, real-time and fast-time simulation undertaken by the U.S. Army Corps of Engineers (USACE) for a U.S. port.

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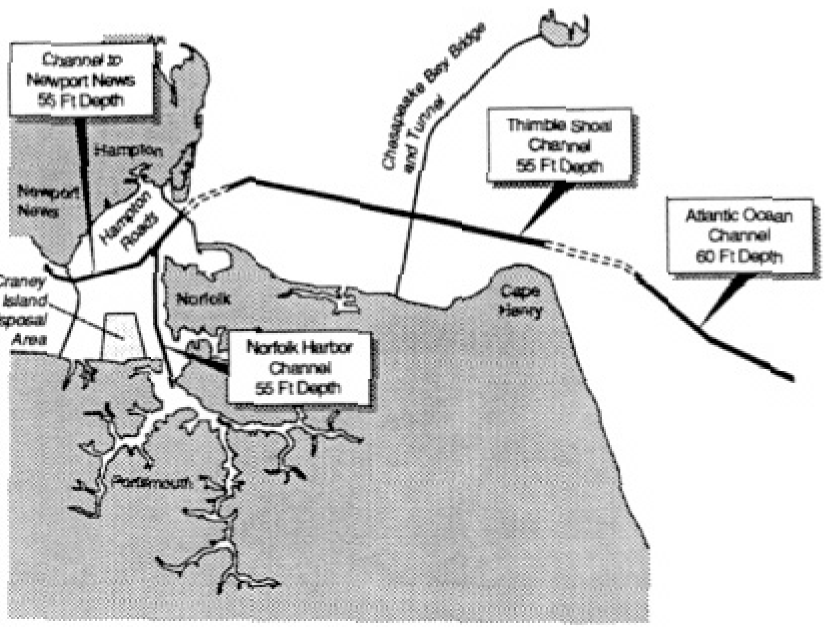

FIGURE C-2 Hampton Roads (*USACE*).

Simulation costs were about $1.3 million. The simulation was performed at the Computer Aided Operations Research Facility (CAORF). Thirty state-licensed pilots from the Virginia Pilots Association and 19 docking masters affiliated with tugboat companies participated in the real-time simulation for the Norfolk and Hampton channels. Fast-time simulation was used to evaluate ship maneuverability in Thimble Shoal Channel and the Atlantic Ocean Channel. The Chesapeake Bay physical model as well as numerical models developed by the USACE Waterways Experiment Station, Vicksburg, Mississippi, were used to evaluate the environmental conditions in these channels (USACE, 1986a).

SIMULATION RESULTS

The simulation indicated that the new channel design would permit bigger and deeper colliers to sail safely from Hampton Roads ports. The simulation recommended maintaining some channel widths as they were initially designed and reducing others, for example, from 1000 feet to 650 feet. Savings of over $100 million were projected as a result of reducing the amount of required dredging (U.S. Maritime Administration, 1985).

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PROJECT IMPLEMENTATION

The project is to be implemented in two phases: channel widening and depth to 50 feet, then depth to 55 feet if economically required. Phase 1 was completed in 1988; Phase 2 is under review.

LESSONS LEARNED

Consensus Building

As a result of the simulation, the channel design was extensively coordinated with the U.S. Coast Guard, U.S. Maritime Administration, Virginia Pilots Association, Virginia Port Authority, USACE, and others. This cooperation resulted in an effective channel design effort with significant cost savings.

Effectiveness as Design Aid

The simulation demonstrated that an asymmetrical channel design would not impair the safe movement of large, deep-draft vessels in confined channels. The combination of real-time and fast-time simulation provided an effective tool for analyzing various channel design options.

Risk Assessment

Simulation runs were not based on worst-case conditions. As a result, vessels may be at risk when encountering these severe conditions, and operating practices need to be developed by the port users to account for these untested risks.

CASE STUDY JOHN F. BALDWIN, PHASE 2 (RICHMOND LONG WHARF) WATERWAY EXPERIMENT STATION, 1983-1984

PROJECT DESCRIPTION

The simulation study was designed to verify the validity of the final design for a major ship channel improvement project in Richmond, California, in the Upper San Francisco Bay (Figure C-3). A design had been completed that involved deepening the Southampton Shoal Channel (connecting channel) and maneuvering areas to the Richmond Long Wharf in

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order to permit the discharge of fully loaded 85,000 DWT tankers and partially loaded 150,000 DWT tankers at this port. The design's suitability for large containership operation into the Richmond Harbor navigation channel was also to be checked.

SIMULATION DESCRIPTION

This simulation was undertaken by the USACE Waterways Experiment Station (WES), located in Vicksburg, Mississippi. It was one of the earliest simulations conducted at this facility. Only modest graphic display capability was available.

Generalized mathematical models were used in the simulation based on material available for similar ships. Environmental data were either measured from scale hydraulic physical models or based on local records as appropriate. Several simplifying assumptions were made in setting up the simulation in the interest of saving time and reducing costs.

Real-time simulations were done for both tankers and containerships. Only limited use was made of experienced pilots, with 36 of the 41 simulation runs being done by WES engineers (Converse et al., 1987; Huval et al., 1985).

SIMULATION RESULTS

The simulation indicated that the initial design was suitable for use by the intended tankers and the smaller (638 foot length overall [LOA]) containerships. However, operation of the larger (810 foot LOA) containerships was not recommended with this design because of tidal currents expected in this port. Significantly less dredging was found to be necessary than was initially proposed for the maneuvering area.

The simulation, which cost only $110 thousand, resulted in a $1.8 million direct savings in dredging costs out of a total project cost initially estimated to be $12.8 million. A value engineering analysis, performed later using additional simulation testing, produced an additional $2.2 million in dredging savings.

PROJECT IMPLEMENTATION

Southampton Shoal Channel and the Maneuvering Area were dredged in 1986 in accordance with the USACE design as revised by the simulation results and the value engineering analysis. Satisfactory operation is reported for the intended tanker traffic and smaller containerships. Additional studies for improvements to Richmond Inner Harbor and approaches are under way.

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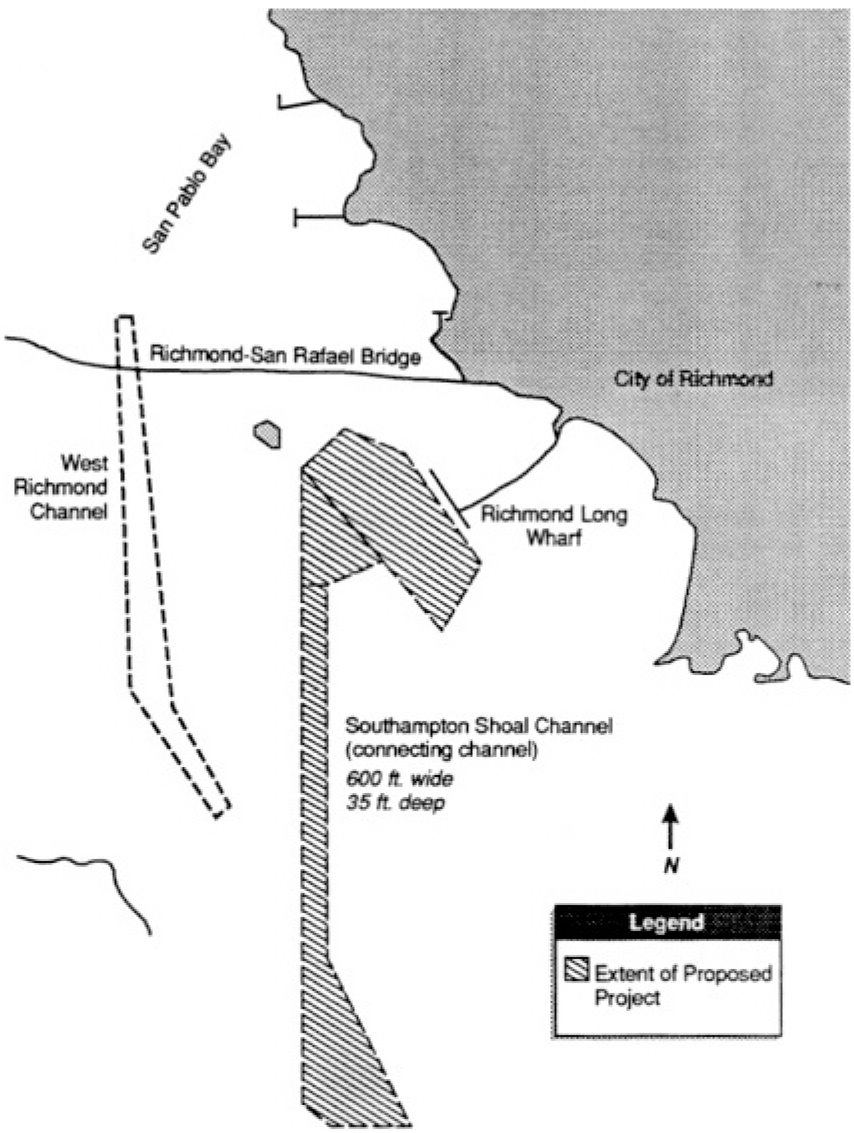

FIGURE C-3 Study area for John F. Baldwin (Richmond Long Wharf), Phase II (*USACE*).

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LESSONS LEARNED

Design Team Skills

This simulation was successfully used for design verification and cost reduction despite its relatively modest level of sophistication and the limited simulator operating experience of the WES staff for this early simulation. These limitations were addressed by using appropriate safety reserves when applying the simulation results.

The success of this particular simulation owed much to the skill of the simulation-design team in simplifying the simulation so as to obtain meaningful results in a timely manner. Their success clearly illustrates the importance of having a skilled team doing simulations.

Pilot Participation

The advice of the experienced ship pilots, although limited, was invaluable in validating the suitability of visual displays and the behavior of known vessels under known conditions.

Despite the significant cost savings achieved, the simulator apparently was not used to its fullest capabilities as a design optimization tool. Additional simulations with experienced pilots might have indicated ways to narrow the design width of the connecting channel (for example, by flaring the upper end, which is critical for setting up the turn). The impact of tug usage was not explored until the value engineering study, due to earlier miscommunications with the pilots.

Consensus Building

The simulation study was reported to be of great value in achieving consensus among various interested groups with divergent views on design requirements.

Graphics Displays

Precise fidelity of the graphic display is not always necessary for a successful simulation, but accuracy of perception is. Correct relative placement of visual objects, navigation channel, and environmental data (for example, currents, winds) is critical. The relative importance of display fidelity varies from project to project.

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CASE STUDY PANAMA CANAL GAILLARD CUT WIDENING STUDY COMPUTER AIDED OPERATIONS RESEARCH FACILITY, 1983-1986

PROJECT DESCRIPTION

The Panama Canal Commission (PCC) conducted a study of canal modifications to permit two-way traffic of Panamax-size vessels throughout its length which in turn would lead to increased throughput of large ships. At present, the Gaillard Cut is the narrowest section of the canal (Figure C-4). It is 500 feet wide with several curves, which makes the meeting of Panamax vessels dangerous at this point.

The Gaillard Cut Widening Study was intended to determine the dimensions for optimum navigation channel that would afford a reasonable balance between excavation cost and safety. Technical, operational, economic, financial, and environmental considerations were evaluated by the PCC during the study.

SIMULATION DESCRIPTION

The simulation, conducted by the Computer Aided Operations Research Facility (CAORF), was the longest waterway design simulation effort undertaken. Real-time and fast-time simulation were used. Field visits were made to develop visual effects, observe vessels using the canal, and mea

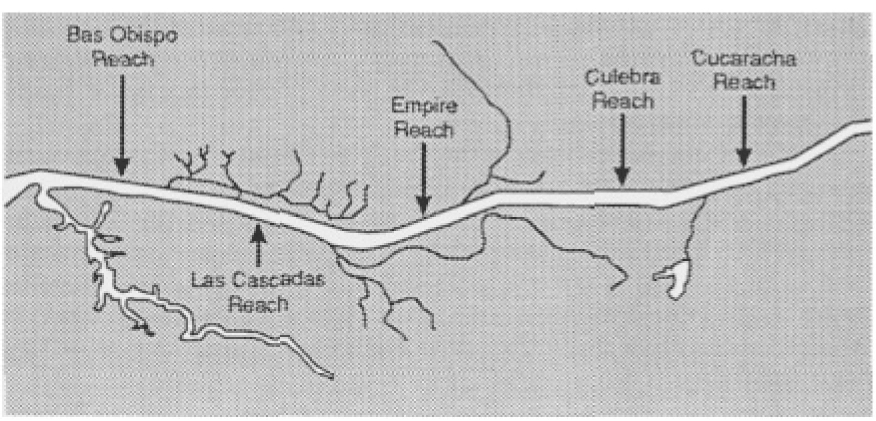

FIGURE C-4 Gaillard Cut, narrowest section of the Panama Canal.

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sure environmental effects for simulation. The model ship was developed by the Swedish State Shipbuilding Tank (SSPA) (Eda et al., 1986; Kaufman, 1986; Moody, 1970; Puglisi, 1986; Puglisi et al., 1984, 1987; U.S. Maritime Administration, 1983-1986, 1986).

Criteria for Measuring Safety Performance

Safety criteria were not available for evaluating ship performance in passing maneuvers relative to alternate channel configurations. Therefore, it was necessary to establish the framework and measures needed to evaluate simulation results, including collection of supporting data. A multidimensional performance measure, referred to as the steering quality profile, was developed for quantifying the degree of safety achieved during passing evolutions. Meetings and passings of the largest ships currently allowed to meet and pass was selected as the baseline for evaluating comparative performance of Panamax ships, the largest allowed to meet and pass in the widened cut. A generic bulk carrier, 608 feet in length with an 85 foot beam, was selected to represent the largest ships currently using the cut.

Model Validation

The mathematical model was validated using comparisons of simulated ship trajectories and actual ship trajectory data collected during transits of the Gaillard Cut. Subjective evaluations of simulator performance by pilots from the Panama Canal Commission were used to further refine the autopilot model. Simulation scenarios were constructed so that meetings and passings would occur in a straight reach near each turn. The scenarios were further refined so that meetings and passings would occur at the most difficult locations for maneuvering. If acceptable performance were achieved at the most difficult locations, then equal or better performance could reasonably be expected elsewhere.

Fast-time simulation was selected to screen hundreds of design variations and eliminate those that were clearly unacceptable. The coefficients used in mathematical models by SSPA and CAORF for fast-time simulation were derived from SSPA model tests for Panamax ships. Comparison of trajectories from the model test and fast-time simulations using the mathematical models determined that performance agreed within ten percent. This level of accuracy was considered acceptable for initial screening of configuration feasibility.

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Fast-Time Screening of Design Alternatives

A screening strategy was developed to permit ranking and selection of alternate waterway configurations. Computer data bases were created for over 1500 configurations. Excavation volumes, determined by the commission for each alternative, were used to rank each in terms of economic desirability. The data bases were organized and stored electronically to facilitate data searches.

For each curve in the waterway, operating conditions were correlated with alternate configurations to form a problem matrix. Fast-time screening began with the least costly configurations. Meeting and passing evolutions were executed under varying operating conditions. Operating conditions were derived from observations of actual shiphandling and ship behavior and ranked according to their effect on passing maneuvers. Progressively wider configurations were used to establish minimum widths needed to permit safe passage under progressively more difficult operating conditions. Following each run, data were examined using regimes built into the computer program to confirm that test parameters for operating conditions were within prescribed tolerances (that is, combined meeting speed within plus or minus 1 knot of designated speed, and meeting location within 1/2 ship-length of the intended location). If tolerances were exceeded, the computer program automatically adjusted the initial speeds or starting location and repeated the run. If a run passed screening criterion, then the next set of operating conditions were selected for that configuration. If a run failed, then the next configuration was loaded according to the ranking strategy. The process was automated so that all runs for each turn could be executed and analyzed without human intervention. Based on the overall results, the commission choose one configuration for each curve which struck a balance between cost and the range of operating conditions for which safe passages could be expected. This constituted the finite number of configurations that would be further evaluated using real-time simulation.

Configuration Assessment Using Real-Time Simulation

Real-time simulation was used to better determine the acceptability of the waterway configurations selected through the screening process for each turn. Pilots employed by the commission participated in full-mission simulation of meetings and passings of Panamax vessels for selected configurations under varying operating conditions. Steering quality profiles generated from pilot directed maneuvers were compared with baseline criteria for measuring safety performance. For 6 of 8 locations for which data had been collected, average performance of the pilot validation group in terms of ship trajectories was better than the baseline safety level. In 7 of the areas

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simulated, average pilot performance was equal to or better than baseline safety levels. Only in one area were minor configuration refinements needed to achieve acceptable performance.

SIMULATION RESULTS

Simulation indicated that if the Gaillard Cut was widened to various widths, then longer and wider (in beam) ships could safely pass each other, which would increase canal throughput by many vessels per year.

PROJECT IMPLEMENTATION

Political instability in Panama has impeded the project schedule. The Pacific Entrance Channel modifications have been partially implemented and were scheduled for completion by late 1990. Widening of the Gaillard Cut began in early 1992.

LESSONS LEARNED

Technical

The study demonstrated that simulation can be used as a cost-effective tool in the design process. It further indicated that

- subjective measures are important in the project evaluation process;
- fast-time analysis can be used to determine what layout alternatives are most likely to succeed, thereby overcoming complex interactions that might have otherwise prohibited analysis;
- accuracy of simulation mathematical models could be achieved within 10 percent of each other; and
- visual observation of vessel tracks could be used to validate fast-and real-time simulation.

Simulation results coupled with design manual guidelines resulted in identifying areas for which dredging was not needed. This finding resulted in projected cost savings of up to $400 million. Simulation showed that alternate vessel tracks fell both inside and outside of the guidelines of the Permanent International Association of Nautical Congresses.

Project Management

Lessons learned relevant to project management included:

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- pilot participation in the real-time simulation could be used to verify the validity of the simulation to the satisfaction of participants,
- all participants in the study wanted considerable confidence in the appropriateness of the selected design vessel, and
- development of the compressed time simulation decision model and automatic execution process was more complex than standard real-time simulation.

CASE STUDY GRAYS HARBOR, WASHINGTON WATERWAYS EXPERIMENT STATION, 1986

PROJECT DESCRIPTION

The Port of Grays Harbor, Washington, wished to verify the feasibility of the final design for a major ship channel improvement project. A design was completed for widening and deepening of 24 miles an estuary and bar channel, improvement of a highway bridge fendering system, and replacement of a rail bridge.

The port sponsored a simulation study by the Waterways Experiment Station (WES) to provide additional input for the final project because of

- high project cost,
- increasing size of the primary vessel type (log carriers) used in original design,
- concern over the adequacy of the turning basin,
- uncertainty over the alignment of the channel in relation to proposed modifications of the bridges, and
- continued concern by environmentalists for a sensitive underwater habitat.

SIMULATION DESCRIPTION

Real-time simulation, using Grays Harbor pilots for verification, was conducted using the WES simulator. Extensive environmental information was available for use in the simulation as part of the basic U.S. Army Corps of Engineers (USACE) navigation project on channel width. All four Grays Harbor pilots participated in the study in close coordination with the local Seattle District, USACE (Hewlett and Nguyen, 1987; Waller and Schuldt, n.d.; Whalin, 1986, 1987).

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SIMULATION RESULTS

The simulation indicated that dredging requirements could be safely reduced in the 8 mile channel section from South Reach to Cow Point from 400 feet to 350 feet (existing width) with widening at bends only (see Figure C-5). This finding resulted in a reduction of 1 million cubic yards of dredging in an environmentally sensitive reach out of a total of 17 million cubic yards.

The simulation also indicated that larger vessels than initially anticipated could be safely used in this harbor with only slight modifications in channel design. The size of turning basin was also determined to be adequate for the large ship.

PROJECT IMPLEMENTATION

Simulation recommendations have been incorporated into the final project specifications. The project is currently under construction.

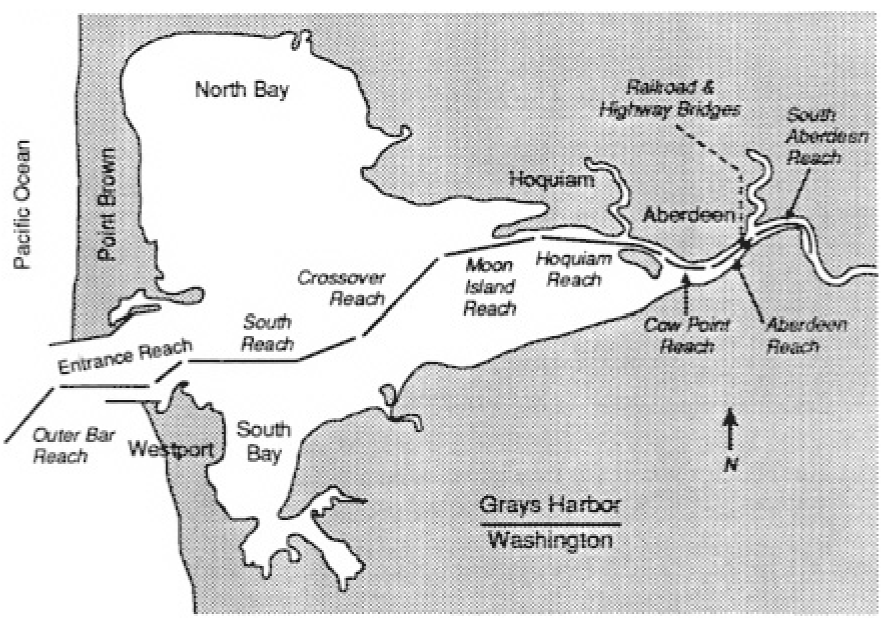

FIGURE C-5 Grays Harbor, Washington.

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LESSONS LEARNED

Consensus Building

The simulation made the basic design project credible for a diverse group of project participants. This result was especially valuable when addressing environmental concerns.

Cost Savings Through Simulation

Cost savings that resulted from the Grays Harbor simulation were significant—about 10 times the cost of the simulation.

Design Tool

Current general design rules for ship turning basins may result in construction of basins larger than necessary, based on the Grays Harbor experience.

CASE STUDY OAKLAND HARBOR COMPUTER AIDED OPERATIONS RESEARCH FACILITY, 1986-1988

PROJECT DESCRIPTION

The Port of Oakland sponsored a simulation study at the Computer Aided Operations Research Facility (CAORF) to develop alternative channel designs for the Inner and Outer Oakland harbors (Figure C-6). The objective was to find suitable designs that would open the port to larger, more cost-efficient containerships in order to maintain the port's competitive position relative to other West Coast container ports. A channel dredged to 42 feet was a key project feature. Ships entering the port are subject to adverse current and wind conditions (U.S. Army Corps of Engineers [USACE], 1988).

SIMULATION DESCRIPTION

The study used the shiphandling simulator at CAORF to evaluate channel designs. Pilots from the San Francisco Bar Pilots Association participated in the real-time simulation. Two other models were used—the San

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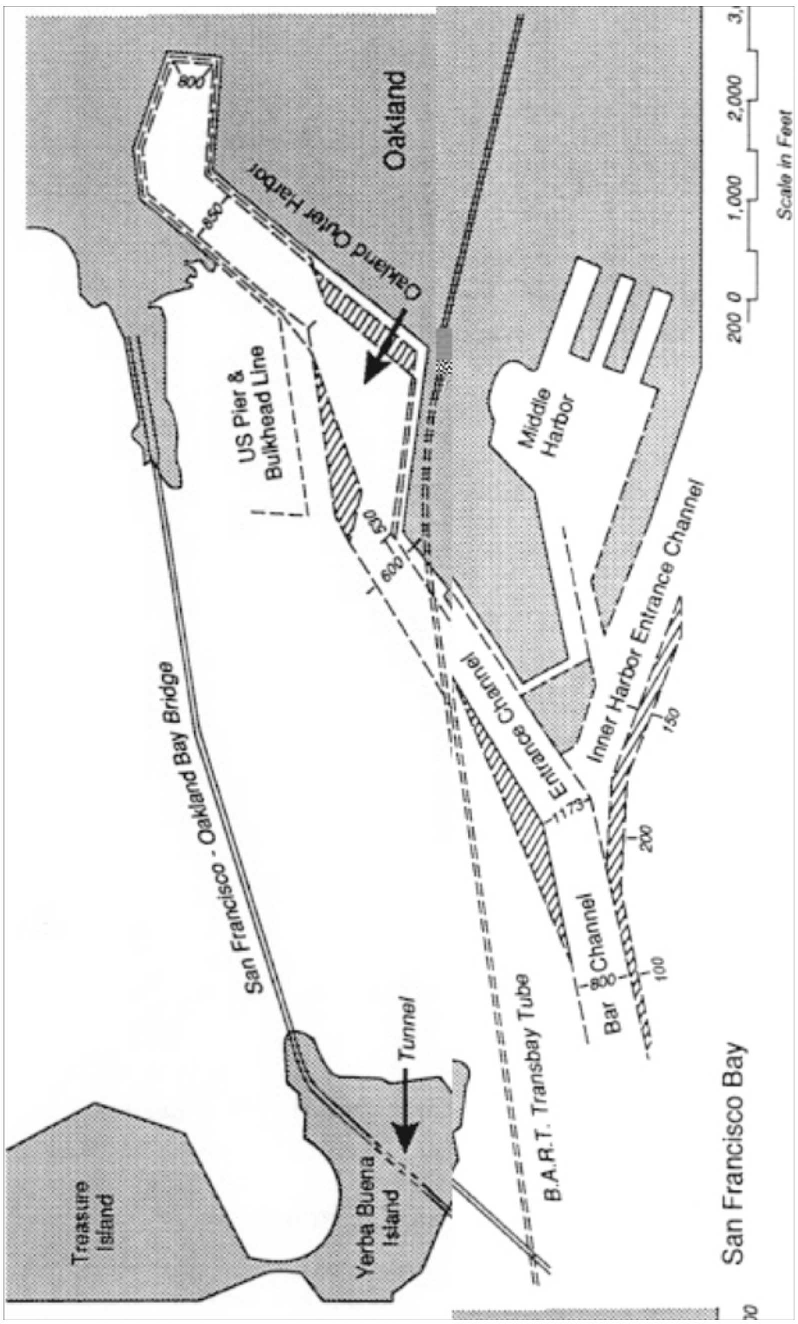

FIGURE C-6 Port of Oakland proposed channel (*USACE*).

Francisco Bay physical model operated by the San Francisco District and the Mooring Line simulation model at the Stevens Institute of Technology. The bay

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model provided values for water currents. The Mooring Line model determined surge effect on moored vessels. The Waterways Experiment Station (WES) in Vicksburg, Mississippi, provided technical support for current modeling (U.S. Maritime Administration, 1987).

PROJECT RESULTS

The simulation indicated that significant safety benefits could be derived by widening the entrance channel and the westernmost part of the outer harbor channel beyond the widths initially proposed and by tapering the width of the remaining outer channel to its present size, thereby minimizing wake damage to moored vessels. Tapering the outer harbor channel precluded the costly relocations of subway (BART) cables and platforms, which was initially planned. Channel width modifications reduced the turning basin design from 1800 to 1600 feet.

PROJECT IMPLEMENTATION

The final proposed design was approved by the USACE in 1988. The Port of Oakland decided to accelerate phase one of the project (deepening the inner harbor to 38 feet). Dredging was to begin in 1988 as a port-sponsored initiative. However, legal and regulatory challenges concerning port involvement and disposal of dredged material effectively halted the port's implementation activities.

Additional interested parties emerged who were not involved in the simulation or other aspects of the design and approval process. The environmental and commercial fishing concerns of these parties were not satisfied by the disposal plans for dredged material from the prospective project, and implementation was stymied. Some objections, especially from the commercial fishing community, were unexpected because fishing concerns apparently had been addressed. However, not all interested fishermen had been involved, and legal challenges were initiated regarding the offshore disposal of dredged material that they alleged could adversely impact their fishing grounds.

The port overcame or accommodated most of the various challenges to the deepening project. However, the port was unable to obtain approval for a suitable offshore disposal site. Escalating costs that occurred in the interim and additional objections to alternate sites have affected the economic viability of what were once promising disposal options. These options included the possible use of dredged material to restore marine habitats within distant reaches of the estuary and to dispose of it in the Sacramento

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River Delta for use as dike construction material by reclamation officials (Kagan, 1990). The port was also unable to resolve legal issues about construction of a part of an authorized federal project by a non-federal organization. As a result, the port discontinued its effort to accelerate completion of phase one and is awaiting USACE implementation following normal procedures.

LESSONS LEARNED

Consensus Building

Simulation brought together parties with interests in project design. It resulted in improved communication and better understanding of project problems, alternatives, and design requirements. Channel design with the aid of simulation provided meaningful data about issues that were previously analyzed subjectively.

Identification of Interested Parties

Although the simulation study was successful, the original identification of parties interested in the project was incomplete, even though some concerns (such as disposal options for dredged material) did not affect design configurations evaluated through simulation. If all parties had been included in the simulation process from the beginning, the same common ground among other parties may not have been achieved. However, the noninvolvement of these late arrivals in the design and approval process has jeopardized project viability (Kagan, 1990).

Design Ship

The appropriate selection of the design ship to be modeled is very important to successful simulation. The Econoline vessel used in this study was not considered to be a good choice. Pilots found it unusually difficult to handle, and it is also believed to be smaller than the ships expected to use the port when the project is completed.

Although additional simulations were recommended to evaluate the performance of the larger vessels expected to use this port (new vessel beam 130 feet versus Econoline beam of 106 feet), the additional work was not done. Thus, the potential exists for larger vessels to operate in a confined, shallow channel without the benefit of supporting simulation data to determine margins of safety for such operations.

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Cost Reductions Through Simulation

Simulation can significantly affect the cost-effectiveness and safety of channel designs. This finding was reflected in changes to channel configuration, which reduced overall dredging costs.

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D

Source Reference List for Mathematical Models

Throughout the study, a vast resource of references were identified that could assist practitioners in applying computer-based simulation to channel design. This appendix characterizes in tabular form a representative number of references on mathematical models of system dynamics and force modules in view of their criticality to simulation. Methods for estimating or describing forces and moments on model elements are included only when they define the form of the model structure.

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
Abkowitz (1964)	Lectures on Ship Hydrodynamics—Steering and manoeuvrability	1	3				
Abkowitz (1980)	Measurement of Hydrodynamic Characteristics from Ship Manoeuvring Trials by System Identification		1				2
Afremoff and Nikolaev (1972)	Yawing of a Ship Steered by an Automatic Pilot in Rough Seas	6,8					
Ankudinov and Barr (1982)	Estimation of Hydrodynamic Maneuvering Models for Six and Fifteen Barge River Tows		7		7		
Ashburner and Norrbin (1980)	Tug-Assisted Stopping of Large Ships in the Suez Canal—A Study of Safe Handling Techniques		7		7		
Åström et al. (1975)	The Identification of Linear Ship Steering Dynamics Using Maximum Likelihood Parameter Estimation	1	1				1
Baker and Patterson (1969)	Some Recent Developments in Representing Propeller Characteristics		4	4			
Bech (1972)	Some Aspects of the Stability of Automatic Course Control of Ships	1,6			1,6		
Bernitsas and Kekridis (1985)	Simulation and Stability of Ship Towing	7			9		
Blanke (1978)	On Identification of Non-Linear Speed Equation from Full-Scale Trials	4					4
Brard (1951)	Maneuvering of Ships in Deep Water, in Shallow Water, and in Canals			2,3			

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
Case et al. (1984)	A Comparative Look at the Performance of Simulator Mathematical Models and Future Considerations	9	1				
Cheng et al. (1982)	Flexible Automatic Ship Controllers for Track-Keeping in Restricted Waterways		6		6		
Chislett and Wied (1985)	A Note on the Mathematical Modelling of Ship Manoeuvring in Relation to a Nautical Environment with Particular Reference to Currents		1,8				
Clarke (1971)	A New Non-Linear Equation for Ship Manoeuvring	2	2				
Clarke (1972)	A Two-Dimensional Strip Method for Surface Ship Hull Derivatives: Comparison of Theory with Experiments on a Segmented Tanker Model	2	2	2			
Clarke et al. (1983)	The Application of Manoeuvring Criteria in Hull Design Using Linear Theory	2	2				
Crane (1966)	Studies of Ship Manoeuvring—Response to Propeller and Rudder Actions		4				
Crane, et al (1989)	Controllability	1,9		1,9			1,9
Dand (1975)	Some Aspects of Tug Ship Interaction			3,7			
Dand (1984)	Optimizing Ship Operations in Open and Confined Waters Using Manoeuvring Simulation Models		3				
De Boer (1983)	Manoeuvring Prediction with the MINISIM, A Simulation Program to Predict the Manoeuvring Performance of a Ship		1				

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
De Kat and Paulling (1989)	The Simulation of Ship Motions and Capsizing in Severe Seas	1,8		8			
Eda (1967)	Steering Control of Ships in Waves	1,8		8	1,8		
Eda (1972a)	Yaw Control in Waves	1,8		8			
Eda (1972b)	Course Stability, Turning Performance and Connection Force of Barge Systems in Coastal Seawaves	7,8			1		
Eda and Crane (1965)	Steering Characteristics of Ships in Calm Water and Waves	1,8		8	8		
Eda and Savitsky (1969)	Experimental and Analytical Studies of Ship Controllability in Canals		3	3	3		
Edwards (1985)	Hydrodynamic Forces on Vessels Stationed in a Current		8	8			
Eskola (1986)	Modelling the Propulsion Machinery Behavior During Model Propulsion Tests in Ice		5,8				
Forsman and Sandkvist (1986)	Brash Ice Effects on Ship Operations—A Presentation of the SSPA Manoeuvring Simulation Model and Other Brash Ice Related Projects		8				
Fujii (1972)	On Manoeuvre Tests to Investigate the Course-Keeping Qualities of Ships				3		
Fujino (1968)	Experimental Studies on Ship Manoeuvrability in Restricted Waters, Part 1	1,3	3	3			
Fujino (1970)	Experimental Studies on Ship Manoeuvrability in Restricted Waters, Part 2	1,3	3	3			

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		A	B	C	D	E	F
Fujino and Ishiguro (1984)	A Study of the Mathematical Model Describing Manoeuvring in Shallow Water—Shallow Water Effects on Rudder Effectiveness Parameters		3,4				
Gertler and Hagen (1967)	Standard Equations of Motion for Submarine Simulation	1,2	2				
Gill (1979)	Mathematical Modelling of Ship Manoeuvring		1				
Glansdorp (1975)	Ship Type Modelling for a Training Simulator		1				
Göransson and Liljenberg (1975)	Simulating the Main Engine—A Comparison of FPP and CPP Arrangements (in Swedish with English Summary)		5		5		
Hagen (1983)	A Catalog of Existing Mathematical Models for Maneuvering		1				
Hirano (1980)	On Calculation Method of Ship Manoeuvring Motion at Initial Design Stage (in Japanese)	1	1,2				
Hirano et al. (1985)	A Computer Program System for Ship Manoeuvring Motion Prediction		1		1		
Hoffman (1972)	Consideration of Sea-Keeping in the Design of a Ship Manoeuvring Simulator	8				1,8	
Holzhüter (1990)	A Workable Dynamic Model for the Track Control of Ships	1,6		6			
Hooft (1968)	The Manoeuvrability of Ships on a Straight Course	1			1		
Hu (1961)	Forward Speed Effect on Lateral Stability Derivatives of a Ship	2		2			

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
Imlay (1961)	The Complete Expressions for Added Mass of a Rigid Body Moving in an Ideal Fluid	2					
Inoue and Murayama (1970)	Calculation of Turning Ship Derivatives in Shallow Water (in Japanese)		3	3			
Inoue et al. (1981)	A Practical Calculation Method of Ship Manoeuvering Motion		1				
Jacobs (1964)	Estimation of Stability Derivatives and Indices of Various Ship Forms, and Comparison with Experimental Results	2	2	2			
Källström (1979)	Identification and Adaptive Control Applied to Ship Steering	6					2
Källström (1984)	A Digital Control System for Ship Manoeuvring in Ports and Waterways	6			6		
Källström and Ottosson (1982)	The Generation and Control of Roll Motion of Ships in Close Turns		1,6		6		
Kijima et al. (1990)	Prediction Method of Ship Manoeuvrability in Deep and Shallow Waters	2,3	3				
Kirchhoff (1869)	Über die Bewegung eines Rotationskörpers in einer Flüssigkeit	1,2					
Kobayashi (1988)	A Simulation Study on Ship Manoeuvrability at Low Speeds		1,4		1		
Koelink (1968)	Approximate Methods in Z-Steering Test Analysis	1	2				
Kose (1982)	On a New Mathematical Model of Manoeuvring Motions of a Ship and Its Applications	1	1,4		1		
Kotschin et al. (1954)	Theoretische Hydromechanik	2					

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		A	B	C	D	E	F
Koyama (1972)	Improvement of Course Stability and Control by a Subsidiary Automatic Control	1,6			6		
Koyama and Jin (1987)	An Expert System Approach to Collision Avoidance	1,6					
Koyama et al. (1977)	A Study of the Instability Criterion on the Manual Steering of Ships		6		6		
Lamb (1918)	The Inertia Coefficients of an Ellipsoid Moving in a Fluid	2		2			
Landweber and de Macagno (1957)	Added Mass of Two-Dimensional Forms Oscillating in a Free Surface	2		2			
Lindström (1989)	Prediction of Ship Manoeuvring in Level Ice by Simulation of the Planar Motions (in Swedish)		8		8		
Mandel (1967)	Ship Maneuvering and Control	1,9		1,9			
Matsumoto and Suemitsu (1984)	Interference Effects Between Hull, Propeller and Rudder of a Hydrodynamic Mathematical Model in Manoeuvring Motion		2	4			
Matthews (1984)	A Six Degree of Freedom Ship Model for Computer Simulation	2	1				
McCallum (1976)	A New Approach to Manoeuvring Ship Simulation	2	1				
McCallum (1980)	A Ship Steering Mathematical Model for All Manoeuvring Regimes		1,4				
McCreight (1986)	Ship Maneuvering in Waves	1,8			8		
Mikelis et al. (1985)	On the Construction of a Versatile Mathematical Model for Marine Simulation		1,2				

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		A	B	C	D	E	F
Miller (1979)	Towboat Maneuvering Simulator		1,4 7				
Motora (1960)	On the Measurement of Added Mass and Added Moment of Inertia of Ships in Steering Motion			2			
Motora et al. (1971)	Equivalent Added Mass of Ships in the Collision			2			
Naegle (1980)	Ice Resistance Prediction and Motion Simulation for Ships Operating in the Continuous Mode of Icebreaking		8		8		
Newman (1966)	Some Hydrodynamic Aspects of Ship Maneuverability	1,2		2			
Newman (1969)	Lateral Motion of a Slender body of Revolution Moving near a Wall	3					
Newman (1972)	Some Theories for Ship Manoeuvring	3					
Nikolaev et al. (1972)	Estimation of the Effectiveness of Lateral Thrust Units			4			
Nomoto (1960)	Analysis of Kempf's Standard Manoeuvre Test and Proposed Steering Quality Indices		1				1
Nomoto (1966)	Unusual Scale Effects on Manoeuverabilities of Ships with Blunt Bodies			2			2
Nomoto (1972)	Problems and Requirements of Directional Stability and Control of Surface Ships	1	1				
Nomoto et al. (1957)	On the Steering Qualities of Ships	1	1				
Norrbin (1960)	A Study of Course Keeping and Manoeuvring Performance	1,6	9				

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
Norrbin (1963)	On the Design and Analysis of the Zig Zag Test on Base of Quasi-Linear Frequency Response	1	2				
Norrbin (1965)	The Technique and Analysis of the Zig Zag Test (in Swedish)	1	1				1
Norrbin (1970)	Theory and Observations on the Use of a Mathematical Model for Ship Manoeuvring in Deep and Confined Waters	1,2	2,6	2,3		1,6	
Norrbin (1972)	Ship Manoeuvring with Application to Shipborne Predictors and Real-Time Simulators		1,6				
Norrbin (1978)	A Method for the Prediction of the Manoeuvring Land of a Ship in a Channel of Varying Width		2,3	3			
Norrbin (1986)	Fairway Design with Respect to Ship Dynamics and Operational Requirements		3,6 7	3	3		
Norrbin (1988)	Head-On Collision or a Planned Encounter—A Contribution to Micro-Navigation		3		6		
Norrbin et al. (1978)	A Study of the Safety of Two-Way Traffic in a Panama Canal Bend		2,3	3	1,6	1	
Ogawa and Kasai (1978)	On the Mathematical Model of Manoeuvring Motion of Ships	1	1				
Oltmann and Sharma (1985)	Simulation of Combined Engine and Rudder Manoeuvres Using an Improved Model of Hull-Propeller-Rudder Interactions	1	1,4				
Onassis and ten Hove (1988)	Modular Ship Manoeuvring Models		1,4				

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		A	B	C	D	E	F
Ottosson and Apleberger (1987)	Real-Time Simulations of Ship Motions—A Tool for the Design of a New Pacific Port		7,8			1,3	
Ottosson and van Berlekom (1985)	Simulations in Real and Accelerated Time—A Computer Study of a Ro-Ro Vessel Entering Different Port configurations				1	1	
Paloubis and Thaler (1972)	Identification of System Models from Operating Data	1					1,5
Perdok and van der Tak (1987)	The Application of Man-Machine Models in the Analysis of Ship Control	6	6				6
Perez y Perez (1972)	A Time Domain Solution to the Motions of a Steered Ship in Waves	1,8	8		1,8		
Pourzanjani (1990)	Formulation of the Force Mathematical Model of Ship Manoeuvring	1	2				2
Pourzanjani et al. (1987)	Hydrodynamic Lift and Drag Simulation for Ship Manoeuvring Models		2				
Price (1972)	The Stability of a Ship in a Simple Sinusoidal Wave	1,8					
Puglisi et al. (1985a)	Direction of International Joint Effort for Development of Mathematical Models and Ship Performance Data for Marine Simulation Application	9					1
Renilsson and Driscoll (1982)	Broaching—An Investigation into the Loss of Directional Control in Severe Following Seas		8				
Rutgersson and Ottosson (1987)	Model Tests and Computer Simulations—An Effective Combination for Investigation of Broaching Phenomena	8			1,8		

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns)					
		A	B	C	D	E	F
Rydill (1959)	A Linear Theory for the Steered Motion of Ships in Waves	1,6			1		
Salo and Heikkilä (1990)	On the Modelling of Hull-Propeller-Rudder Interactions in Manoeuvring of Twin-Screw ships		4				4
Sargent and Kaplan (1970)	System Identification of Surface Ship Dynamics						2
Schmidt and Unterreiner (1976)	Ein Mathematisches Modell zur Simulation des Manövrierverhaltens von Schiffen für die Anwendung in Trainings-Simulatoren		1				
Schoenherr (1960)	Data for Estimating Bank Suction Effects in Restricted Water and on Merchant Ship Hulls			3			
Shooman (1980)	Models of Helmsman and Pilot Behavior for Manoeuvring Ships		6		6		
Smitt (1970)	Steering and Manoeuvring: Full-Scale and Model Tests	1	2	2			
Smitt and Chislett (1972)	Course Stability While Stopping	2	2,4	4			
Society of Naval Architects and Marine Engineers (1950)	Nomenclature for Treating the Motion of a Submerged Body Through a Fluid	1,2	2				
Strøm-Tejsen (1965)	A Digital Computer Technique for Prediction of Standard Maneuvers of Surface Ships		1,2				

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AUTHOR (date)	TITLE	Nature of Treatment or Topic[a] (see note[b] for subject area codes within columns) A	B	C	D	E	F
Strøm-Tejsen and Chislett (1966)	A Model Testing Technique and Method of Analysis for the Prediction of Steering and Manoeuvring Qualities of Surface Ships		2	2			
Stuurman (1969)	Modelling the Helmsman: A Study to Define a Mathematical Model Describing the Behavior of a Helmsman Steering a Ship Along a Straight Course		6		6		
Tasai (1961)	Hydrodynamic Force and Moment Produced by Swaying Oscillation of Cylinders on the Surface of a Fluid	2		2			
Thöm (1975)	Modellbildung für das Kursverhalten von Schiffen	6	6				
Trägårdh (1976)	Simulation of Tugs at the SSPA Manoeuvring Simulator		7				
Tuck (1966)	Shallow Water Flows Past Slender Bodies	3		3			
Tuck and Newman (1974)	Hydrodynamic Interactions Between Ships	3		3			
Van Amerongen and van der Klugt (1985)	Modelling and Simulation of the Roll Motions of a Ship	1			1		
Van Berlekom (1978)	Simulator Investigations of Predictor Steering Systems for Ships	1,6			6		
Van Berlekom and Goddard (1972)	Maneuvering of Large Tankers		1	2			
Van Leeuwen (1964)	The Lateral Damping and Added Mass of an Oscillating Shipmodel			2			

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		A	B	C	D	E	F
Van Leeuwen (1972a)	Some Aspects of Prediction and Simulation of Manoeuvres		1		1		
Van Leeuwen (1972b)	Course Keeping Going Astern		2,4	2,4			
Veldhuijzen and Stassen (1975)	Simulation of Ship Manoeuvring Under Human Control		6		1		
Vugts (1968)	The Hydrodynamic Coefficients for Swaying, Heaving and Rolling Cylinders in a Free Surface	2		2			
Webster (1967)	Analysis of the Control of Activated Antiroll Tanks	4,8					
Weinblum (1952)	On the Directional Stability of Ships in Calm Water and in a Regular Seaway	1,8					
Wendel and Dunne (1969)	Dynamic Analysis and Simulation of Ship and Propulsion Plant Manoeuvring Performance		4				
Yeung (1978)	Applications of Slender Body Theory to Ships Moving in Restricted Shallow Water	3		3			
Zhao (1990)	Theoretical Determination of Ship Manoeuvring Motion in Shallow Water	3					
Zhou and Blanke (1987)	Nonlinear Recursive Prediction Error Method Applied to Identification of Ship Steering Dynamics	1					1
Zuidweg (1970)	Automatic Guidance of Ships as a Control Problem	6	6				

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[a] Codes for nature of treatment or topic:
A Theory and theoretical models
B Semiempirical models
C Data figures
D Applications in compressed time
E Applications in real time
F Identification, validation
[b] Codes for subject areas:
1 System dynamics
2 Hull forces in deep water
3 Hull forces in confined water (shallow, restricted)
4 Control forces (propulsive, lateral)
5 Engine functioning (propulsive and lateral control)
6 Control automatics, human pilots (including fast time/compressed simulation)
7 Tug assistance, mooring, fendering
8 External forces from wind, waves, current, mud, ice
9 General or nonspecific

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E

Papers Prepared for This Study

Barr, R. 1991. Comparison of simulation models and validation studies for the *Esso Osaka*. Background paper prepared for the Committee on Assessment of Shiphandling Simulation, National Research Council, Washington, D.C.

Norrbin, N. H. 1991. Source reference list on mathematical models. Background paper prepared for the Committee on Assessment of Shiphandling Simulation, National Research Council, Washington, D.C.

Norrbin, N. H., R. A. Barr, C. L. Crane, Jr., and W. C. Webster. 1989. A summary of findings from task group visits to a number of european ship manoeuvreing simulator centers. Background paper prepared for the Committee on Assessment of Shiphandling Simulation, National Research Council, Washington, D.C.

Puglisi, J. J. 1989. European trip report. Background paper prepared for the Committee on Assessment of Shiphandling Simulation, National Research Council, Washington, D.C.

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F

Validation of Aircraft Flight Simulators

OVERVIEW

Computer-based simulations are used widely in commercial aviation to assist in airframe design, flight operations, and pilot training (Stix, 1991). Development of aircraft flight simulators is directly linked to development of specific aircraft. The extensive data generated as part of aircraft design and testing are used as a technical resource for developing a simulator for training pilots in that aircraft's operation (aircraft flight simulators are airframe-specific). Thus, aircraft flight simulators cannot be modified to permit training in multiple airframes nor are they used for designing air routes.

Validation of an aircraft flight training simulator's fidelity to represent an aircraft's performance and handling historically has been the task of the chief pilot for an airframe manufacturer, a pilot selected by the Federal Aviation Administration (FAA), or a military officer assigned the role of project pilot for the Department of Defense. Evaluations have been based on a subjective opinion of the pilot relative to how well the cockpit controllers (such as stick, throttles, rudder pedal, and brakes), cockpit instrumentation, aural system (used to generate engine sounds and wind noise), visual system, and motion system are designed, modeled, and integrated to recreate the true behavior of the aircraft for various flight mission phases (for example, ground handling, takeoff, and climb). Today, pilots still play a role in the simulation validation process. However, many quantitative tests have been designed and used for evaluating the correctness of the simulator.

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VALIDATION POLICY

Strict guidelines are followed for the design and validation of military operational flight and weapon system trainers. The military software specification MIL-2167A defines the procedure by which simulator software is designed, documented, and validated. Simulators for aircraft under the jurisdiction of the FAA are validated under criteria specified by an FAA Advisory Circular. Currently, this is AC120-45A Draft: *Airplane Flight Training Device Qualification*. The FAA's interest in certificating an aircraft flight simulator can be traced to its philosophy concerning the role of flight simulators. This viewpoint is stated in the introduction to the circular, which follows.

> The primary objective of flight training is to provide a means for flight crewmembers to acquire the skills and knowledge necessary to perform to a desired safe standard. Flight simulation provides an effective, viable environment for the instruction, demonstration, and practice of the maneuvers and procedures (called training events) pertinent to a particular airplane and crewmember position. Successful completion of flight training is validated by appropriate testing, called checking events. The complexity, operating costs, and operating environment of modern airplanes, together with the technological advances made in flight simulation, have encouraged the expanded use of training devices and simulators in the training and checking of flight crewmembers. These devices provide more in-depth training than can be accomplished in the airplane and provide a very high transfer of skills, knowledge, and behavior to the cockpit. Additionally, their use results in safer flight training and cost reductions for the operators, while achieving fuel conservation, a decrease in noise and otherwise helping maintain environmental quality.
>
> The FAA has traditionally recognized the value of training devices and has awarded credit for their use in the completion of specific training and checking events in both general aviation and air carrier flight training programs and in pilot certification activities. Such credits are delineated in FAR Part 61 and Appendix A of that part; FAR Part 121, including Appendices E and F; and in other appropriate sources such as handbooks and guidance documents. These FAR sources, however, refer only to a "training device," with no further descriptive information. Other sources refer to training devices in several categories such as Cockpit Procedures Trainers (CPT), Cockpit Systems Simulators (CSS), Fixed Base Simulators (FBS), and other descriptors. These categories and names have had no standard definition or design criteria within the industry and, consequently, have presented communications difficulties and inconsistent standardization in their application. Furthermore, no single source guidance document has existed to categorize these devices, to provide qualification standards for each category, or to relate one category to another in terms of capability or

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technical complexity. As a result, approval of these devices for use in training programs has not always been equitable.

The circular, under Evaluation Policy, addresses the scope of quantification testing that is required in order to certificate (validate) the operation of a simulator, as follows:

> The flight training device must be assessed in those areas which are essential to accomplishing responses and control checks, as well as performance in the takeoff, climb, cruise, descent, approach, and landing phases of flight. Crewmember station checks, instructor station functions checks, and certain additional requirements depending on the complexity of the device (i.e., touch activated, cathode ray tube instructor controls; automatic lesson plan operation; selected mode of operation for "fly-by-wire" airplanes; etc.) must be thoroughly assessed. Should a motion system or visual system be contemplated for installation on any level of flight training device, the operator or the manufacturer should contact the NSPM for information regarding an acceptable method for measuring motion and/or visual system operation and application tolerances. The motion and visual systems, if installed, will be evaluated to ensure their proper operation.
>
> The intent is to evaluate flight training devices as objectively as possible. Pilot acceptance, however, is also an important consideration. Therefore, the device will be subjected to the validation tests listed in Appendix 2 of this Advisory Circular and the functions and subjective tests from Appendix 3. These include a qualitative assessment by an FAA pilot who is qualified in the respective airplane, or set of airplanes in the case of Level 2 or 3. Validation tests are used to compare objectively flight training device data and airplane data (or other approved reference data) to assure that they agree within a specified tolerance. Functions tests provide a basis for evaluating flight training device capability to perform over a typical training period and to verify correct operation of the controls, instruments, and systems.

QUANTITATIVE TEST PROCEDURES

Systematic procedures have been and are continuing to be developed to aid the validation of all components that comprise a modern aircraft simulator. Parameter identification is now being used routinely to extract aerodynamic models from flight test measurements. The parameter identification results are used to validate the simulation mathematical model (Anderson et al., 1983; Anderson and Vincent, 1983; Hess and Hildreth, 1990; Trankle et al., 1981; Trankle et al., n.d.).

Validation of an aircraft flight simulation model typically involves four levels of testing (actual procedures vary by facility). At the first level, individual modules or sub-programs (down to the smallest practical subdivision) are tested individually. This insures that each module has been

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coded correctly (that is, it satisfies the design requirements for that module). The second level involves testing of small program packages or groups of sub-programs that are related in functionality (such as those modules that comprise the propulsion system). These are tested as separate packages to further debug them and to test the input/output interaction between each module. Model validation also begins in its simplest form.

Test drivers are used in both the first and second levels. For example, a test driver has been developed for static testing of subroutines by allowing control of the input and output variables to each group of program packages. Inputs are generated to stimulate each individual program package in a controlled manner so that the resulting outputs can be examined, usually graphically. For example, in aero models, the angle-of-attack is varied at-180° to +180° for given Mach numbers. The coefficients that comprise the aero model are then plotted as a function of angle-of-attack to assure that their value is correct and continuous. Testing at the second level completes the static testing of the math model.

The complete math model is tested for dynamic response verification at level three. Two test tools are used for analysis. An open loop test generator generates step, sine wave, or ramp or doublet inputs to the simulation. These are used to assess dynamic responses. Since the inputs are computer generated, they can be reproduced exactly and can be used to produce easily analyzed inputs. A second program is used to drive a simulator with aircraft flight test data. This program has the capability of over-driving aircraft math model states or controls with those of the aircraft. For instance, the flight control system can be completely validated by using the flight test feedbacks such as pitch rate and normal acceleration and other measures as inputs to the flight controls along with input from the pilot. This way, the outputs of the flight controls such as control surface positions can be examined on a one-for-one basis with the output of the flight controls in the aircraft. If the simulator flight controls have the same inputs as the aircraft flight controls, their control surface deflection should be the same. Likewise, the aero response of the simulator can be isolated from the effect of the flight controls. This can be done by driving the aero simulation with the actual control surface deflections recorded in the flight test program and then examining the dynamic response of the simulator compared to the aircraft. The same procedure can be followed for engine validation.

Final testing, consisting of pilot-in-the-loop, is performed at level four. By this time, the math model has already been validated but adjustments may have to be made to gain pilot approval. These adjustments primarily result from the limited ability of the motion and visual system to realistically simulate pilot cues. Adjustments determined necessary are satisfied by improving cuing system compensation.

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