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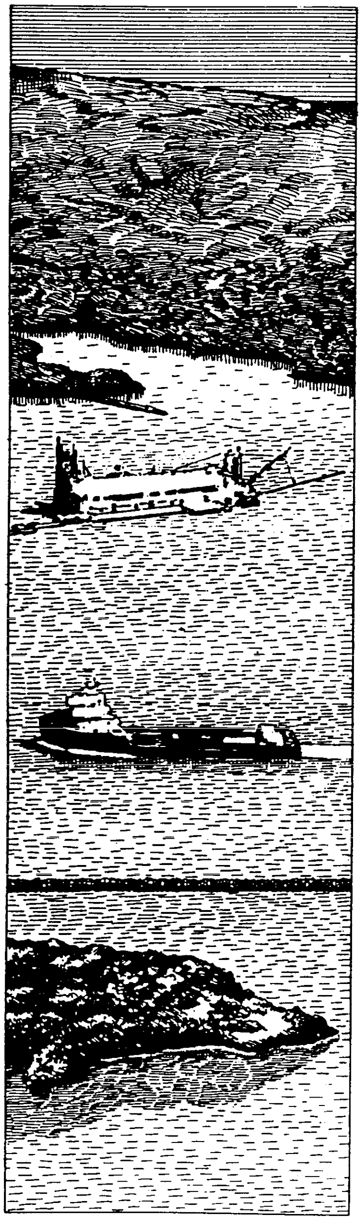

DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-96-4

ANALYSIS OF DREDGED MATERIAL DISPOSED IN OPEN WATER: SUMMARY REPORT FOR TECHNICAL AREA 1

compiled by

Lyndell Z. Hales

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

May 1996

Final Report

Approved For Public Release; Distribution Is Unlimited

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

Under Work Unit 32492

The Dredging Research Program (DRP) is a seven-year program of the U.S. Army Corps of Engineers. DRP research is managed in these five technical areas:

- Area 1 - Analysis of Dredged Material Placed in Open Water
- Area 2 - Material Properties Related to Navigation and Dredging
- Area 3 - Dredge Plant Equipment and Systems Processes
- Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
- Area 5 - Management of Dredging Projects

US Army Corps
of Engineers
Waterways Experiment
Station

Dredging Research Program Report Summary

Analysis of Dredged Material Disposed in Open Water: Summary Report for Technical Area 1 (TR DRP-96-4)

ISSUE: The navigation mission of the Corps of Engineers entails maintenance dredging of about 40,000 km of navigable channels at an annual cost of about $400 million. Deficiencies in the dredging program have been documented by the Corps field operating Division and District offices. Implementation of the Dredging Research Program (DRP) to meet demands of changing conditions related to dredging activities, and the generation of significant technology that will be adopted by all dredging interests, are means to reduce the cost of dredging the Nation's waterways and harbors and save taxpayer dollars.

RESEARCH: Investigations under DRP Technical Area 1, "Analysis of Dredged Materials Disposed in Open Water," included (a) better understanding of the boundary-layer properties of both cohesive and noncohesive sediments, (b) development of instrumentation for monitoring suspended-sediment plumes and for determining resuspension from disposal mounds, (c) formulation and verification of short- and long-term numerical models for determining fate of material disposed in open water, and (d) improved field techniques for collecting long-term data pertaining to movement of nearshore berms designed as feeder beach material or wave-attenuation devices.

SUMMARY: Fundamental knowledge was acquired pertaining to boundary-layer flow properties of both cohesive and noncohesive materials to better formulate numerical expressions describing movement of these materials under wave and current conditions. The plume measurement system (PLUMES) was developed to track suspended-sediment plumes in open waters. The acoustic resuspension and measurement system (ARMS) was developed for determining resuspension from existing or proposed open-water disposal sites. Short- and long-term fate (STFATE and LTFATE) and multiple dump fate (MDFATE) numerical models were developed for simulating placement, resuspension, and migration of dredged materials from open-water disposal sites. ADCIRC was formulated for generating long time periods of hydrodynamic circulation for very large computational domains to provide input for long-term sediment transport computations. Databases of tidal constituents and tropical storms for U.S. coastlines were generated. Instrumentation and techniques for monitoring nearshore berms and mounds placed as feeder beach-nourishment material in the littoral zone were developed. The EBERM model was developed to determine whether berms in the nearshore zone will be active or stable.

AVAILABILITY OF REPORT: The report is available through the Interlibrary Loan Service from the U.S. Army Engineer Waterways Experiment Station (WES) Library, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, telephone (601) 634-2355. National Technical Information Service report numbers may also be requested from the WES librarians.
To purchase a copy of the report, call NTIS at (703) 487-4780.

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Dredging Research Program

Technical Report DRP-96-4
May 1996

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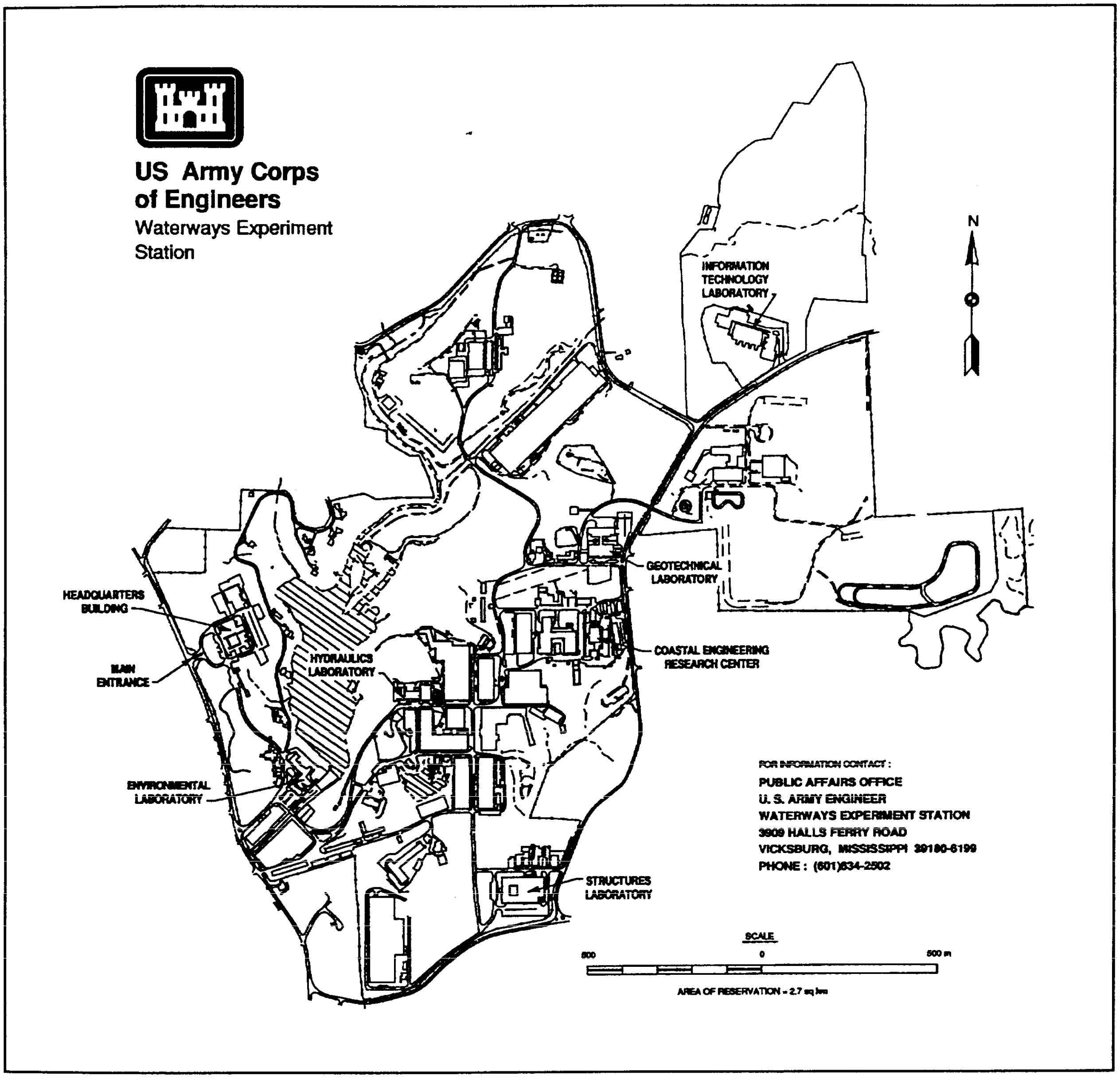

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Preface

This report summarizes research conducted by U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program (DRP), Technical Area 1, "Analysis of Dredged Materials Disposed in Open Water." The DRP was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Technical Monitors for Technical Area 1 were Messrs. John H. Lockhart, Jr., and Glenn Drummond. Chief Technical Monitor was Mr. Robert H. Campbell, HQUSACE.

This summary report was compiled by Dr. Lyndell Z. Hales, Coastal Engineering Research Center (CERC), WES, and was extracted essentially verbatim from Technical Area 1 reports.

Technical Area 1 studies were conducted by or under the following WES supervision:

CERC—Dr. Nicholas C. Kraus, Principal Investigator, CERC; Dr. Norman W. Scheffner, Principal Investigator, Coastal Oceanography Branch (COB), Research Division (RD); Mr. Michael W. Tubman, Principal Investigator, Prototype Measurement and Analysis Branch (PMAB), Engineering Development Division (EDD); Mr. Edward B. Hands, Principal Investigator, Coastal Structures and Evaluation Branch (CSEB), EDD; Dr. James R. Tallent, Ms. Michelle M. Thevenot, and Mr. David J. Mark, Coastal Processes Branch (CPB), RD; Ms. Terri L. Prickett, Mr. David D. McGehee, Mr. James P. McKinney, and Mr. William E. Grogg, PMAB. Additional supervision was provided by Dr. Martin Miller, Chief, COB; Mr. H. Lee Butler, Chief, RD; Mr. William L. Preslan, Chief, PMAB; Mr. Thomas W. Richardson, Chief, EDD; Ms. Joan Pope, Chief, CSEB; Mr. Bruce A. Ebersole, Chief, CPB; Mr. Charles C. Calhoun, Jr., Assistant Director, CERC; and Dr. James R. Houston, Director, CERC.

Hydraulics Laboratory (HL)—Dr. Billy H. Johnson, Principal Investigator, HL; Mr. Allen M. Teeter, Principal Investigator, Estuarine Processes Branch (EPB), Estuaries Division (ED); Ms. Dinah N. McComas, Math Modeling Branch (MMB), Waterways Division (WD); Ms. Darla McVan, Hydraulic Analysis Branch (HAB), Hydraulic Structures Division (HSD); Mr. R. Charlie Berger, ED; and Mr. Walter Pankow, Estuarine Engineering Branch (EEB), ED. Additional supervision was provided by Mr. William H. McAnally, Jr., Chief, ED; Mr. William D. Martin, Chief, EEB; Mr. Michael J. Trawle, Chief, MMB; Dr. Larry L. Daggett, Chief, WD; Dr. Bobby J. Brown, Chief, HAB; Mr. Glenn A. Pickering, Chief, HSD; Mr. Richard A. Sager, Assistant Director, HL; and Mr. Frank A. Herrmann, Jr., Director, HL.

Instrumentation Services Division (ISD)--Ms. Moira T. Fong, Operations Branch (OB). Additional supervision was provided by Mr. Leiland M. Duke, Chief, OB; and Mr. George P. Bonner, Chief, ISD.

Drs. Kraus and Johnson were the Technical Area Managers for Technical Area 1.

Mr. E. Clark McNair, Jr., CERC, and Dr. Hales were Manager and Assistant Manager, respectively, of the DRP. Dr. Houston and Mr. Calhoun were Director and Assistant Director, respectively, of CERC, which conducted the DRP.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Bruce K. Howard, EN.

For further information on this report or on the Dredging Research Program, please contact Mr. E. Clark McNair, Jr., DRP Program Manager, WES, at (601) 634-2070.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02832	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
inches	2.54	centimeters
inches	25.4	millimeters
knots	1.852	kilometers per hour
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

Summary

This report summarizes research conducted by the Dredging Research Program, Technical Area 1, "Analysis of Dredged Materials Disposed in Open Water," to (a) establish a better understanding of boundary-layer properties of both cohesive and noncohesive materials for developing short- and long-term numerical approximations for determining fate and disposition of dredged materials disposed in open water, and (b) develop field instrumentation for tracking suspended sediment plumes and monitoring nearshore berms and disposal mounds for resuspension and migration of the dredged material.

"Calculation of Boundary-Layer Properties (Noncohesive Sediments)" included determination of (a) the potential of sand for beach nourishment, (b) numerical models of the longshore current, (c) expressions for cross-shore movement of bars and berms, and (d) noncohesive boundary-layer movable-bed friction factors and total sediment transport by combined waves and currents.

"Calculation of Boundary-Layer Properties (Cohesive Sediments)" (a) improved methods for assessing cohesive-sediment erodibility, (b) formulated PC programs to assist in disposal-site management including nearshore-berm movement by wave/mud interaction modeling, and (c) conceived evaluation methods for cohesive sediment fluidization and transport.

"Measurement of Entrainment and Transport (Noncohesive Sediments)" developed a plume measurement system (PLUMES) and an acoustic resuspension and measurement system (ARMS) for tracking suspended-sediment plumes in the open ocean arising from hopper-dredge or barge disposal and for determining resuspension from existing disposal mounds or potential disposal sites, respectively.

"Numerical Simulation Techniques for Evaluating Short-Term Fate and Stability of Dredged Material Disposed in Open Water" (a) addressed scaling laws for development of laboratory facilities and tests for physically modeling disposal in open water and (b) generated a short-term fate (STFATE) model for simulating water column effects and bottom deposition from open-water disposal.

"Numerical Simulation Techniques for Evaluating Long-Term Fate and Stability of Dredged Material Disposed in Open Water" (a) generated a long but realistic wave and current time series from existing databases, (b) developed a long-term fate (LTFATE) model for simulating resuspension and migration of material from open-water disposal sites, (c) formulated an advanced 3-D circulation (ADCIRC) model for generating long time periods of hydrodynamic circulation for very large computational domains, and (d) generated databases of tidal constituents and tropical storms for U.S. coastlines.

Both the short-term fate and the long-term fate research resulted in the development of the multiple dump fate (MDFATE) model, which combined features of both STFATE and LTFATE.

"Field Techniques and Data Analysis to Assess Open-Water Disposal" (a) developed instrumentation and techniques for long-term monitoring of nearshore berms and mounds placed as feeder beach-nourishment material in the littoral zone or as devices to attenuate wave energy and reduce shoreline erosion, (b) investigated how seabed drifter data might be better interpreted in terms of likely fate of materials moving with coastal currents, and (c) developed the EBERM model to determine whether nearshore berms will be active or stable.

1 Introduction

The U.S. Army Corps of Engineers is involved in virtually every navigation dredging operation performed in the United States. The Corps' navigation mission entails maintenance and improvement of about 40,000 km of navigable channels serving about 400 ports, including 130 of the nation's 150 largest cities. Dredging is a significant method for achieving the Corps' navigation mission. The Corps annually dredges an average of 230 million cu m of sedimentary material at an annual cost of about $400 million. The Corps also supports the U.S. Navy's maintenance and new-work dredging program (McNair 1989).

Background

Genesis of the Dredging Research Program

Significant changes occurred in the conduct of U.S. dredging operations and the coordination of such dredging with environmental protection agencies as a result of the National Environmental Policy Act of 1969. Subsequent Federal legislation authorized a study of the ability of private contractors to perform the nation's required navigation dredging activities. That study determined that, from national emergency considerations, only a minimum Federal dredge fleet was necessary, and the bulk of hopper-dredge activities shifted from the once large Corps fleet to private sector contract hopper dredges (Hales 1995).

A long period in which the Corps' dredging activities consisted almost totally of maintaining existing waterways and harbors changed with passage of the Water Resources Development Act of 1986. This legislation authorized major deepening and widening of existing navigation projects to accommodate modern Navy and merchant vessels. Future changes in dredging are not expected to be any less dramatic than those which occurred in recent years. The Corps will continue to be challenged in pursuing optimal means of performing its dredging activities. Implementation of an applied research and development program to meet demands of changing conditions related to Corps dredging activities and the generation of significant technology that will be adopted by all dredging interests are means of reducing the cost of dredging the nation's waterways and harbors.

Research program

The concept of the Dredging Research Program (DRP) emerged from leadership of Corps of Engineers Headquarters (Navigation and Dredging Division and Directorate of Research and Development (CERD)) in the mid-1980s (McNair 1988). It was realized early in the program development that research should be directed toward addressing documented deficiencies identified by the primary Corps users, namely the field operating Division and District offices. The problems identified by the field offices were formulated into specific applied research work tasks describing objectives, research methodologies, user products, and time/cost schedules. CERD delegated primary responsibility for developing the DRP to the U.S. Army Engineer Waterways Experiment Station (WES). The 7-year $35-million DRP, initiated in FY88, achieved all major milestones, goals, and objectives scheduled in the program-planning process.

A major DRP objective was the development of equipment, instrumentation, software, and operational monitoring and management procedures to reduce the cost of dredging the nation's waterways and harbors to a minimum consistent with Corps mission requirements and environmental responsibility. The DRP consisted of five technical areas from which many distinct products were generated and annual and one-time direct and indirect benefits are quantifiable. These technical areas are as follows:

a. *Technical Area 1.* Analysis of Dredged Materials Disposed in Open Water.

b. *Technical Area 2.* Material Properties Related to Navigation and Dredging.

c. *Technical Area 3.* Dredge Plant Equipment and Systems Processes.

d. *Technical Area 4.* Vessel Positioning, Survey Controls, and Dredge Monitoring Systems.

e. *Technical Area 5.* Management of Dredging Projects.

Technical Area 1

Objectives of Technical Area 1, "Analysis of Dredged Materials Disposed in Open Water," included (a) better understanding of the boundary-layer properties of both cohesive and noncohesive sediments so that their potential for resuspension and transport from an open-water disposal site could be better described mathematically and numerically, (b) development of instrumentation for monitoring and tracking suspended-sediment plumes resulting from hopper-dredge and barge disposal in open water and instrumentation for determining resuspension and movement of material from existing or potential open- water disposal sites, (c) formulation and verification of short- and long-term numerical simulation techniques for determining fate and ultimate disposition of material deposited in open water, (d) improved field techniques for collecting long-term data pertaining to movement of nearshore berms placed in the littoral zone to serve as either feeder material or wave-attenuation devices to reduce shoreline erosion, and (e) developed a numerical model to determine whether berms in the nearshore zone will be active or stable.

Report Organization

Chapter 2 of this report describes (a) refined techniques for evaluating the potential of sands for beach nourishment, (b) development of numerical models for determining the longshore current, (c) formulation of expressions for cross-shore movement of bars and berms, and (d) mathematical investigations of the physics of bottom boundary-layer flow, including movable-bed friction factors and sediment entrainment, for use by numerical simulation modeling to describe long-term fate and ultimate disposition of disposed sediments.

Chapter 3 describes (a) development of improved methods for assessing cohesive sediment erodibility, (b) formulation and verification of PC programs for Corps field use to assist in disposal-site management, including understanding nearshore-berm movement by wave/mud interaction modeling, and (c) evaluation methods for cohesive-sediment fluidization and transport.

Chapter 4 discusses the laboratory development and field calibration and verification of two procedures for measuring entrainment and suspended-sediment transport during and after dredged material disposal in open water: (a) PLUMES, used to obtain water-column concentrations of sediment plumes and provide a means of tracking plumes below the surface that are not otherwise visible and (b) ARMS, employed to provide a mechanism for obtaining accurate data regarding sediment resuspension and transport from the boundary layer of open-water disposal sites.

Chapter 5 describes (a) determination of the appropriate scaling laws to simulate prototype dredged material disposal behavior in a physical test facility for cohesive and noncohesive sediments, (b) recommendation of instruments and measurement techniques to monitor cloud descent, rates of material spreading, and suspended-sediment concentrations, (c) conduct of large-scale laboratory tests for disposal from a split-hull barge and a multiple-bin vessel (hopper dredge) to obtain verification data for numerical models for determining short-term fate of disposed materials, and (d) development of the numerical model STFATE for computing water-column concentrations and bottom deposition for open-water disposal of dredged materials.

Chapter 6 discusses (a) a viable approach for easily generating arbitrarily long but realistic wave and current time-series characteristics from existing databases, (b) the numerical model LTFATE for systematically estimating the long-term response of a cohesive or noncohesive dredged material disposal site to local environmental forcings of waves and currents, and (c) the development of the ADCIRC model for generating long time periods of hydrodynamic circulation for very large computational domains (i.e., the entire east coast of the United States) and generation of tidal-constituent databases for the Gulf of Mexico and western North Atlantic and eastern Pacific coasts of the United States and tropical storm databases for the Gulf of Mexico and east coast of the United States.

Chapter 7 discusses the multiple dump fate (MDFATE) numerical model, which combines features of STFATE and LTFATE to dynamically simulate the building and possible erosion of mounds created by multiple disposal operations.

Chapter 8 provides insight into required instrumentation and techniques for conducting long-term monitoring, data collection, and analysis procedures for determining evolution of nearshore berms and mounds placed in the littoral zone to (a) conserve sediments suitable for beach nourishment by allowing onshore movement from feeder deposits, and (b) serve as wave-attenuation devices to reduce wave energy reaching the shoreline and, ultimately, shoreline erosion. Seabed drifters were evaluated to determine how data from their utilization might be better interpreted in terms of the likely fate of materials moving with coastal waters. An empirical berm (EBERM) fate model was developed to determine siting for active or stable berms constructed in the nearshore zone.

Chapter 9 is a synopsis of a summary of technical reports pertaining to technology and analyses developed by research conducted by the DRP to better describe the physics of bottom boundary-layer movement of noncohesive and cohesive sediments and to develop instrumentation for monitoring and determining the short- and long-term fate of dredged material placed in open-water disposal sites or nearshore berms.

2 Calculation of Boundary-Layer Properties (Noncohesive Sediments)

Much of the difficulty in obtaining accurate estimates in simulating the movement of dredged material disposed in open water results from limited understanding of the water and sediment interaction at the bed. Improvement in quantification of the sediment/fluid interaction required intensive mathematical investigation into boundary-layer mechanics and verification with high-quality field data (obtained by other related DRP research) in order to supply DRP numerical-simulation modelers with more accurate algorithms.

The objectives of this research task were to (a) refine techniques for evaluating the potential of sands for beach nourishment, (b) develop numerical models to describe the longshore current, (c) formulate expressions for cross-shore movement of bars and berms, and (d) mathematically describe physics of the bottom boundary layer at disposal sites and develop accurate and efficient algorithms to calculate shear stress, movable-bed friction factors, and sediment entrainment and transport for use by other related DRP numerical-modeling components pertaining to dredged material movement by waves and currents.

Dredged material disposal-site management relies heavily on numerical simulation models of currents and sediment transport. Acceptability of these models depends on the accuracy of the physics-based fundamental relationships used in the calculations. Improved understanding of the physics of water and sediment motion reduces conservatism in site designation and management, and allows maximum site usage with minimal design and operating expenses.

Evaluation of the Potential of Sands for Beach Nourishment[1]

The rational design of beach-nourishment projects requires the ability to calculate the final configuration of the added sand volume. This capability is essential for quantitative evaluation of the relative merits of various borrow areas and in benefit/cost analysis of such projects. A new methodology was developed by Dean and Abramian (1993) for predicting the equilibrium beach profile resulting from placement of an arbitrary volume of material with an arbitrary grain-size distribution on a profile of arbitrary shape and arbitrary grain-size distribution. The methodology depends on the theory of equilibrium profile shape and is proposed as an alternative to traditional compatibility and overfill ratio factors for borrow and native material.

Other methodologies

Various available methods for relating the overall qualities of borrow and native sediments were reviewed by Dean and Abramian (1993). These methods generally focused on comparing grain-size characteristics rather than response to a wave and tide regime. Thus, the procedures must be considered ad hoc and the results not truly representative of a beach-nourishment material. Also, the methods cannot be used to determine additional dry-beach width, a factor necessary in benefit/cost analysis and for project design and planning operations. A new methodology and computer program were developed for predicting beach shapes relevant to beach nourishment using sediments of arbitrary sorting. The method is considered to be one step toward a rational procedure for assessing the complex performance of nourishment projects with realistic sediment characteristics.

Dean and Abramian methodology

The methodology developed by Dean and Abramian is based on an equilibrium profile for a sediment volume with a distribution of sediment sizes. The following assumptions/considerations are made:

a. A volume of sand V per unit beach length is placed at a slope steeper than equilibrium in conjunction with a beach-nourishment project.

b. The sand is well mixed at the time of placement.

c. The sand will be reworked such that the volume removed from the placement cross section is sufficient to extend the nourished equilibrium

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[1] This section of Chapter 2 was extracted from Dean and Abramian (1993).

profile out to a specified depth h_* of limiting motion (Figure 1) or to its intersection with the initial profile.

d. Within the zone of sediment removal from the placement cross section, sorting occurs down to a specified thickness Δh_{mix}.

e. The available sediment is sorted across the profile with a coarser fraction remaining in the berm and shallower water region and the finer sediment distributed offshore.

f. The volumes of sediment removed and deposited are equal (i.e., volume is conserved).

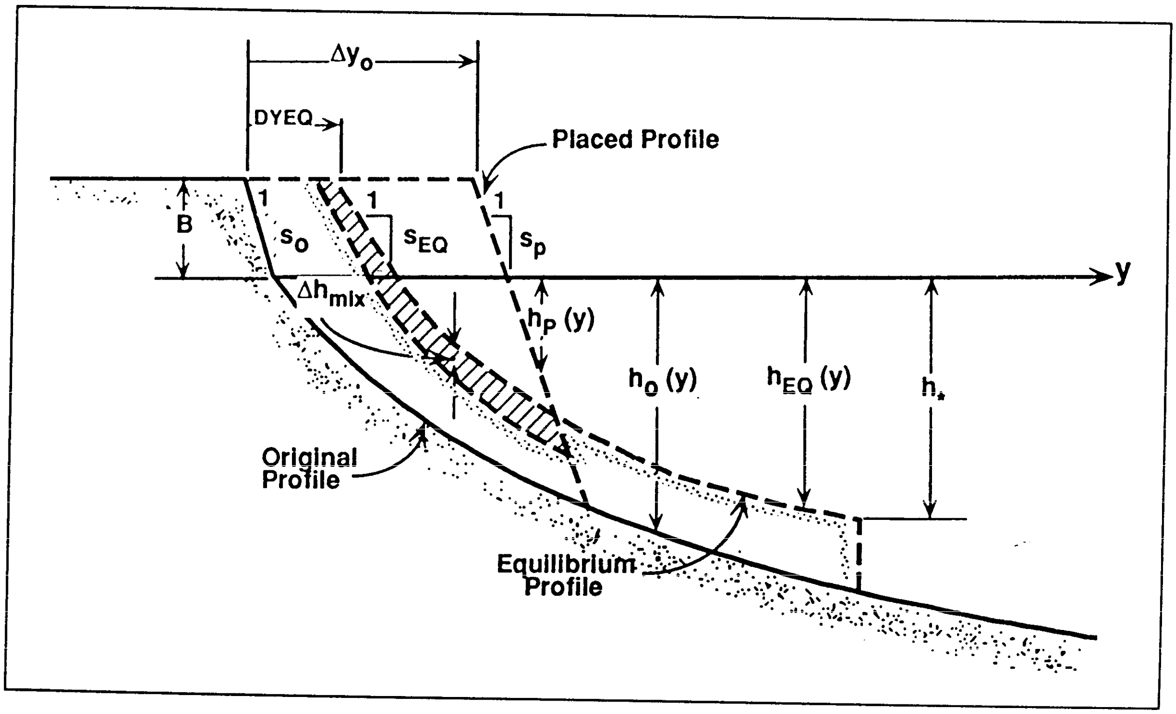

Figure 1. Definition sketch for equilibrium beach profile

With the above basis, the procedure can be considered as one of locally establishing segments of an equilibrium profile consistent with the local A-value of the equilibrium beach profile and of balancing sediment volumes. Because the equilibrium beach profile form $h = Ay^{2/3}$ yields an unrealistic infinite slope at $y = 0$, a modified form was used that recognizes the effect of gravity for the larger slopes:

$$y = (h/s) + \left(h^{3/2}/A^{3/2}\right) \tag{1}$$

as initially proposed by Dean (1983) and later shown by Larson and Kraus (1989) to be derivable from the breaking-wave model of Dally, Dean, and Dalrymple (1985) under the consideration of uniform wave-energy dissipation per unit volume. In Equation 1, s is the beach face slope, and in shallow water $h = sy$ (i.e., the beach is planar, consistent with measurements in nature). In deeper water, Equation 1 approximates $h = Ay^{2/3}$. Because the A value is now local, the depth at a location $y + dy$ is referenced to the depth at y based on Equation 1, and the dy values are maintained reasonably small, on the order of 1 to 2 m.

A step-by-step discussion of the procedure follows and is illustrated in the program flowchart, Figure 2.

a. With the specified initial profile $h_o(y)$, added volume V, berm height B, and placement slope s_p, the placed profile $h_p(y)$ is determined by iteration such that the volume out to the location where $h_p(y) = h_o(y)$ is the volume placed. This procedure also determines the berm placement Δy_o.

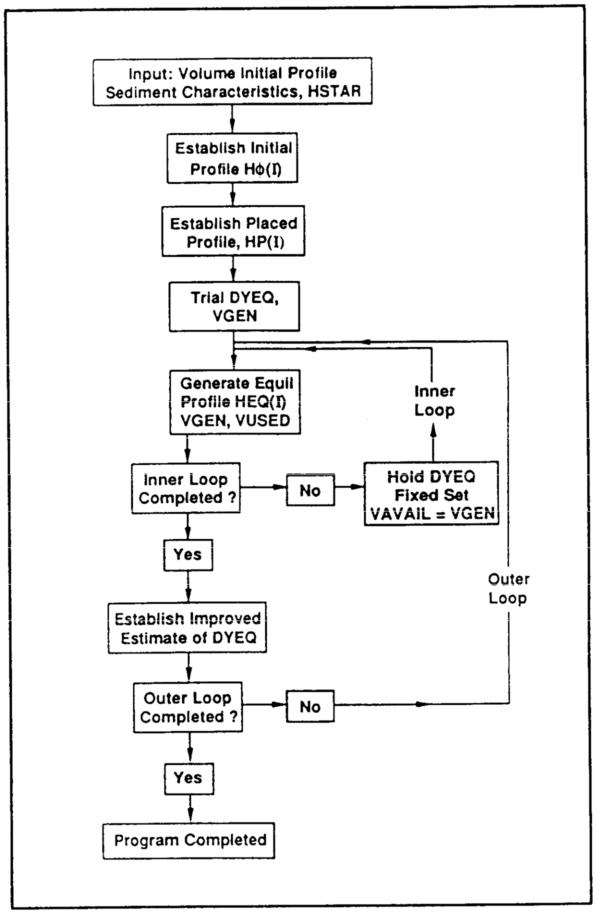

Figure 2. Flow diagram for equilibrium beach profile development

b. Trial values of the volume sorted V_{GEN} and equilibrium berm advancement $DYEQ$ are assumed (Figure 1). For each pair of these quantities, the equilibrium profile is advanced from y to $y + dy$, where dy is constant, say 1 to 2 m. The A value varies with sediment diameter (Dean 1977). The local A value is that associated with the diameter for the coarser fraction of the sediments that has not been deposited up to y in the equilibrium process (Figure 3). This step-by-step advancement is continued until the depth equals the specified terminal depth h_* or until the equilibrium profile intersects with the initial profile. At that stage, the volume actually generated through erosion of the placed profile is

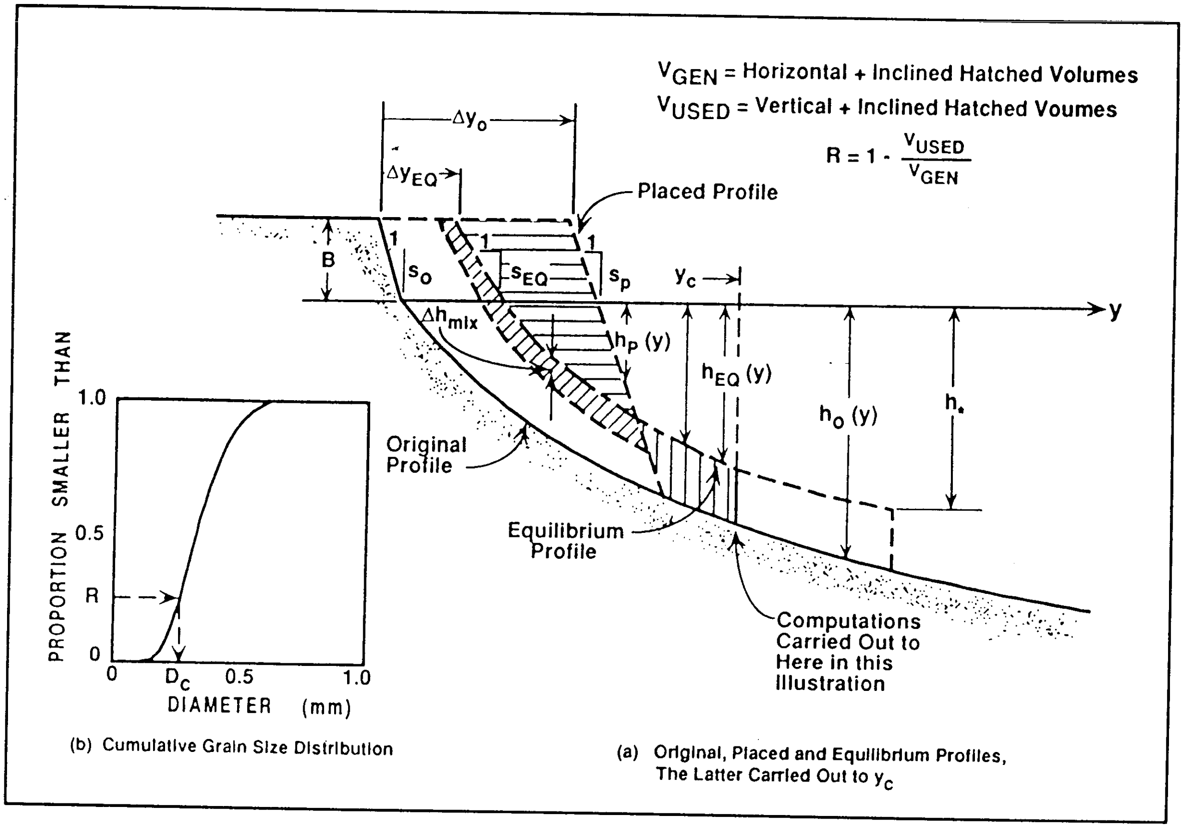

Figure 3. Determination of grain size D_c for computation of increment of equilibrium profile

substituted for the volume available, the equilibrium berm advancement *DYEQ* is held fixed in this inner loop, and the process repeated. This inner look (with *DYEQ* fixed) is repeated until V_{GEN} values in two successive iterations agree within an acceptable limit.

c. The value of *DYEQ* is changed to attempt to ensure that the associated value of $h = h_*$ or profile intersection will be achieved coincident with the deposition of V_{GEN} for that value of *DYEQ*. The *DYEQ* at the k + 1 iteration is based on the following simple algorithm:

$$(DYEQ)^{k+1} = (DYEQ)^k + F^{k+1}(\Delta DYEQ) \tag{2}$$

in which $\Delta DYEQ$ is specified as some reasonable value, say 2 to 5 m, and $F^1 = +1$, $F^2 = \pm 1$ for $k = 2$, and the positive and negative signs apply depending on whether $V_{GEN} > V_{USED}$ ($F^2 = +1$) or $V_{GEN} < V_{USED}$ ($F^2 = -1$). In subsequent iterations ($k > 2$), $F^{k+1} = F^k$ if the sign of $V_{GEN} - V_{USED}$ did not change in the preceding iteration and $F^{k+1} = -0.5\ F^k$ if a sign change did occur.

Numerical Model of the Longshore Current (NMLONG)[1]

A numerical model of the longshore current (NMLONG) was formulated and verified by Kraus and Larson (1991). The model incorporates all known features of the wave and longshore current system that appear in research-type engineering models run on mainframe computers: wave and wind driving, wave breaking and re-formation over multiple bar and trough profiles, and lateral mixing. Several time-saving algorithms were developed that enable NMLONG to run effectively on a personal computer (PC). Graphical output consists of the beach profile and the wave height and longshore current velocity along the profile (cross-shore). The main restriction of the model is longshore uniformity of the waves and beach topography.

In recent years, the concept of placing dredged material in the nearshore as shore-parallel longshore bars (i.e., underwater berms) has been advanced as a beneficial use of dredged material for shore protection. Such berms may act to break erosive storm waves and possibly serve as a source of beach nourishment. It is necessary to know the properties of the longshore current profile over these bar and trough features both to understand the nearshore hydrodynamic environment and to estimate the longshore sand transport and evolution of such bars.

Calculation of the longshore current as a function of distance across the shore requires knowledge of the driving wave characteristics at intervals inside and outside the surf zone. A strict limitation of both the wave and longshore current models presented by Kraus and Larson (1991) arises from the requirement of alongshore uniformity in forcing conditions. This limitation allows a one-dimensional (1-D) approach to be taken in which the wave (current) distribution along a single cross-shore transect is sufficient to describe the local wave (current) conditions.

Wave model

The Dally (1987) breaker-decay model was selected for use because of the extensive verification that had been made for a variety of wave conditions and bottom topographies. An appealing feature of the model is the demonstrated reliability of the values of its two empirical parameters. Thus, a satisfactory description of wave-height transformation across the surf zone using average parameter values was expected without additional calibration effort. The model is formulated in terms of wave-energy flux and is therefore quite general.

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1 This section of Chapter 2 was extracted from Kraus and Larson (1991).

For the 1-D case with straight and parallel bottom contours alongshore (but allowing the depth to be nonmonotonic with distance offshore, such as in the case of multiple bars and troughs), wave characteristics across the profile are determined by four fundamental equations:

a. Wave-energy flux equation.

b. Cross-shore momentum equation.

c. Wave number equation (Snell's Law).

d. Wave-dispersion relation.

The explicit finite-difference scheme used to numerically solve these governing equations determines wave height as a function of distance across the surf. The numerical calculation starts at the most seaward point on the grid and proceeds onshore, where quantities known at one grid point are used to determine corresponding quantities at the next grid point closer to shore. A Rayleigh distribution is used as the input wave-height distribution at the most seaward grid in water deep enough so that depth-limited breaking does not occur. At every calculation step, a check is made to determine if depth-limited wave breaking has occurred. Once breaking is initiated, wave-energy dissipation is allowed, and wave re-formation takes place. Wave propagation, breaking, and re-formation continue until the wave reaches shore.

Longshore current model

The numerical model of longshore current developed by Kraus and Larson (1991) calculates the longshore current across a barred profile under forcing by arbitrary combinations of waves arriving at an oblique angle to shore and a steady wind blowing over the sea surface at an arbitrary angle. The longshore components of the wave and wind forces generate a longshore current, and the shore-normal components change the mean water-surface elevation, resulting in setup and setdown. The governing equations are derived from the time-averaged and depth-integrated equations of motion.

Formulation of the bottom friction terms in the alongshore momentum equation was examined with various approximations to determine the accuracy of simplifications made to increase computational efficiency. Two mathematical descriptions of the bottom friction were presented, resulting in a linear and a nonlinear longshore current model. Representation of lateral mixing was also discussed, and an eddy-viscosity coefficient was proposed for calculating currents generated over a barred profile. Finally, the discretization procedure for the governing equations and the numerical solution scheme were described, leading to the computationally efficient double-sweep implicit technique for obtaining the longshore-current velocity.

The numerical model for the longshore current, NMLONG, was verified using three data sets: (a) wave-induced longshore currents, wave heights, and mean water levels from laboratory experiments by Visser (1982); (b) field data on the current from Kraus and Sasaki (1979); and (c) field data on waves and currents from Thornton and Guza (1983, 1986). Goodness of fit of the linear and nonlinear current model versions of NMLONG versus measured current are shown in Figure 4, as well as calculated and measured wave heights.

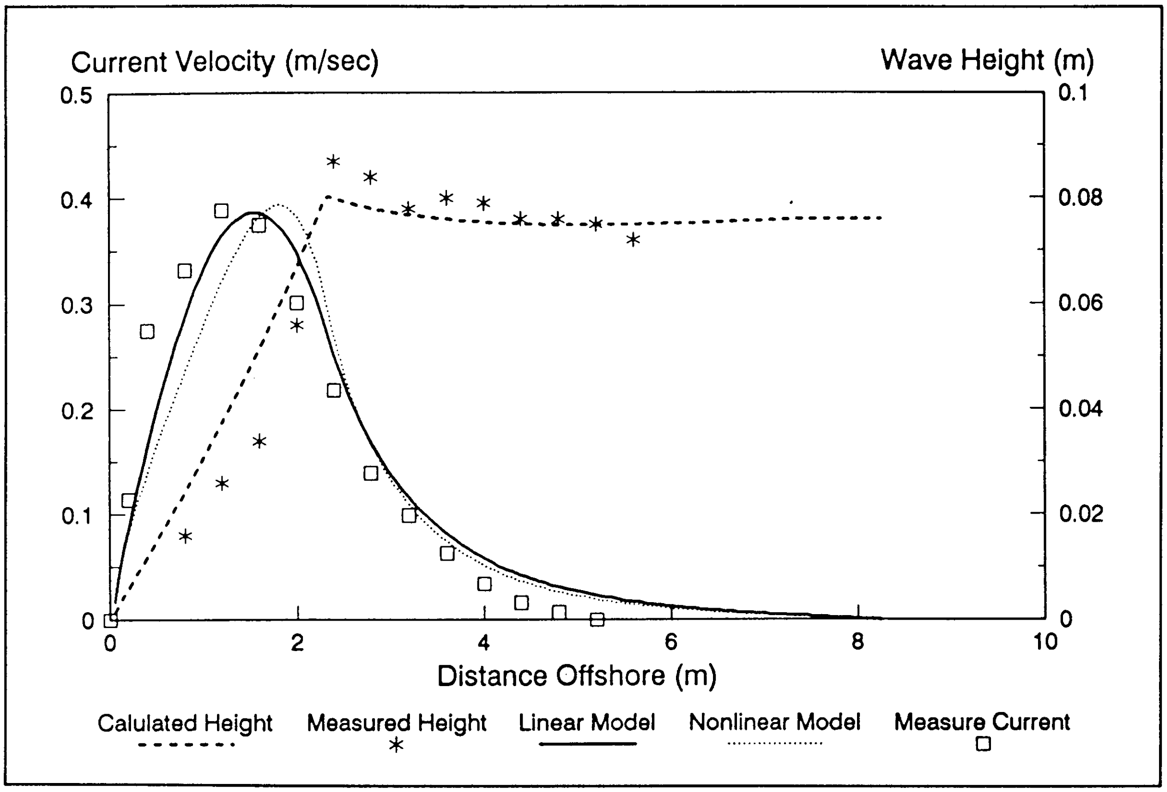

Figure 4. NMLONG longshore current and wave distributions across the surf zone

Cross-Shore Movement of Longshore Bars and Berms[1]

The main objective of Larson and Kraus (1992) was to develop rational criteria and a procedure for predicting the movement of material placed in the nearshore zone to perform as a feeder berm. Repetitive high-accuracy beach-profile surveys made north and south of a pier at the WES Field Research Facility (FRF) located at Duck, NC, were analyzed to determine the properties of natural longshore bars and their response to the wave climate. Profiles were

[1] This section of Chapter 2 was extracted from Larson and Kraus (1992).

surveyed along four shore-normal lines at approximately biweekly intervals from 1981 to 1989, and the associated waves were recorded with a time resolution of at least 6 hr. In total, between 200 and 300 measured profiles were available from the survey lines.

By determining the properties of natural longshore bars and how they interact with the prevailing wave climate, the reliability of predicting the behavior of artificial bars or nearshore berms created by placing dredged material in the nearshore should increase. Beach nourishment through nearshore placement of dredged material is a desirable technique, but present engineering methods are limited for predicting the response of such berms to nearshore waves and where the material will be transported by the waves.

Surveyed profiles at the FRF[1]

To investigate if the surveyed profiles at the FRF exhibited long-term trends, time variation of subaerial and subaqueous sand volumes above specific contours was evaluated. The movement of contours with time was calculated for the same purpose. The subaerial volume calculations showed a net long-term increase in the volume above national geodetic vertical datum (NGVD), particularly for the survey lines north of the FRF pier, indicating accretion of sand in the dune region. However, the subaqueous volume was approximately constant over the measurement period, although considerable short-term fluctuations were encountered. Calculated average profile shapes for the different survey lines were very similar, but the two survey lines south of the FRF pier had a profile somewhat closer to the FRF pier profile. Analysis of long-term variation in volume and contour location indicated that the beach at the FRF accreted slightly above National Geodetic Vertical Datum (NGVD), with little change below NGVD.

Because behavior of the profiles on the four survey lines was similar, and to decrease the great amount of effort involved in the analysis, only one line was used in the analysis of bar properties. The chosen line encompassed the largest number of individual surveys and displayed the closest response in bar evolution. To determine the bar properties, a reference profile was developed by fitting a modified equilibrium profile to the average profile, taking into account varying grain size across shore. The studied bar properties were:

a. Depth to bar crest.

b. Maximum bar height.

c. Bar volume.

d. Bar length.

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[1] This section of Chapter 2 was extracted from Larson and Kraus (1992).

e. Location of bar mass center.

f. Speed of bar movement.

Also, characteristic time scales of bar movement were established using the box-counting method (Larson and Kraus 1992).

Longshore bar analysis

For the nearshore profile at the FRF, two bars were typically present, one located 100 m from the mean shoreline (inner bar) and the other located about 300 m from the shoreline (outer bar). These two bar features were analyzed separately because they displayed different behavior with respect to time evolution and response to the waves. The inner bar was often exposed to breaking waves and thus large cross-shore sand transport, whereas the outer bar only experienced wave breaking during severe storms.

The average depth to crest for the inner bar was 1.6 m, the average maximum bar height was 0.9 m, and the average bar volume was 42 cu m/m. Comparison between inner bar properties from the surveys at the FRF and results from experiments carried out in large wave tanks indicated that behavior of the bar in the laboratory was similar to that in the field. Thus, data from large wave tanks should be of considerable value for investigating the fundamentals of cross-shore transport and bar movement. Average speed of inner bar movement was 1.5 m per day for onshore movement and 2.9 m per day for offshore movement, with maximum recorded speeds of 8.7 m per day and 18 m per day, respectively. Box-counting analysis showed that the typical maximum duration between wave conditions that moved the inner bar offshore was about 2 months.

Average depth to crest for the outer bar was 3.8 m, average maximum bar height was 0.4 m, and average bar volume was 45 cu m/m. Although the outer bar on the average had a volume similar to the inner bar, the maximum height was considerably lower, producing a much more gentle bar shape. The average speed of the outer bar movement was 0.6 m per day for onshore and 1.1 m per day for offshore movement, with maximum recorded speeds of 6.1 m per day and 15.2 m per day, respectively. Box-counting analysis showed that the typical maximum duration between wave conditions that moved the outer bar offshore was about 4 months.

Correlation analysis

Extensive correlation analysis of bar and wave properties was carried out to determine linear dependence among the properties and to establish predictive relationships for engineering applications. Mean wave properties were employed, and different nondimensional parameters such as wave steepness and dimensionless fall speed were formed to achieve greater generality in the obtained results. In most of the analysis, deepwater quantities were used, derived by shoaling waves to deep water from the measurement depth, neglecting refraction. The grand average of significant wave height at the FRF was 1.1 m, and the average peak spectral period was 8.4 sec at the gauge depth of 18 m.

Significant correlation was found between several of the geometric bar properties such as volume versus height, volume versus length, and depth to crest versus distance to mass center, both for the inner and outer bars. The correlation is a consequence of the fact that as a bar moves offshore, its size increases with a corresponding increase in volume, height, and length. To arrive at significant correlation between bar and wave properties, threshold values had to be employed to include only events with marked profile change. After this data screening, several correlations could be obtained.

The typical time interval of 10 days between surveys made it difficult to determine appropriate wave properties for use in the analysis. In the study by Larson and Kraus (1992), mean quantities were employed as the characteristic measure, although considerable variability in wave conditions occurred between profile surveys. Regression relationships were derived for some combinations of bar and wave properties, but the coefficient of determination was too low to be significant. Thus, results of the correlation and regression analysis were mostly of a qualitative nature.

Determining onshore and offshore bar movement

Several different criteria were derived to determine onshore and offshore movement of the inner and outer bars. To determine the direction of bar movement, and thus the net direction of sand transport across the bar, both change in bar volume and change in the location of the bar mass were employed. Furthermore, a threshold value was applied to include only events with a marked profile change. Criteria were expressed in terms of nondimensional parameters characterizing wave and profile properties, where the wave properties referred to deepwater conditions.

The following nondimensional-parameter combinations were evaluated with respect to separating onshore and offshore bar movement:

a. H_o/L_o versus H_o/wT

b. H_o/L_o versus H_o/D_{50}

c. H_o/wT versus $w(gH_o)^{1/2}$

where H_o is the deepwater wave height; L_o is the deepwater wavelength; w is the sediment fall velocity; T is the wave period; g is the acceleration due to gravity; and D_{50} is the sediment median grain size.

The dividing line that best separated points corresponding to onshore and offshore bar movement was subjectively drawn in the respective diagrams for the parameter-pair combinations, and empirical coefficient values were established. Similar relationships were obtained as previously derived for beach erosion and accretion predictors, but the empirical multiplier was different. The dividing lines were displaced towards erosion for the criteria describing onshore and offshore bar movement in comparison with the criteria for beach erosion and accretion. A typical example of parameter correlation is presented in Figure 5. Acceptable distinction between onshore and offshore bar movement can be obtained by the criterion:

$$H_o/L_o = 3.92 \times 10^{-5} (H_o/wT)^3 \tag{3}$$

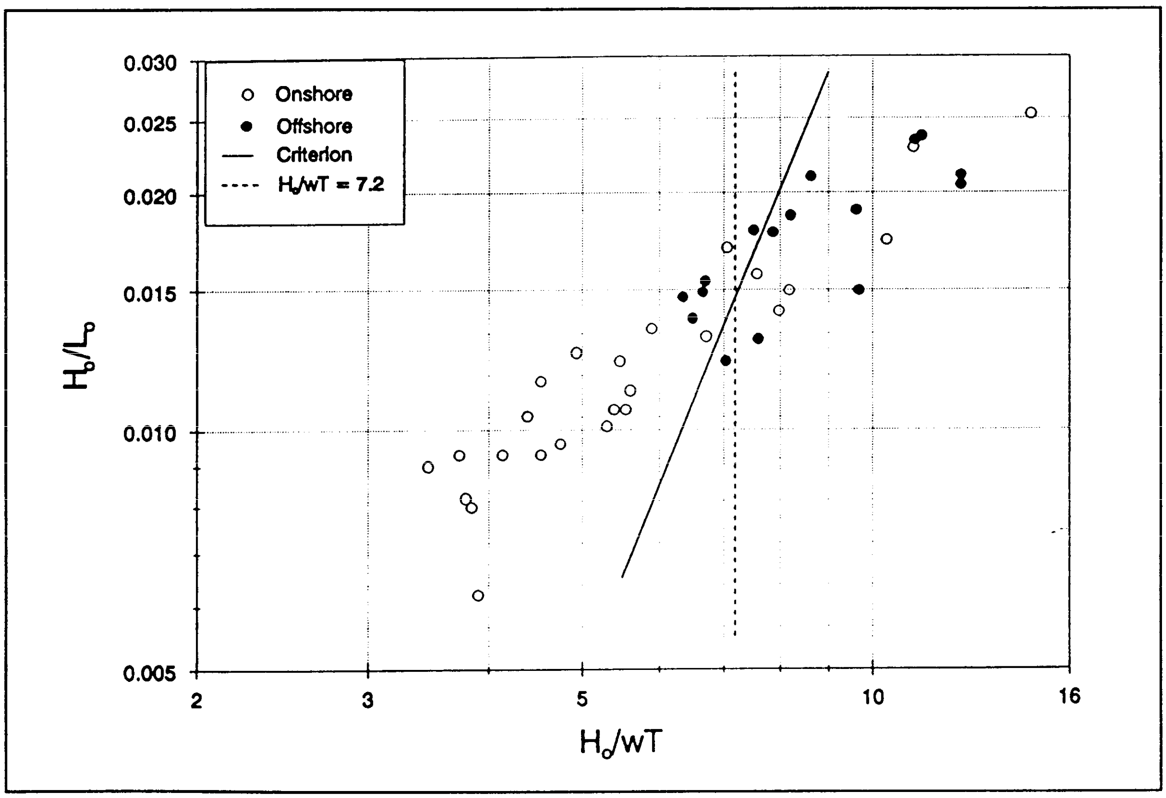

Figure 5. Prediction of cross-shore movement of longshore bar or nearshore berm

Prototype field application

The criteria developed by Larson and Kraus (1992) through analysis of natural longshore bars on an east coast beach were applied to predict the movement of a longshore bar-like feature or nearshore berm constructed of mainly littoral material dredged from the entrance to San Diego Harbor, CA, and placed in the littoral zone offshore from Silver Strand, CA. Bathymetric surveys of the berm made during a 5-month period when a wave gauge operated at the site indicated onshore movement of the berm, in agreement with unambiguous predictions of the criterion. Although not serving as conclusive validation, the agreement suggests that the criteria for predicting the direction of cross-shore movement of bars and placed berms based on readily available or estimated information in coastal studies may have generality for all coasts exposed to energetic waves (Kraus 1992).

Turbulent Wave/Current Bottom Boundary-Layer Flow[1]

A simple yet realistic model of the interaction between the turbulent wave and current boundary layers was developed by Madsen and Wikramanayake (1991). Closure of the turbulence problem by an assumed eddy-viscosity model was selected to permit analytic solution of the governing equations.

A review of previously proposed eddy-viscosity models revealed that many of them had not been tested against experimental data. Therefore, three of the more recent models were selected and compared with data from laboratory experiments and the results of a higher-order turbulence model. The comparison revealed that the model of Grant and Madsen (1986) was the most successful of the existing models. However, the physically unrealistic, discontinuous eddy viscosity used in that model resulted in a poor representation of the velocity at the top of the wave-boundary layer. This deficiency was removed by the development of an improved model with a continuous eddy viscosity, which resulted in a greatly improved fit to the data. While the new model had a more complicated solution, it used just one fitting parameter, as did all the existing models. However, the new model was unable to represent adequately the effect of a change in the angle between the waves and the current. This drawback was due to the assumption of a time-invariant eddy viscosity made in all the other models.

Therefore, a model that allowed the eddy viscosity to vary in time was developed by Madsen and Wikramanayake (1991). The assumption of a weak current relative to the waves was made to simplify the governing equation and an approximate solution obtained for the wave- and current-velocity profiles. While this model involves much more algebra than before, the solution for the wave problem was found to be very similar to that from the time-invariant model. The solution for the current problem, which involved numerical integration, was simplified by the development of an accurate analytic approximation.

1 This section of Chapter 2 was extracted from Madsen and Wikramanayake (1991).

Finally, the concepts of the modified wave-friction factor f_w and excursion amplitude A_{brms} were used to develop analytic approximations to the friction factor curves. Here A_{brms} is the bottom orbital horizontal excursion based on the representative wave that has a height equal to H_{rms} (the root-mean-square wave height) and a period equal to the average wave period. These simplifications allowed the development of a procedure whereby practical problems can be solved efficiently using no more powerful a tool than a hand calculator.

Movable-Bed Friction Factors[1]

When waves propagate from the deep ocean onto the continental shelf and shoreward, they will eventually begin to feel the effects of the bottom. Bottom friction arises due to the no-slip bottom boundary condition. This condition gives rise to a bottom shear stress and a thin boundary layer where significant energy dissipation can take place. This energy dissipation results in a decrease in the wave height. Therefore, to predict the wave height in coastal areas, it is necessary to quantify the bottom shear stress.

The objective of a study by Wikramanayake and Madsen (1994a) was to develop a simple physically realistic model to predict the friction factor over a movable sand bed under field conditions. Since reliable field measurements were available only for the ripple geometry, it was necessary to use laboratory data to formulate some aspects of the model.

After investigating various methods of measuring the friction factor, it was concluded that the only reliable method was through measurements of energy dissipation. Analysis of laboratory data showed that the friction factor f_w defined using the maximum shear stress was nearly equal to the energy-dissipation factor f_e for rippled sand beds. Therefore it was decided to assume that f_w and f_e were equal and to calculate f_w from energy-dissipation measurements.

It was found that the bed ripple geometry was well correlated by the parameter X, defined by:

$$X = \frac{4 \nu u_{brms}^2}{d((s-1)gd)^{3/2}} \tag{4}$$

[1] This section of Chapter 2 was extracted from Wikramanayake and Madsen (1994a).

where

ν = kinematic viscosity of water

u_{brms} = bottom velocity obtained from the representative wave that has a height equal to H_{rms} (the root-mean-square wave height) and period equal to the averaged wave period

d = bottom sediment grain diameter

s = specific gravity of sand grains

g = acceleration due to gravity

The rippled height is given by:

$$\frac{\eta}{A_{brms}} = \begin{cases} 0.27X^{-0.5} & X < 3 \\ 0.47X^{-1.0} & X > 3 \end{cases} \tag{5}$$

where

A_{brms} = bottom horizontal excursion of the orbital motion given by $A_{brms} = u_{brms}/\omega$

ω = radian frequency of the oscillatory motion. The equivalent roughness k_n is then found from:

$$k_n = 4\eta \tag{6}$$

The movable-bed wave-friction factors for fully rough turbulent flow are presented in Figure 6.

Sediment Transport by Combined Wave/Current Flow[1]

Sediment grains on the ocean bottom will move when the shear stress exerted on the bottom by the flow exceeds a critical value. The limited height of the wave boundary layer means that the shear stress due to a wave motion

[1] This section of Chapter 2 was extracted from Wikramanayake and Madsen (1994b).

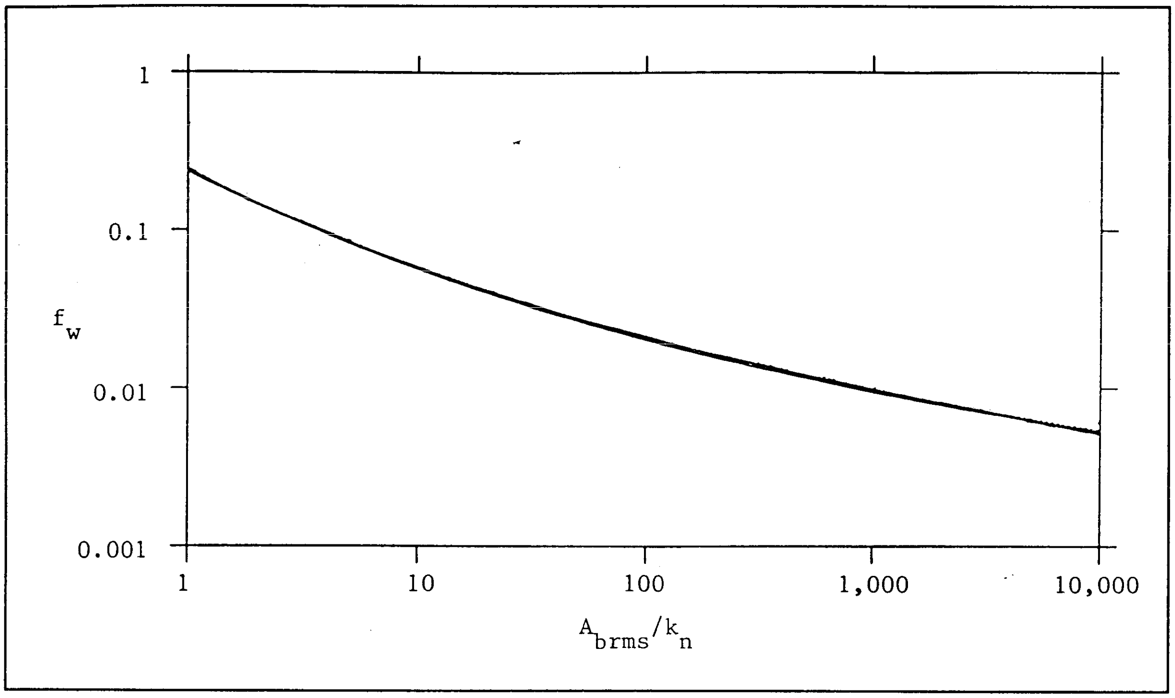

Figure 6. Movable-bed wave-friction factors for fully rough turbulent flow

is much greater than the shear stress due to a current of comparable magnitude. Therefore, the motion of sediment on the bottom in coastal regions is nearly always governed by the wave motion.

After the critical shear stress for initiation of motion is exceeded, sediment grains will be transported by the flow. Transport is usually divided into two modes: bed load and suspended load. Bed load is transport taking place near the bed where motion is primarily due to grains rolling and jumping along the bottom. Suspended-load transport takes place in the main body of the flow where grain-grain collision is negligible and the grains are carried in suspension by the fluid turbulence. Bed-load flux can be thought of as being a function of the bottom shear stress, while the suspended-load flux is a function of both the bottom shear stress (which controls the quantity of entrained sediment) and the fluid velocity. Shear stress and velocity are, in turn, a function of fluid forcing and bed forms.

The purpose of a study by Wikramanayake and Madsen (1994b) was to extend the turbulent eddy-viscosity models (an older time-invariant model and a newer enhanced time-variant model) developed by Madsen and Wikramanayake (1991), which dealt with purely hydrodynamic aspects of wave/current interaction, to the case of suspended sediment under wave and current flows. The objective was to formulate a theoretical framework for the problem that, together with recent field measurements of the instantaneous suspended-sediment concentration, could be used to develop a predictive model for sediment transport (bed load and suspended load) in the coastal zone.

Wave/current/sediment transport (WCSTRANS) model input

Results of the two eddy-viscosity models were compared with experimental data. It was concluded that the newer time-varying eddy-viscosity model brought out aspects of wave/current interaction not shown by the older time-invariant model. However, in the context of suspended-sediment transport computations, those effects are not very significant when compared to other possible uncertainties (specification of the wave and current conditions, bottom roughness, grain diameter, resuspension coefficient, etc.). The time-invariant model has the advantage of a relatively simple solution and validity over the full range of wave/current interaction. Therefore, it was decided to use the time-invariant eddy-viscosity model to calculate the fluid velocities and sediment concentrations needed to obtain suspended-sediment transport.

The wave/current/sediment model requires input values that describe the wave, current, sediment, and bed conditions. The computational logic and flowchart for the computer program WCSTRANS that carries out the model calculations is described in detail in Wikramanayake and Madsen (1994b). This program computes velocity, concentration, and flux profiles and bed-load and suspended-load transport. The model can be prescribed either as a single wave component or as two components in phase, one with twice the frequency of the other to simulate wave asymmetry. Use of the program is outlined in the report by two example calculations from prototype field data sets VG2046 and CC2. Input values for these examples are given in Table 1.

Table 1
Input for WCSTRANS Model Example Computer Runs VG2046 and CC2

Input Parameter	Unit	Symbol in Report	Variable in Program	Example Run	
				VG2046	CC2
Principal wave velocity	cm/sec	u_{b1}	UB1	34.7	62.9
Secondary wave velocity	cm/sec	u_{b2}	UB2	7.8	15.4
Frequency of principal component	rad/sec		FRE	1.08	1.15
Current specification flag			FLAGC	2	2
Current specification values			T1 T2	18.0 20.0	37.1 15.0
Angle between waves and current	deg		PHICWD	-70.6	96.1
Mean grain diameter	mm	d	DIAM	0.023	0.018
Sediment fall velocity	cm/sec	w_f	FALLV	2.25	0
Sediment specific gravity		s	S	0	0
Equivalent bottom roughness	cm	k_n	KN	0	0
Bottom slope	deg		SLOPED	0	0
Angle between bottom slope direction and wave direction	deg		PHISWD	0	0
Flow depth	cm	h	HEI	180.0	200.0

WCSTRANS output

Output from example computer run VG2046 is given in Table 2.

Table 2
Output from WCSTRANS Model Example Computer Run VG2046

Input Values	
Wave Specification	
First harmonic wave velocity	= 34.7 cm/s
Second harmonic wave velocity	= 7.8 cm/s
Wave frequency	= 1.080 rad/s
Current Specification	
Current specified by a given reference value	
Given current velocity	= 18.0 cm/s
At an elevation	= 20.0 cm
Counterclockwise angle between wave and current	= -70.6 deg
Sediment Specification	
Given mean grain diameter	= 0.023 mm
Given sediment fall velocity	= 2.25 cm/sec
Given sediment specific gravity	= 2.65
Nondimensional grain size (SSTAR)	= 3.508
Critical Shields parameter for initiation of motion	= 0.0465
Flow Specifications	
Flow depth	= 180.0 cm
Bottom slope	= 0.0 deg
Counterclockwise angle between wave direction and bottom slope	= 0.0 deg
Assumed water temperature	= 20.0 °C
Bottom Roughness Not Given	
Output Values	
Results of Wave/Current Model	
Current shear velocity	= 2.26 cm/sec
Wave shear velocity	= 6.70 cm/sec
Combined shear velocity	= 6.84 cm/sec
Value of parameter EP (= USC/USWC) (USC = current shear velocity; USWC = Combined wave/current shear velocity)	= 0.3301
Boundary/layer length scale	= 2.53 cm
Nondimensional z0	= 0.03601
Relative roughness for wave 1	= 11.74
	(Continued)

Table 2 (Concluded)	
Output Values (Continued)	
Results of Skin-Friction Model	
Current skin-friction shear velocity	= 0.88 cm/sec
Wave skin-friction shear velocity	= 2.85 cm/sec
Phase lead of wave skin-friction shear stress over the near-bottom velocity	= 0.260
Shields parameter based on wave skin-friction shear stress	= 0.21846
Value of nondimensional ripple parameter z	= 0.062267
Bottom Roughness Not Given	
Bottom is Rippled	
Ripple height	= 0.6840 cm
Ripple steepness	= 0.06667
Calculated bottom roughness	= 2.736 cm
Results of Reference Concentration Model	
Resuspension coefficient	= 0.00180
Mean reference concentration	= 0.00181
Ratio of reference concentration of principal component to mean	= 0.39645
Ratio of reference concentration of secondary component to mean	= 0.87781
Results of the Solution of Sediment Problem	
Nondimensional fall velocity	= 0.8225
Nondimensional reference level	= 0.06356
Results of Transport Calculations	
Bed-Load Transports	
In wave direction	= 0.008672 cm^3/cm/sec
In wave-normal direction	= 0.003650 cm^3/cm/sec
Suspended-Load Transports	
Transport Due to Mean Components	
In wave direction	= 0.002258 cm^3/cm/sec
In wave-normal direction	= -0.641200 cm^3/cm/sec
Transport Due to Periodic Components (in Wave Direction)	
Principal components	= 0.003175 cm^3/cm/sec
Secondary components	= 0.001197 cm^3/cm/sec
Total wave transport	= 0.004372 cm^3/cm/sec
Total suspended-load transport in wave direction	= 0.006630 cm^3/cm/sec

Transport calculations showed that the bed-load transport was larger than the suspended-load transport, though the two values are of the same order of magnitude. This result is contrary to some previous calculations that, however, were carried out for finer sediments than those observed in the prototype field experiments. The WCSTRANS model developed by Wikramanayake and Madsen (1994b) for both bed-load and suspended-load estimation provided good agreement with available data. The model was able to reproduce the shape of the wave-flux profiles estimated from the field data despite the use of a boundary condition that was not derived for the case of a rippled bed.

3 Calculation of Boundary-Layer Properties (Cohesive Sediments)[1]

Prediction of the movement of fine-grained sediment disposed in open water is extremely difficult. Hydraulic shear stresses must be properly evaluated to understand the mechanisms involved with resuspension and movement. Sediment erodibility is a complex, generally time-varying function of sediment composition and state. Mixtures of various size fractions can act either as a cohesive mass or as a loose winnowable material. Fine sediments can become fluidized by both currents and wave motion and lose mechanical and hydraulic shear resistance. Fluidized sediments can then be easily entrained by flows, either unidirectional (tidal or river) or reversing (waves), and the materials transported great distances. Entrainment, mass erosion, and surface erosion are erosion modes that must be better understood to make evaluations and predictions regarding movement of cohesive sediments from open-water dredged material disposal sites.

To establish and manage open-water disposal sites, assessment of the dispersion of disposed materials from the sites is required. Here dispersion alludes to the main effect of erosion and transport from the bed under the action of waves and currents. Erodibility of fine-grained sediments depends on a number of parameters. Erodibility and the correlations between erodibility and sediment parameters are both highly variable and difficult to predict.

Objectives of the DRP research included (a) development and verification of improved methods for assessing cohesive sediment erodibility, (b) development of PC programs for Corps field use to assist in disposal-site management, and (c) development and verification of methods for evaluating fluidization and transport of cohesive sediment.

[1] Sources used to compile Chapter 3 are cited within the text.

Erosion of Cohesive Dredged Material at Open-Water Disposal Sites

Cohesive sediments are a special class of fine-grained sediments that exhibit interparticle cohesion and are composed of particles less than about 0.015 mm in diameter. Erosion of cohesive sediment is defined by the various processes by which stationary particles become available for transport. Erosion is related to breakage of cohesive bonds and structural changes in the fine-grained sediments. Once mobilized, the fine particles are generally transported for long durations and distances due to their low settling velocities.

Cohesive-sediment structure

Erodibility of cohesive sediments is related to interparticle cohesion and, hence, to the physicochemical characteristics of the sediments and fluids involved. Cohesive sediments form electrochemical bonds that must be broken before erosion can take place. The ability to exchange positive salt ions, or cation exchange capacity (CEC), is a measure of the activity of the cohesive fraction of the sediment. CEC, usually expressed as milliequivalents (meq) per 100 gm of dry sediment or centimoles of negative charge per kilogram of dry sediment, depends on surface charge, density, and surface area per unit dry weight of clays and fine silts. A milliequivalent is one-thousandth of a gram-equivalent weight, or mole.

Clay content and mineral type are the principal factors affecting CEC. Organic matter also affects CEC and is normally removed before analysis. If organics are not removed, then the CEC reflects the total material. CEC provides a relative measure of the potential interparticle bond strength, depending on the ions actually available in the sediment or eroding fluid and on the presence of colloidal organics. Typical ranges of values of CEC are shown in Table 3 (Teeter 1990). In general, the greater the CEC, the more erosion-resistant the material.

Table 3
Typical CEC Ranges

Mineral Fraction	CEC, meq/100 gm
Kaolinite	1-15
Illite	10-40
Montmorillonite	50-150
Chlorite	10-40
Vermiculite	100-150
Organic fraction of solids	150-500

When clay and water (plus other organic/inorganic materials) are mixed together, they form a viscoelastic material having two ideal behaviors: elastic deformation and viscous-flow properties. Elastic deformation is reversible, while viscous flow is nonreversing, dissipative, and structure altering (energy loss, wave attenuation). A pure uniform clay suspension can form a near-ideal elastic gel with a continuous three-dimensional (3-D) interparticle-bond network supported by adsorbed water. Increased particle volume increases sediment viscosity by forcing pore fluid to move in concentrated regions between particles. A linear (Hookean) elastic material will strain in proportion to the imposed stress while a linear (Newtonian) fluid will strain at a rate proportional to the imposed stress.

Natural cohesive sediments have a combination of elastic and viscous behaviors. Unfortunately, they almost always exhibit non-Hookean and non-Newtonian behavior when subjected to a range of shear stresses representative of a dredged material open-water disposal site. Nonlinearity is an important aspect of mud behavior. Some clays have yield stresses or critical shear stresses for erosion below which no irreversible strain or erosion takes place. The concept of yield stress has therefore been used to describe cohesive-mud behavior in terms of a plastic model and has been related to a critical shear stress for erosion. Shearing breaks cohesive bonds, rearranges particles and aggregates, and alters microstructure. The material is weakened with respect to resisting imposed shear stress. This process is reversible, however, and once shearing stops, the material recovers with time.

Dredging and disposal effects on cohesive sediment

Dredging has a variety of effects on cohesive sediments. Hydraulic dredging can dilute muds with water and shear sediments, greatly decreasing strength relative to original in situ conditions. On the other hand, hopper-dredged material can maintain high densities, and flow in pipes can be quite laminar. Disruption under these conditions is partial, with some sediment structure remaining intact (clay balls and clumps). Likewise, mechanical dredging usually causes little dilution and only a moderate disruption to sediments.

During disposal, muds are diluted and sheared to various degrees. The depth of water at the disposal site, method of disposal, ambient currents, and characteristics of the disposed material affect dilution. Dilution during dredging is compounded during disposal. However, mechanically dredged or clumped material may be deposited at the disposal site in the same condition it left the dredging site. Thus, mud density can vary widely at a disposal site, and the disposal-site deposit is usually very nonuniform with respect to properties that affect erodibility. Grain-size mixtures and densities will cause erodibility to vary with vertical position in the deposit, and armoring becomes an important issue.

General dispersion processes

Cohesive muds are evidently most susceptible to erosion immediately after disposal, and erodibility decreases rapidly during the first few days after disposal. Thus, starting immediately after the disposal of material, a number of erosion processes can mobilize cohesive-sediment particles. Erosion processes involve shear-stress force applied to sediment by waves, currents, or the weight of sediment acting along a slope (Teeter 1992).

A fluid-mud layer lying at the bottom of a water body can be defined as having three regions in the vertical direction. Vertical layering above a dense layer suspension is shown in Figure 7 for low- and high-current conditions (Teeter 1994). The upper region of the water column is called the mixed layer and is assumed to be turbulent. The intermediate layer is called the stable layer, lutocline, or interfacial layer; its presence depends on the entrainment process. The intermediate layer may move with the flow and be at least partially turbulent. The lower layer of the fluid mud is called the dense layer. It is stationary or slowly moving as a laminar flow. Because of their relatively low settling velocities and cohesive properties, fine-grained sediments can remain in a fluid state and susceptible to entrainment for long periods. Surface waves can easily fluidize cohesive sediments, but suspended fine-grained cohesive particles aggregate so their transport characteristics do not necessarily depend on dispersed particle characteristics (Teeter 1993). When a low-density slurry is disposed, the material will accumulate in the disposal area if no slope is present and will level itself by flowing radially and forming a static mass with a horizontal surface. This material can be relatively easily entrained and redispersed by the overlying flow.

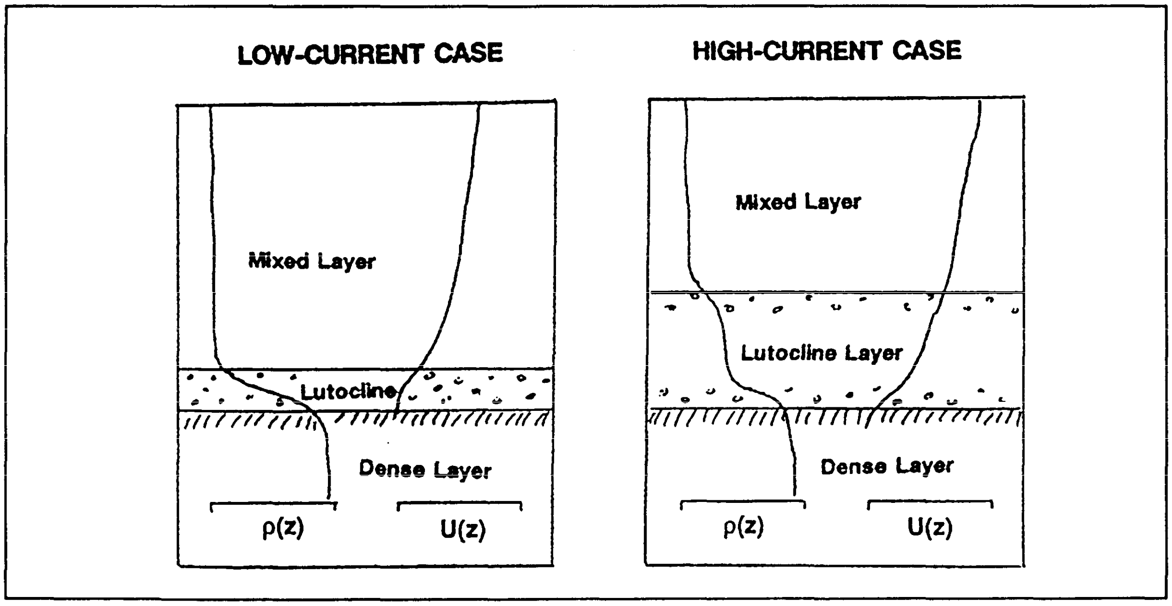

Figure 7. Vertical structure above a fluid-mud layer for low- and high-current conditions

Entrainment

The entrainment process is analogous to mixing between density layers, as shown in Figure 8 (Teeter 1992). Net entrainment through the lutocline will depend on conditions in both the mixed layer and the dense layer and thus will generally be time and space dependent. Net entrainment across the fluid-mud dense layer interface is the difference between the upward turbulent and downward settling vertical flux components. The turbulent component is initiated by motions generated by the mixed-layer flow that penetrate the lutocline layer and is the flux rate at which sediment is mixed upward from the dense layer (Teeter 1994). DRP field monitoring of a pipeline disposal (Thevenot et al. 1992) suggested that the viscous characteristics of dredged material greatly inhibit entrainment over that estimated based on density effects alone. (The effect of dense layer thickness was tested in the laboratory and found to have little effect on entrainment rate (Teeter 1994)).

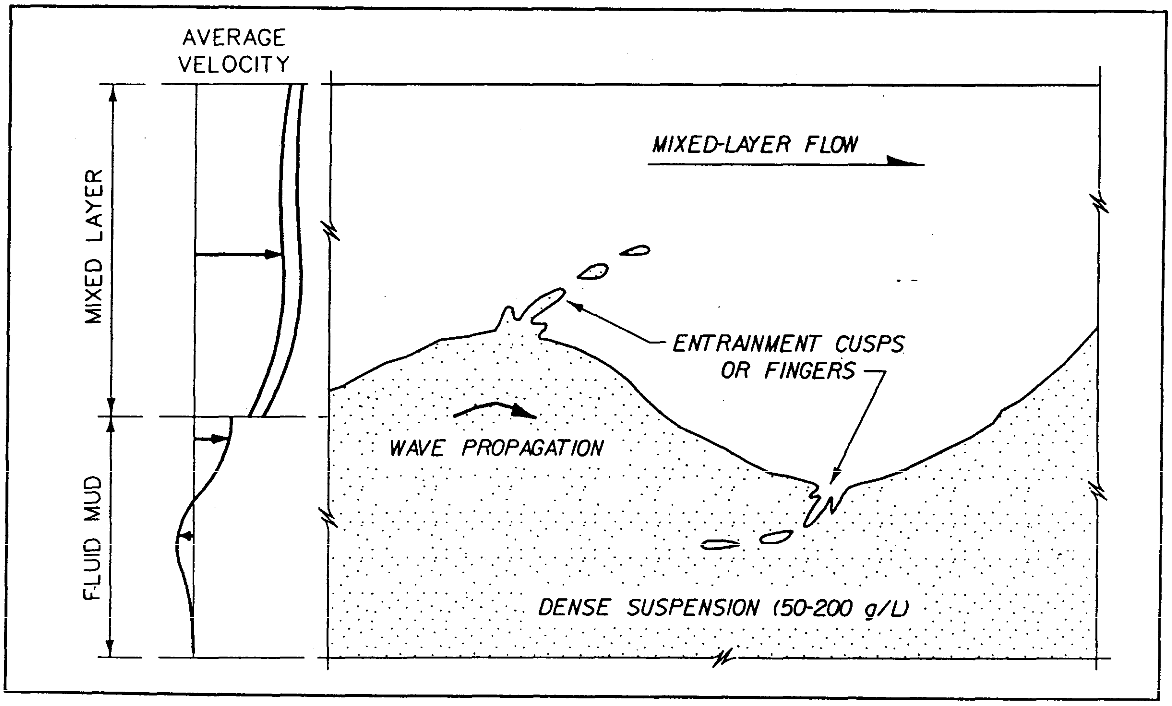

Figure 8. Entrainment of fluid mud into a mixed layer by internal instabilities generated by unidirectional flow

Soft cohesive muds can easily be fluidized by waves. Wave motion is transmitted to the mud according to its stress-strain properties. The mud deforms and endures pressure fluctuations. The water waves, especially short-period waves, are damped by viscous dissipation in the mud. A fluidized layer develops at the mud surface (Figure 9) and deepens with duration of wave exposure (Teeter 1992). The density of the fluidized layer does not necessarily change, but pore pressure becomes equal to the total vertical stress, particles

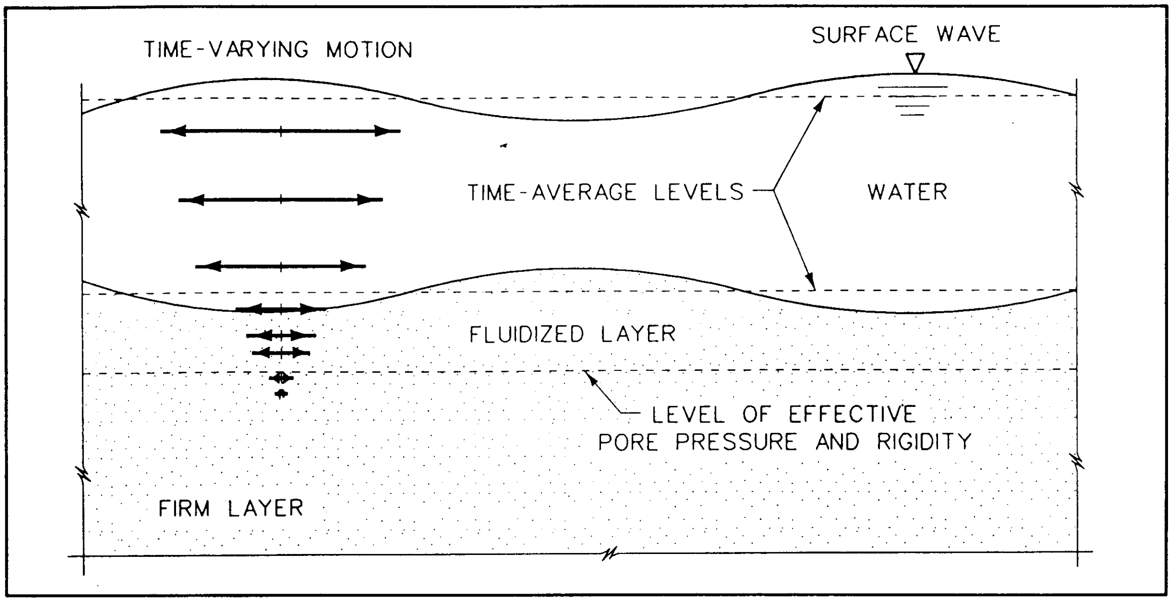

Figure 9. Mud layer fluidized by surface gravity waves

become fluid-supported, and rigidity decreases drastically. The fluidized mud is much more susceptible to mobilization via entrainment, mass-erosion and surface-erosion mechanisms. This time-dependent behavior reverses when wave action ceases and the strength of the mud returns.

Mass erosion. Thick layers of partially consolidated sediments can suddenly mobilize by a mass-erosion mechanism. Mass erosion occurs when a layer within the sediment bed fails. This can occur if large hydraulic shear stresses are applied to the surface, the layer has fluidized, or the layer builds on a slope as a result of successive disposal operations. This latter situation is equivalent to a submarine slope failure, where the weight of the material increases shear stress within the layer to a point where the material fails or reverts to a much lower viscosity. A sheet slide is thus formed: the mud breaks through a vertical section on the upslope end, a slip layer forms at a uniform depth in the mud, and the mud slides downslope. The layer thicknesses where this occurs within man-made reservoirs and on the ocean continental slope are in the 1- to 10-m range. These failures have been observed on slopes ranging from 1 to 8 deg and may occur depending on the sediment density and critical stress. When such failures occur, much material moves, and a turbidity current can be triggered.

Surface erosion. Surface erosion occurs at the surface of a well-settled cohesive bed. Particles or small aggregate groups are removed from the sediment surface individually during surface erosion. This is the most widely studied mode of erosion and is driven by hydraulic shear stress generated by the overlying flow. Surface erosion is probably the predominant mode of erosion in nature and occurs at low-to-moderate shear stress. Descriptors for the process of surface erosion are physics-based but have a large empirical content.

A large number of sediment characteristics affect mud erodibility. The expense and time required for laboratory experiments have limited the availability of data sets with which to construct functional relationships between sediment characteristics and erosion-process parameters. In addition, much of the available data is either poorly documented with respect to sediment characteristics that affect erodibility or was collected under conditions that were not representative of erosion at a disposal site, thereby limiting its usefulness. For example, Lee and Mehta (1994) analyzed 152 pairs of measured erosion rates versus constant-bed shear strengths gleaned from the literature and obtained from various types of laboratory flumes. Data were limited to cases exhibiting a linear relationship linking the rate of erosion to the bed shear strength. The nomograph developed from these data is applicable only for placed beds/undisturbed beds/remolded beds that have a uniform shear strength with depth (Lee and Mehta 1994).

If a laboratory cohesive bed with unidirectional flow does not erode uniformly over its surface, secondary flows evolve that can attack the bed locally, and misleading erosion test data may be produced. Yet often the sediment bed condition is not observable during testing. Test repeatability appears, from the data available, to be no better than $\pm$15 percent. Still, erosion test data are the major source of erosion information.

Temperature has been shown to strongly affect mud erosion. The viscosity of some muds has about the same temperature dependence as erosion, but few measurements are available for correlations. The viscous effect is dependent on Brownian motion that randomizes mud structure and increases inter-particle repulsion. Temperature dependence is greatest for fine clay-sized particles.

Conclusions

Open-water dredged material disposal-site erosion depends strongly on bed shear stress, while shear stress is related to velocity profiles existing above the bed. For first-approximation estimates of material movement, Berger et al. (1993) developed a simple model to calculate velocity profiles over changing bed slopes to infer shear stress. Much more complicated conditions can be encountered in estuarine areas with tidally reversing flows, density stratification, suspended-sediment contributions, and combined current and wave effects. Approaches to calculating boundary layers under estuarine conditions have been advanced by McAnally and Hayter (1992). These avenues include modified steady-flow equations, variable eddy-viscosity and mixing-length equations, and turbulence-transport equations. Interim recommendations by McAnally and Hayter (1992) for calculation methods are based on the specific situation and location under evaluation.

Because cohesive-sediment behavior depends on such a large number of sediment and flow properties and also is time dependent, adjustment of erosion-process models is a difficult task, and results are unreliable without site-specific field and characterization data. Fortunately, the variation of cohesive-sediment conditions is not so wide in the coastal area. For a given coastal sediment composition, conditions having the greatest effect on mud erodibility at a disposal site are most likely to be sediment density or related parameters, clay content, and temperature.

Water Wave Attenuation by Underwater Mudbanks and Mud Berms

A key feature of the interactive process between progressive water waves and a compliant mud bottom in the shallow coastal environment is the ability of waves to fluidize bottom mud and sustain it in that state as long as wave action continues. Compliant or fluid mud is a highly viscous medium that can oscillate as waves pass over and cause wave heights to attenuate significantly. The wave/mud interaction problem involving the prediction of surface wave attenuation, bottom mud motion, and interfacial entrainment or erosion was treated by Mehta, Lee, and Li (1994) as one concerned primarily with vertical exchanges of momentum and sediment mass. A dichotomy inherent in such a treatment arises from the need to assume mud to be a continuum when simulating wave attenuation and mud motion, while considering the vertical transport of sediment in the water column to be a two-phased problem amenable to classical approaches in sediment transport.

Naturally occurring underwater mudbanks are known to absorb water wave energy on the order of 30 percent to as much as 90 percent, even in the absence of any measurable wave breaking. In recent years engineering interest has grown in the beneficial use of fine-grained material dredged from navigation channels to create offshore underwater berms that can absorb wave energy and thus act as buffers against wave attack in areas in the lee of the berms. To that end, applications of wave/mud interaction modeling have been carried out by Mehta, Lee, and Li (1994) to simulate the degree of wave damping that will occur for a berm of given dimensions and mud rheology. This type of modeling can be used for developing guidelines for designing wave-energy-absorbing berms for future applications.

Physical setting and processes

The physical setting relative to a mudbank or underwater berm is conceptually shown in Figure 10. Seawater having density and dynamic viscosity surrounds the mud berm that is in general a viscoelastic material having density and possessing both an elastic component characterized by the shear modulus and viscosity. Most muds are pseudoplastics in terms of the relation

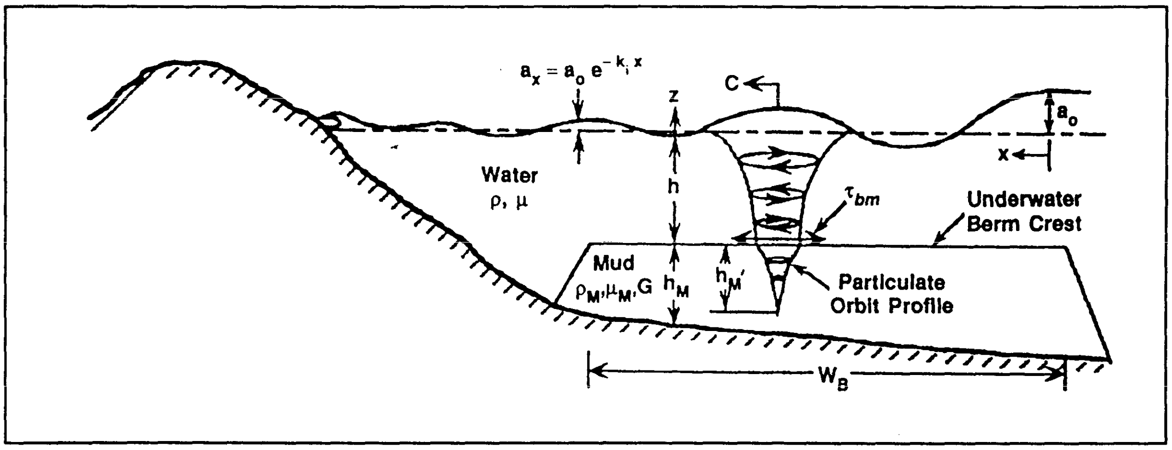

Figure 10. Schematic of wave propagating over an underwater mud berm

between the shear stress and the rate of strain, so they exhibit creep even at very low applied stress.

When subjected to wave action, bottom muds respond by oscillating at the forcing wave frequency. As a result of high viscosity, the oscillations attenuate much more rapidly with depth within mud than in the water column above. A high rate of energy dissipation within the mud causes the surface wave height to decrease rapidly with onshore distance. Given the surface amplitude at the seaward edge of a berm crest, the amplitude at any other location over the berm depends on the wave-attenuation coefficient k_i. If the bottom were rigid, k_i would be on the order of 10^{-5} per m, whereas for mud, values as high as 10^{-4} to 10^{-3} per m are common. The effect is much reduced wave activity in the area leeward of a mud berm compared with areas where the bottom is composed of sand.

Mud oscillation primarily occurs as a result of wave-induced pressure work within the body of the material, while the effect of shear stress is more important at the mud surface where it can cause particulate resuspension. Thus, under continued wave action, the long-term equilibrium water depth above the crest is that depth at which the wave-induced hydraulic shear stress amplitude is equal to the erosion shear strength of the mud. Until the berm erodes to equilibrium conditions, resuspension and transport will continue.

However, the stability of the berm crest is not ensured solely through this criterion for erosion since, due to open particle orbits (Figure 11) arising from nonlinear wave effects, the residual velocity u_L (Stokes' drift) can cause the mud mass to be transported landward. The impetus for this motion is the net wave-induced thrust that occurs in the mud due to rapid wave attenuation with onshore distance. Thus, hypothetically starting at a time with a mud/water interfacial profile that can be shown to be near-exponential in form (Jiang 1993), the depth-averaged value of u_L will become nil everywhere at some later time when an equilibrium interfacial profile is established. Such a condition will result from a balance between the wave-induced thrust and the

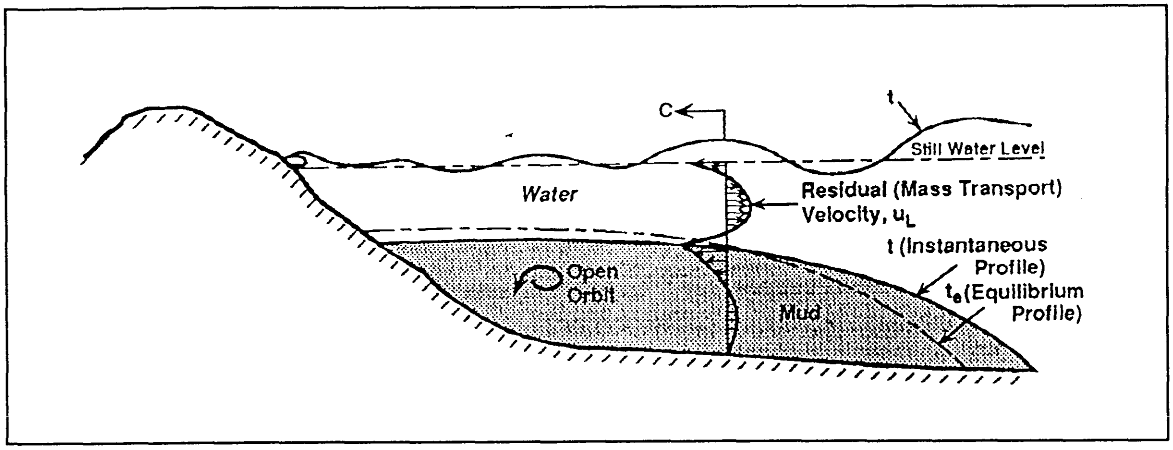

Figure 11. Shoreward migration of mudbank due to Stokes' drift

adverse hydrostatic gradient in the presence of a sloping bottom. This phenomenon can contribute to the migration of nearshore berms toward the coastline.

Nearshore berm effects, Mobile, AL

The sediment-placement site for the Mobile, AL, underwater berm off Dauphin Island was established as a national berm demonstration project (NBDP) to highlight the beneficial role (wave-height reduction) of dredged material nearshore placement. Material was dredged from the ship channel within Mobile Bay. Examples of offshore and inshore wave spectra are given in Figure 12 under two different offshore wave conditions: H_{max} = 0.9 m and H_{max} = 1.5 m. Wave-energy reductions were significant; 29 and 46 percent, respectively.

Using a fixed-bed hydrodynamic model, McLellan, Pope, and Burke (1990) showed that assuming a rigid (i.e., fixed-bed) berm crest produced negligible wave-energy dissipation. It is believed by Mehta, Lee, and Li (1994) that as a result of the shallow depth of water, on the order of 6.5 m over the berm, the main cause of damping is energy absorption by the deposited mound. Diver observations at the site suggested the occurrence of surface wave-forced interfacial mud waves propagating along the compliant crest. Such a movement can be construed as a manifestation of the participation of the bottom material in the energy-dissipation process. Furthermore, the rapid high degree of stability of the berm against displacement and deterioration pointed to the fact that wave action became sufficiently weak over the berm to prevent significant scour of the berm (Hands et al. 1992).

A wave/mud interaction model of Jiang (1993) was used by Mehta, Lee, and Li (1994) to simulate the inshore wave spectra at the Mobile berm site. These results are shown on Figure 12. The computations were done on a

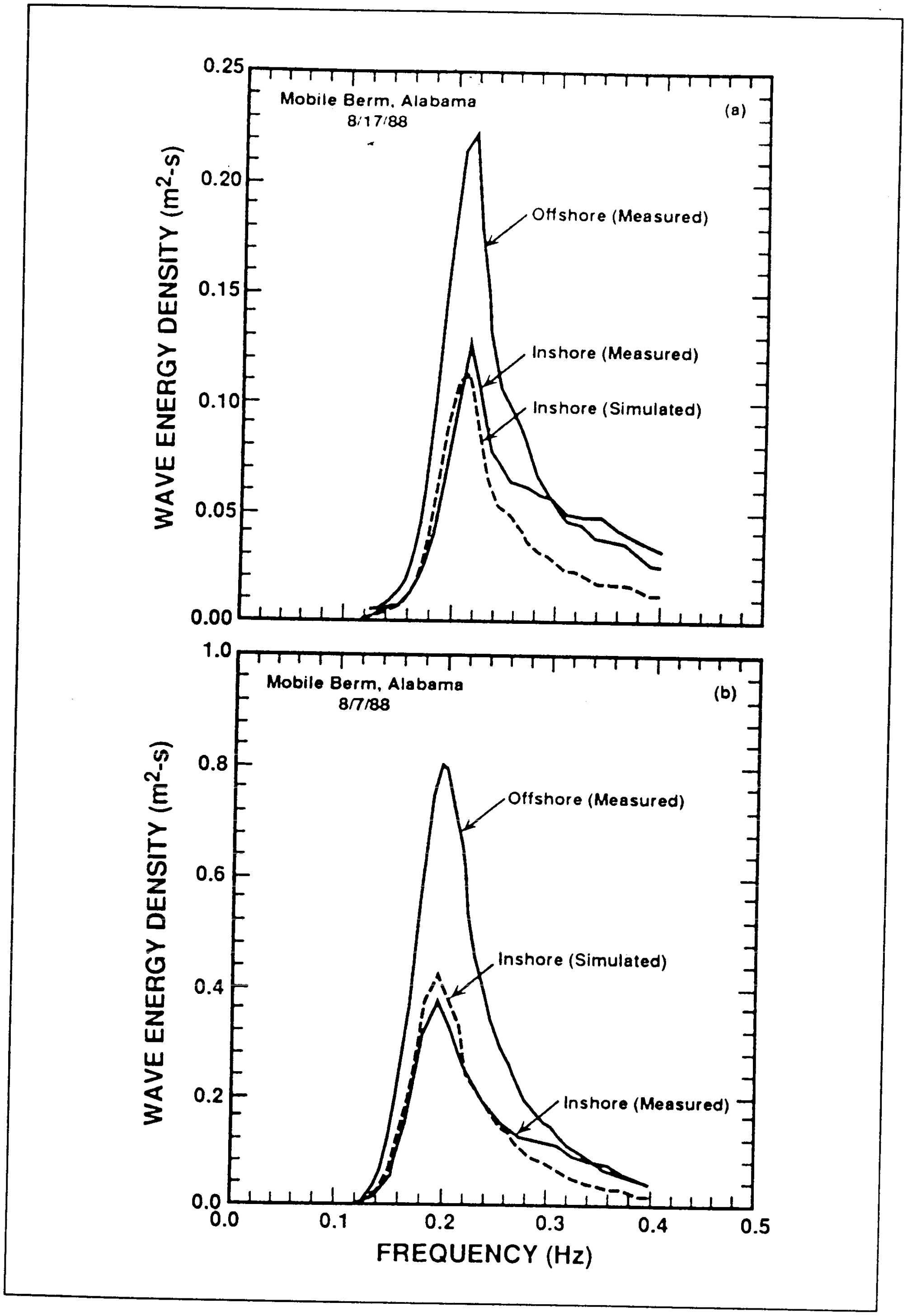

Figure 12. Comparison between measured and model-simulated inshore wave spectra at Mobile nearshore berm site for two offshore wave conditions: (a) H_{max} = 0.9 m and (b) H_{max} = 1.5 m

frequency-by-frequency basis. A 6-m berm height and the 6.5-m water depth were selected as representative vertical dimensions. In general, the effective berm width for calculating the degree of wave attenuation would depend on the direction of wave approach; for the purpose of the study by Mehta, Lee, and Li (1994), a width of 140 m was selected, giving some allowance for the berm slopes. Thus, dissipation was assumed to occur over this distance only.

Comparisons between simulated and measured inshore spectra also are given in Figure 12. The simulated spectral energy is observed to be generally in agreement with the measurement at low frequencies but is consistently lower than measured for frequencies exceeding about 0.25 Hz (i.e., periods smaller than 4 sec). In that context it must be noted that, as a rule, the output spectrum from the model will have the same general shape as the offshore one, which also is the case here.

Note that for frequencies greater than about 0.30 Hz the measured inshore wave energy was actually slightly higher than that at the offshore location. This feature suggests that the source of the high-frequency inshore waves may have been at least partly different from that represented by the measured offshore spectrum, possibly from short-period waves (sea) generated on the landward side of the berm and propagating oceanward. Diagnostics such as this provide a basis for developing design guidelines for wave-absorbing berms in future applications.

4 Measurement of Entrainment and Transport (Noncohesive Sediments)[1]

At the start of the DRP, the Corps had no capability to make direct measurements of sediment movement on the seafloor or lake beds or in the water column except by water bottle samplers at specific points in time and space. There were no accurate or complete field data sets for verifying algorithms used in sediment-transport simulation models. Instruments had to be developed and data collected to understand both short-term and long-term movement of dredged material disposed in open waters.

A plume measurement system (PLUMES) was developed to obtain information on water-column concentrations of sediment plumes and to provide a means of tracking suspended-sediment plumes below the surface that are not otherwise visible. The development of an acoustic resuspension measurement system (ARMS) was also begun to provide a mechanism for obtaining accurate data regarding sediment resuspension and transport from disposal mounds or potential disposal sites. Each of these systems was fully developed, laboratory calibrated, and tested in prototype field disposal operations during the DRP.

Plume Measurement System

Suspended-sediment clouds or plumes develop in open water both at the site of dredging operations and at dredged material placement areas. Such dredging activities and plume generation take place in estuaries, rivers, lakes, and oceans. Environmental concerns often require an assessment by direct monitoring, numerical modeling, or both, of the extent, movement, and longevity of suspended-sediment plumes. Typical environmental issues concern whether suspended sediments leave the placement site, where the material goes, and how much material remains in the water column after a certain time. Such issues pertain to shallow or deep water and to high- or low-velocity fields. Temporal and spatial distribution of turbidity from plumes and the

[1] Sources used to compile Chapter 4 are cited within the text.

ultimate fate of the suspended sediment in the plumes must be ascertained. PLUMES was developed to provide direct quantitative information on these issues (Kraus and Thevenot 1992).

Background

PLUMES uses acoustic backscatter instruments to provide near-synoptic data on the 3-D spatial distribution of suspended sediments. Advantages of acoustic systems are: (a) they are remote sensing and thereby noninterfering, (b) they have long ranges (10 to 100 m), and (c) they are suitable for mounting on surface vessels.

An early version of PLUMES was field tested from 18 August to 2 September 1989 during a Mobile, AL, field data collection program (Kraus 1991) and later from 27 September to 4 October 1991 by monitoring the plume around a dredging operation at Tylers Beach, VA (Thevenot, Prickett, and Kraus 1992). The primary acoustic system at Mobile consisted of a four-beam, narrow-band (1.2-MHz transducers) acoustic doppler current profiler (ADCP) for measuring current velocities and a separate 20- to 200-kHz transducer acoustic concentration profiler (ACP) for measuring acoustic backscatter intensity profiles within the water-column plume. The primary acoustic system at Tylers Beach was a four-beam (2.4-MHz transducers) broad-band ADCP (BBADCP) for measuring current velocities and a separate single-beam narrow-band 600-kHz transducer for measuring backscatter intensity. Subsequently, the DRP supported development of a five-beam (600-kHz transducers) BBADCP by RD Instruments (RDI), San Diego, CA. A commercial system is now available from RDI with PLUMES capabilities (Tubman 1994a). The five-beam BBADCP was used in September 1993 to monitor disposal operations in deep water at a disposal site 80 km offshore of San Francisco, CA. Here, profiles of suspended-sediment plumes were made to a maximum depth of 800 m from a towed vessel.

PLUMES system description

The PLUMES BBADCP system has five transducers on a single head. Data from the four transducers on the outside are used to calculate horizontal and vertical current velocities. The center transducer points straight down and measures acoustic backscatter intensity. Data from these measurements can be used to theoretically calculate suspended-sediment concentrations. The system can be mounted on the side of a survey boat or towed at depth in a towed body.

Figure 13 illustrates PLUMES in operation. The four main functional components of the overall system are:

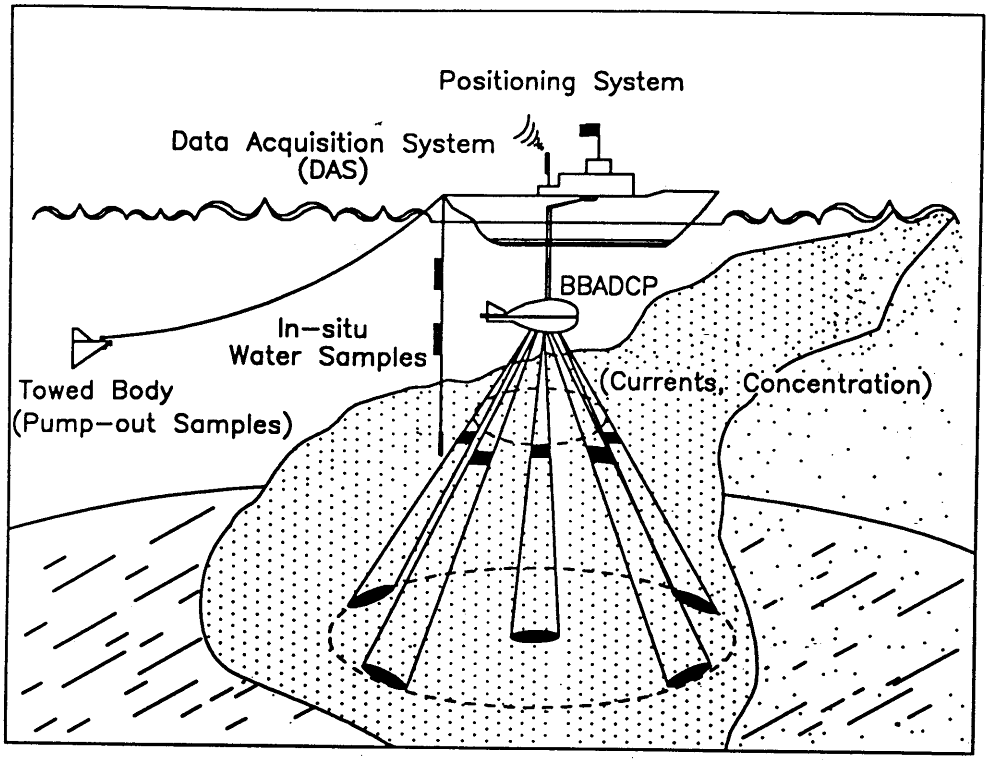

Figure 13. Plume measurement system

a. A five-beam broad-band acoustic doppler current profiler (BBADCP).

b. In situ samplers.

c. Positioning system.

d. Data-acquisition system (hardware and software).

BBADCP. The heart of the PLUMES system is the BBADCP. This is a multiple-beam doppler sonar system that can measure vertical profiles of 3-axis velocities and acoustic-backscatter intensity by transmitting short acoustic pulses and processing the backscattered acoustic signal from small particles in the water. The term "broad band" refers to the capability of the system to employ very short pulses and spread-spectrum techniques to achieve good vertical and temporal resolution. As the principal frequency of an acoustic transmitter increases, the range decreases and resolution of the instrument increases. Because many dredged material placement operations conducted by the Corps are within a depth of 100 ft[1], the DRP constructed the 600-kHz system which has a typical operational range of about 45 m and a typical operational resolution of 25 cm.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

In situ samplers. Backscatter intensity and acoustic losses depend on grain size and sediment type. Therefore, in most situations it is necessary to take suspended backscatter sediment samples during the survey to use in analyzing the acoustic backscatter intensity measurements. These samples can be taken either by water sample bottles or by continuously pumping out samples through a tube in the water. In addition to suspended-sediment water samplers, in situ instrument packages may contain such instruments as a transmissometer, optical backscatter sensor (a device that measures sediment concentration at higher concentration ranges than a transmissometer), conductivity, temperature, and pressure sensors to determine important water properties.

Positioning system. The principal function of a horizontal positioning system is to provide the location of a sediment plume as it moves with the current and disperses. In shallow water the BBADCP can measure the velocity of the system over the bottom and directly output earth-referenced current velocities. In deep water the positioning system must make the measurements of the system over the bottom so the earth-referenced velocities can be calculated. The required degree of accuracy of the positioning system depends on the application. Operations in rivers and estuaries may require the horizontal position of a plume to within 1 m. The PLUMES data-acquisition system will allow direct interfacing with a differential Global Positioning System (GPS) receiver.

Data-acquisition system (DAS). The DAS consists of hardware (computer console and monitor) and software to operate the PLUMES and to record, analyze, and display data. The DAS also records locations from the positioning system. The DAS operates the BBADCP and any electronics associated with the in situ sampling and records the output of these instruments. Measurements from the BBADCP can be viewed in real time. Screens on the control console of the PLUMES display vertical profiles of the backscatter intensity in the sediment plume, and north-south and east-west current velocity vectors. A PLUMES technical manual and data-analysis procedure have been prepared by Tubman (1995).

Current measurements

The BBADCP produces current-velocity measurements in a series of so-called "bins" along each of the outside four beams out to the maximum range. The maximum operational range depends on the acoustic energy-loss mechanisms. The minimum recommended size of each bin, which determines the maximum vertical resolution of the current measurements, is 25 cm. Smaller bin sizes will significantly degrade the accuracy of the measurements. As a result of the 30-deg orientation of each beam from the vertical, the beams diverge away from the instrument. At maximum range, the beams span approximately 55 m horizontally. The BBADCP calculates the horizontal and vertical current velocities from these four beams, assuming the currents are uniform over the entire region covered by the beams. Considering the orientation of the beams, the BBADCP measures the currents 35 to 55 m below the instrument when operating at maximum range. The BBADCP can detect the bottom at a distance closer than approximately 55 to 90 m and can measure the velocity of the instrument over the bottom.

Suspended-sediment measurements

The fifth beam of the system is used to measure acoustic backscatter intensities. At 600 kHz, the acoustic wavelength is much greater than the size of the suspended-sediment particles at most dredging operation sites. As the wave passes through the water, it causes the particles to move back and forth; however, their motion lags behind the wave. This lagging oscillation reradiates acoustic energy in all directions, with some going back toward the source. The acoustic energy detected by the source transducer is called backscatter, and its intensity depends on the number of sediment particles in the beam. Thus, the intensity of the backscatter provides information on sediment concentration.

An experimental laboratory study of acoustic backscattering from particles equivalent in size to those potentially found at dredging and dredged material disposal sites was conducted by RDI. The objective of the study was to determine the relationship between acoustic backscatter and sediment size, composition, and concentration to be used to analyze and interpret field data from PLUMES. To achieve the objective, a calibration chamber was designed and built. Particles of uniform size were suspended in the calibration chamber and backscatter and attenuation measurements were made using two different acoustic systems, one operating at a nominal frequency of 600 kHz and one operating at 2 MHz. The experiments were successful for glass beads and sand particles ranging in size from 0.038 to 0.850 mm at nominal concentrations of 5 to 1,000 mg/m. It was concluded that backscatter is proportional to concentration for a fixed size distribution (Lohrmann and Huhta 1994).

Deployment

Shallow water. For shallow-water deployments, PLUMES is easily suspended over the side of a small survey boat and is held in place by clamps attached to the gunwale. In this configuration, the data are transmitted over a seven-conductor neoprene-jacketed electronics cable that is subject to negligible strain. The normal practice is to use the conductivity-temperature-depth (CTD) gauge with the optical backscatter sensor attached as a separate profiling device. To perform this operation, the survey boat is stopped and the sensors are lowered to the bottom near the BBADCP system and then immediately raised and placed on the vessel. This produces a continuous CTD and optical backscatter profile. The CTD data provide information on important water properties at the site. The optical backscatter sensor (OBS) responds to sediment in the water but not to biological backscatter. Thus, the OBS data can be used to identify biological sources of acoustic backscatter.

Deep water. For deep-water deployments, a towed body is used. In this configuration, the data are transmitted over a seven-conductor electromechanical tow cable that has haired fairing on it for approximately 20 percent of its length. To tow the system at a depth of 300 m, the tow cable must be approximately 1,000 m long. The towed body, manufactured by Endeco/YSI, Marion, MA, is constructed of fiberglass in a dihedral-winged, passive depressor design.

Prototype field applications

Mobile, AL, 1989. A field data collection project was conducted off Mobile, AL, during the period 18 August through 2 September 1989 with the objectives of testing first-generation PLUMES acoustic instrumentation for measuring sediment-plume dynamics and bottom boundary-layer processes and to develop and refine plume-tracking procedures for monitoring the movement of dredged material placed in shallow water (Kraus 1991). This early version of PLUMES consisted of a four-beam narrow-band (1.2-MHz transducers) ADCP for measuring current velocities and a separate 20- to 200-kHz transducer ACP for measuring acoustic backscatter intensity profiles. All measurements of plume movement were conducted in the vicinity of a stable berm where placement operations were taking place. The stable berm consisted of estuarine mud, clay, silt, and sand and was designed to serve as a wave breaker and fish habitat. The dredging contractor consented to disposal at two fixed locations: one in deeper water at a nominal depth of 40 ft and the other in shallower water at a nominal depth of 25 ft.

A large comprehensive and varied data set on plume dynamics was obtained. Distinguishing features of the data set include (a) data collection at two shallow-water sites, (b) simultaneous operation of two acoustic systems together with water and sediment sampling, (c) precise measurement of monitoring vessel and hopper barge positions, and (d) availability of bathymetric data and regional oceanographic and meteorological data provided by the Corps' NBDP. The concept of an operational project-level plume monitoring instrument was confirmed.

Tylers Beach, VA, 1991. An enhanced PLUMES system was field tested at Tylers Beach, VA, during the period 27 September through 4 October 1991 (Thevenot, Prickett, and Kraus 1992). The primary acoustic system was a four-beam (2.4-MHz transducers) BBADCP for measuring current velocities and a separate single-beam narrow-band 600-kHz transducer for measuring acoustic backscatter intensity. Objectives of this field research included (a) collection of suspended-material concentration data and current data to determine the potential for dredged material issuing from a pipeline discharge to reach environmentally sensitive areas adjacent to the placement site and (b) continued development of PLUMES for monitoring dredged material plumes.

Background conditions and dredged material plumes were monitored for 5 days in the James River off Tylers Beach. The project-specific objective was to determine if dredged material would reach Point of Shoals, a shallow rock outcrop located adjacent to the discharge site. Point of Shoals is an important environmental resource in the Chesapeake Estuary. The DRP research objective was to conduct a field test of PLUMES' capabilities to acquire data from which suspended sediment concentrations could be calculated. To meet these objectives, equal emphasis was placed on in situ acoustic monitoring and water sampling.

The acoustic instrumentation served a critical function of detecting and tracking the dredged material discharge plume to guide the in situ monitoring, because the plume could not be located visually on the surface owing to the natural turbidity of the river estuarine environment. The acoustic surveys efficiently and effectively delineated the perimeter and movement of the plumes as they responded to changes in the current and depth at the study area. The backscatter-intensity data and the suspended sediment water samples provided a comprehensive data set for looking at the relationship between backscatter-intensity measurements and suspended sediment concentrations in the field. The results are discussed in Thevenot, Prickett, and Kraus (1992).

San Francisco, CA, 1993. In September 1993, PLUMES was used in its deep-water configuration and towed at depth at a location approximately 80 km off San Francisco, CA, in 3,000 m of water (Tubman 1994b). Here the five-beam (600-kHz transducers) BBADCP developed by RDI was utilized. Ten disposal operations were monitored by towing the system behind the ship, generally at depths between 10 and 450 m. Each disposal operation consisted of a scow releasing 1,000 to 2,000 cu yd of dredged material. After each release the ship was stopped, and the towed vehicle was lowered into the resulting plume to a maximum depth of approximately 800 m. Plumes from the releases were monitored in excess of 6 hr.

Even in rough weather with waves up to 5 m, PLUMES towed stably and produced good-quality acoustic data. Plumes with horizontal extents of 100 to 2,100 m were tracked. These plumes were monitored by crossing back and forth perpendicular to the current for distances of approximately 1,000 to 2,500 m. The crossings were spaced approximately 1,000 m apart along the axis of the plumes' trajectory. Navigation was accomplished using differential GPS (DGPS).

Operationally, the most significant problem was obtaining samples of suspended sediment. It was thought that a separate ship dedicated solely to obtaining water samples could successfully obtain samples from within the plumes. After the position of an acoustically measured plume was established by DGPS and acoustic data, the ship with the sampler was directed to the position where the plume was predicted to be at the time of the sampling. This procedure was not successful for several reasons. First, the plumes had relatively small horizontal extents and were rapidly advected by the current. Second, the time required to get on station and lower the water sampling system to sequential depths to obtain samples was generally unpredictable and lengthy compared with the plume movement. A second operational procedure that proved more successful was one in which the ship moved in directly behind the barge and lowered the sampling system as the barge discharged material. However, this made it difficult for the ship with PLUMES to get into position to monitor the discharge. All other operational techniques worked well at this deepwater site.

Acoustic Resuspension Measurement System

ARMS was developed to measure sediment resuspension and movement in the water column at existing and proposed dredged material disposal sites (Van Evra et al. 1992). In field conditions, depending on the amount of energy being imparted to the area from wind, waves, and currents, there is a varying amount of sediment that is being resuspended into the water column off the seafloor. The manner in which this occurs determines the physical transport of bottom material at the site.

To observe the time history of bottom-material transport accurately, an instrument must sample rapidly enough to capture all of the small and complex motions that are occurring. Since sediment concentrations in the bottom boundary layer may vary on the order of seconds, a device must sample on the order of 1 to 5 Hz, depending on the temporal resolution desired. The small-scale structure occurring right at the bottom is especially important to what happens to the sediment higher in the water column. To see the fine structures in both cases, a remote instrument must be able to measure variations within a centimeter. Again, high-frequency sound has wavelengths small enough to effectively sample and differentiate in this scale.

ARMS Concept

To measure in situ properties of the boundary layer above dredged material mounds in open-water disposal areas, an optimally arranged ensemble of specialized underwater instruments must be used. The instruments must be carefully mounted into specific positions on a rugged yet portable frame and interrogated at sampling rates frequent enough to allow observation of short-term as well as long-term physical processes.

ARMS is an integrated ensemble of seven specialized underwater sensors designed to accurately measure in situ properties of the bottom boundary layer in open-water areas. The seven instruments that comprise ARMS are (a) an acoustic sediment-concentration profilometer, (b) four acoustic velocity sensors, (c) a pressure gauge, (d) a thermistor, (e) a transmissometer, (f) a multi-frequency sediment-particle sizer, and (g) an optional video camera (Figure 14).

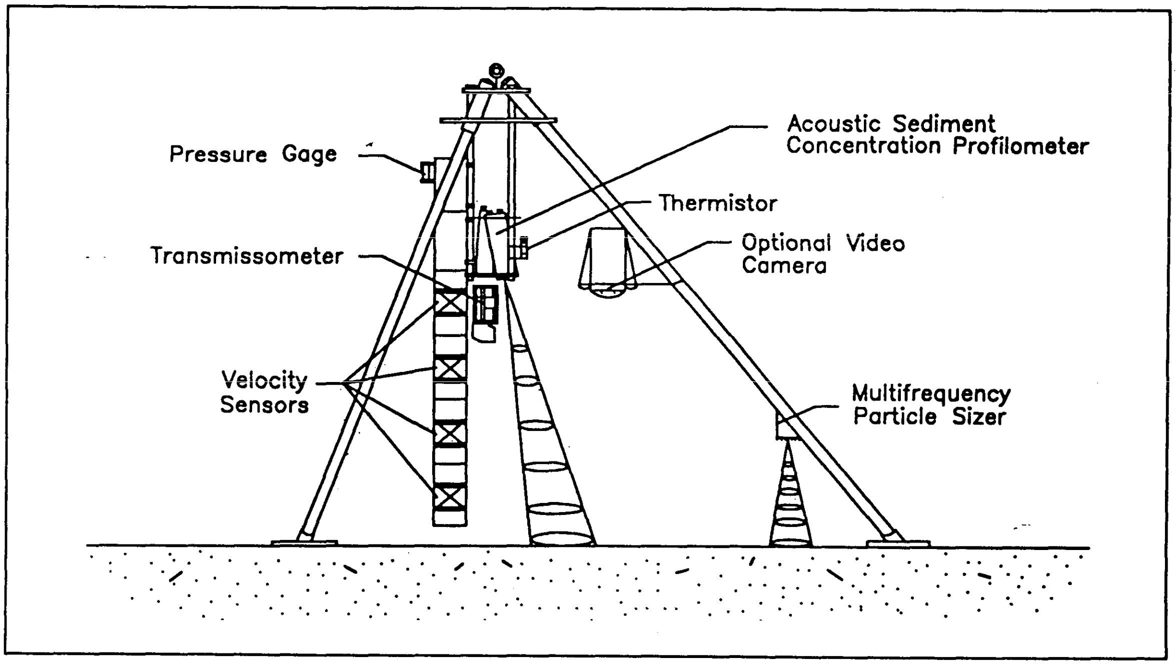

Figure 14. Acoustic resuspension measurement system

ARMS was designed and constructed for the DRP by Ohio State University. It was verified as a practical engineering tool in the laboratory and was deployed successfully in the field during the Mobile, AL, prototype data-collection project of 1989.

ARMS Instrumentation

The ARMS instrumentation manual was prepared by Van Evra and Bedford (1994).

Acoustic sediment-concentration profilometer

The central instrument in the ARMS ensemble is an Edo-Western Model 563 3-MHz acoustic transceiver, referred to as a profilometer. Created originally as a high-accuracy depth indicator, the electronics of the self-contained device were modified to increase its sensitivity near the face of the transducer. This increased sensitivity allows the profilometer to detect minute-intensity sound reflections from individual sediment particles that can be interpreted as sediment concentration by the methodology of Libicki, Bedford, and Lynch (1989). The profilometer operates by first transmitting a finite-length pulse of 3-MHz sound, called a ping, and immediately switching into a receive mode, sequentially reading the intensity of sound reflected from any suspended particles located along the ensonified beam. By collecting data returns in short time windows, the relative sediment concentration in each of the corresponding depth intervals or bins along the beam path can be measured.

Velocity sensors

A benthic acoustic stress sensor (BASS) measures the 3-D water velocities rapidly and accurately. The BASS detects the time of travel of high-frequency sound to determine the water velocity producing variations along the direction of travel between pairs of small transducers. Each BASS sensor is a cylindrical cage of stainless steel that holds eight 1.75-MHz transducers (four in an upper ring and four in a lower ring). In operation, the four transducers in the upper ring are pinged, and their signals are received by the corresponding transducers on the lower ring. The lower-ring transducers then are pinged to be received by the upper transducers. Travel times for each pair of sensors are calculated (to cancel electronic drift), and the velocity along the path results. By using trigonometric relationships among the four mutually orthogonal velocity vectors, three velocity components of water motion are obtained. Measurements are taken several times per second to a resolution of approximately 0.03 cm/sec. With four BASS cages, ARMS can make as many as twenty 3-D velocity measurements each second.

Pressure gauge

To correlate surface wave and tidal activity with measurements being taken on the bottom, a sensitive pressure transducer records the hydraulic pressure time history. A Wika Model ST-420 pressure sensor, which has a linearity of 0.05 percent of full scale and a water surface resolution of approximately 1 cm (in shallow water), is used.

Thermistor

A Yellow Springs, Inc., 44018 linearized thermistor takes measurements of ambient water temperature. This instrument has 0.1 °C accuracy.

Transmissometer

The transmissometer measures the total suspended-mass concentration at a fixed point in the water column. ARMS uses a Sea Tech, Inc., transmissometer with a 5-cm path length and wavelength of 660 n.m.

Sediment-particle sizer

A multifrequency device developed by Ohio State University yields the necessary particle-size information to convert the profilometer returns into concentration data without in situ water sampling. Information obtained from the acoustic sediment-concentration profilometer and knowledge of the suspended-particle size allow calculation of absolute sediment concentration in each range bin, yielding a sediment-concentration profile for each transmitted ping from the profilometer.

Optional video camera

An optional video camera for providing real-time observation of pertinent events and for making periodic checks on other instrumentation can be installed on ARMS. The camera can also inspect for damage, obstructions, evolving bottom-ripple formations, and biofouling.

ARMS controller circuitry

The central processing core of the system performs all of the onboard timing, communications, and data-manipulation functions necessary to process the desired information. The central processing unit can be programmed for many different sampling routines to conserve battery power. The programs are written in a compartmented fashion, commanding the power-controller board to turn on instruments only when needed. In the overall scheme, the microcontroller's capability to retain only clock function allows ARMS to perform multiple interrupted sampling schemes in which all instruments and electronics shut down completely while the system waits to begin another sampling run. These power-down periods may be prearranged to allow longer deployments or conditionally inserted during periods when the physical activity (i.e., wave height) at the site has dropped below a predetermined threshold level. The deployments can last from 24 hr for constant data collection to 3 months for interrupted usage.

Data from the instruments are processed onboard the central processing unit (CPU) circuitry. The resulting complete data sets are sent via serial line to a streaming tape drive for mass storage. This tape drive is housed in a separate pressure case with its own battery supply so that its relatively noisy operation does not interfere with other devices. The tape drive uses standard DC-600A computer tapes that hold 60 MB of data. The tape drive lies dormant except for the 128-KB memory buffer that constantly accepts data while the ARMS is operating. When the buffer is full, the drive turns itself on, dumps the contents of the buffer onto tape in about 5 sec, and then shuts itself off.

ARMS Deployment

The inherent stability of the tripod makes lowering the ARMS a straightforward procedure. ARMS can be deployed at sites up to 100 ft in depth. It is optimal to place the tripod on a flat bottom that is clear of large debris, not only because the BASS cage protrudes down through the middle of the space under the tripod, but also because measurements in unobstructed conditions are preferred. To guarantee this, if divers are not available to check before and after placement, inspection of the bottom with a drop video camera run from the surface is required.

Prototype Field Application, Mobile, AL, 1989

During the Mobile, AL, prototype field data collection project (18 August through 2 September 1989) a limited amount of data was collected with ARMS placed near the disposal site. Only a limited amount of data was obtained because the primary purpose of that effort was to obtain knowledge about plume dispersion and movement and not predominantly about the mechanisms causing resuspension after the material had reached a resting place on the seafloor.

At the Mobile deployment, ARMS was configured as an instrumented tripod approximately 10 ft high with a 15-ft span between the legs. ARMS obtained comprehensive and accurate measurements of sediment and fluid movement in the lower 1 m of the water column above the seafloor. While being a first generation of ARMS, the tripod contained a 3-MHz acoustic transducer to measure sediment concentration, two electromagnetic current meters, a pressure gauge for water-surface elevation measurement, and other sensors to measure water properties. ARMS was deployed in shallow water away from the site of dredged material placement operations.

5 Numerical Simulation Techniques for Evaluating Short-Term Fate and Stability of Dredged Material Disposed in Open Water (STFATE)

An integral part of the problem of managing a dredged material disposal site is the ability to determine the physical fate of materials immediately after an individual disposal operation and, ultimately, the long-term movement and/or accumulation of the material deposited initially within the site. Knowledge of the short-term fate of dredged material disposed in open water also is an integral part of assessing the water-column environmental impacts.

Field evaluations by Bokuniewicz et al. (1978) showed that the placement of dredged material generally follows a three-step process (Figure 15):

a. Convective descent, during which the material falls under the influence of gravity.

b. Dynamic collapse, when the descending cloud or jet either impacts the bottom or arrives at a level of neutral buoyancy, in which cases the descent is retarded and horizontal spreading dominates.

c. Passive transport-dispersion, commencing when the material transport and spreading are determined more by ambient current and turbulence than by the dynamics of the disposal operation.

Mathematical models for predicting the short-term fate of material from individual disposal operations that consider these three phases were developed by Koh and Chang (1973) and subsequently were modified by Brandsma and Divoky (1976) and Johnson (1990). All of these models suffer from a lack of data for verification and the inadequacy of their representation of the convective descent and collapse phases that occur in real disposal operations. For

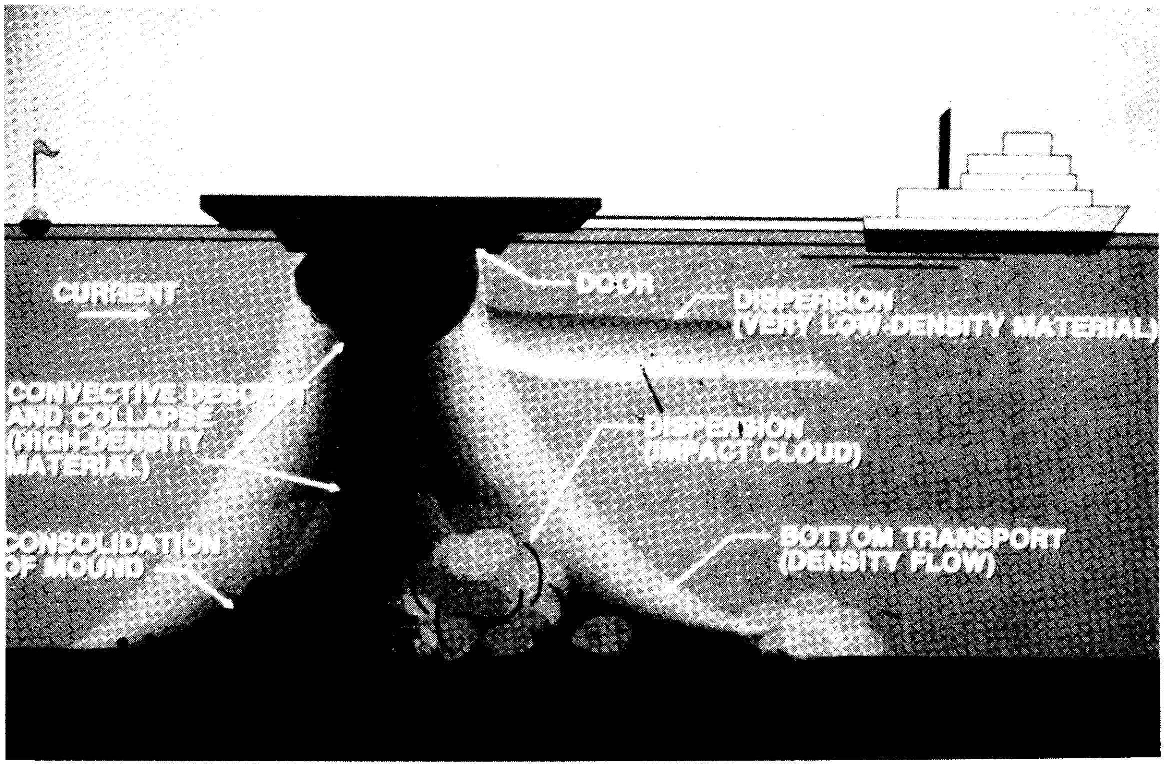

Figure 15. Schematic of barge disposal of dredged material in open water

example, disposal from a split-hull barge is treated as a single hemispherical cloud descending through the water column. Such assumptions prohibit the accurate simulation of water-column concentrations of suspended sediments. Additional deficiencies were emphasized during Mobile Bay field data collection efforts (Johnson, Tallent, and Fong 1992).

The appropriate scaling laws to simulate prototype dredged material disposal behavior in a physical test facility for various cohesive and noncohesive sediments have been developed to obtain calibration and verification data for enhancing numerical models of this behavior (Soldate, Pagenkopf, and Morton 1992). Various types of equipment and measurement techniques to monitor cloud descent, rates of spreading, and suspended-sediment concentrations also were recommended. Large-scale laboratory tests in the facility designed for disposal from a split-hull barge and a multiple-bin vessel (hopper dredge) to obtain verification data for numerical models for determining short-term fate of disposed materials were conducted by Johnson et al. (1993). Those tests resulted in development, calibration, and verification of the numerical model STFATE for computing water-column concentrations and bottom deposition resulting from open-water disposal of dredged materials. STFATE represented extensive modifications to an earlier disposal model (DIFID) (Johnson and Fong 1995).

Design of Dredged Material Placement Physical Modeling Facilities[1]

Physical model tests of open-water dredged material disposal operations were conducted at WES to develop enhancements to numerical models for describing these processes. As in any physical model testing program, scaling effects had to be considered in the design of the physical modeling basin.

Scaling laws for dredged material disposal

A detailed investigation of scaling laws for the physical modeling of dredged material disposal is presented by Soldate, Pagenkopf, and Morton (1992) to determine the minimum size of the physical model necessary to avoid scale effects. Only undistorted models were considered because distorted models have inherent disadvantages.

The characteristics of dredged material vary substantially. The material ranges from gravel to clays with particle-size distributions depending on the site. Sediment-particle densities usually range from 2.6 to 2.7 gm/cu cm. In situ densities commonly range from 1.3 to 1.7 gm/cu cm or more. Clamshell dredging does not tend to disturb the in situ properties of the dredged material. In contrast, hydraulic dredging tends to destroy the in situ properties of the material and mixes the sediment with water, lowering the bulk density of the water/ sediment mixture. The particle fall velocities of sand and gravel particles are usually assumed to obey Stokes Law. Clay and silt particles are usually cohesive, and particle velocity is a function of sediment concentration. Commonly, fall velocities for dilute clay-silt mixtures are dependent on the concentration to a power, usually 4/3. If the particles are bound together in clumps, then the fall velocity of the clump is calculable as a noncohesive particle. The volume of dredged material discharged instantaneously from barges and hopper dredges typically ranges from around 500 to 4,000 cu yd. The speed of the barge or hopper dredge during discharge operations usually does not exceed 4 knots.

A dimensional analysis was performed by Soldate et al. (1992) for a stationary or moving vessel that discharged material instantaneously or over a relatively short time period. That analysis determined that scaling of the prototype is possible for both convective descent and dynamic collapse provided that the Reynolds number appropriate for each phase is high enough so that turbulent flow occurs (except during the end of dynamic collapse). Froude number similitude is always required. Flow Reynolds number may never be fully achieved in the water column, but is required (assuming that dynamic collapse occurs on the bottom) for the roughness Reynolds number applicable

[1] This section of Chapter 5 was extracted from Soldate, Pagenkopf, and Morton (1992).

to the bottom sediments. This is achieved by increasing the bottom sediment diameter.

The Reynolds number requirements put a limit on the scales that can be used. The flow Reynolds number in the model at the beginning of either the convective descent or dynamic collapse phases should be high enough to cause turbulent flow. If this number is, say 10^4, then the prototype Reynolds number is $10^4 T_R / L_R^2$, where T_R and L_R are the time and length scale factors between the prototype and model, respectively. For many discharge possibilities, the length scale factor should exceed 1/100 (i.e., $L_R \geq 1/100$). Decreasing the particle densities used in the model compared to those in the prototype is a method of enlarging the range of permissible length scales.

The physical size of the testing facility is influenced by the range of test conditions for anticipated experiments. The ranges of various prototype parameters to be investigated included:

a. Water depth: 100 to 300 ft.

b. Disposal volume: 4,000 to 8,000 cu yd.

c. Bulk density: 1.05 to 2.60.

d. Vessel speed: 0.0 to 2.0 knots.

e. Material size classifications and settling velocities as follows:

Classification	Settling Velocity, ft/sec
Clumps	0.50
Clay	0.0004
Silt	0.008
Fine sand	0.03
Medium sand	0.08

To ensure the Reynolds criteria were met, a length scale factor of 1/50 was used in the physical model tests.

Physical test facility

Soldate, Pagenkopf, and Morton (1992) suggested several factors to consider in developing a model facility. The geometric scales of the model were fixed through a combination of numerical model predictions and results from a scaling laws investigation. For an undistorted facility, it was believed that a 40-ft by 40-ft basin would be sufficient to prevent the bottom surge from striking the boundaries of the basin, based on a model-to-prototype scale of 1 to 100 or greater.

The physical test facility was constructed in an existing deep basin to yield a test area of 40 ft by 50 ft by 8 ft. Braced 1-ft-thick concrete walls fitted with two 10-ft by 13-ft windows were built to enclose an L-shaped viewing area. The windows provided views of the test area that were perpendicular to each other. The floor and walls were painted white with a black 1-ft spacing grid superposed for ease of observation and measurement.

Disposal vessels

Two types of disposal vessels were used for testing: a split-hull scow and a hinged-door hopper. The split-hull barge was constructed to a 1:50 scale and was based on an actual design. Its dimensions were 57 in. by 13.5 in. by 7.5 in., with a disposal volume of 0.9 cu ft. Opening and closing of the barge were controlled by an air line attached to two small hydraulic cylinders mounted on the vessel. The barge opens essentially instantaneously.

The hinged-door multihopper disposal vessel was roughly based on the design of the Corps hopper dredge *Wheeler*. Dimensions of the test model were 2.09 ft by 2.96 ft, with six hoppers. Each hopper had a maximum capacity of 0.28 cu ft. This vessel was designed as a free-standing unit with flotation provided separately by a modified 12-ft-long john boat. The doors were always opened two at a time, usually in the following order: 1 and 2, 5 and 6, and 3 and 4.

Physical Model Tests[1]

Physical model testing was conducted by Johnson et al. (1993). Tests were concerned with tracking the movement of the disposal material from the vessel to its final resting place. All tests were conducted in a static and unstratified pool. Each test was videotaped from each of the viewing windows. Cameras were placed to provide maximum viewing of the descent and bottom surge. Water samples were taken to determine suspended-sediment concentrations. Samplers were placed in three different locations, each simultaneously taking three to five samples from the water column.

For tests in which the vessel was stationary, the video recorders were mounted on tripods and focused to provide maximum viewing of the convective descent and the bottom surge. Each sampler was opened when the

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[1] This section of Chapter 5 was extracted from Johnson et al. (1993) and Johnson and Fong (1995).

bottom surge had travelled 1 ft past the sampler location. The cameras generally ran until the energy of the surge had dissipated. Overhead photos were taken throughout the tests from various above-surface viewpoints.

The procedure changed slightly for moving disposal tests. The vessel was manually pulled in a straight line toward one viewing window with the direction of movement being parallel to the other viewing window. Both cameras were mounted on tripods as for stationary tests, but the side-view camera followed the barge, keeping the plume centered. The velocity of the vessel was constant.

Four materials were used as disposal material: sand, finely crushed coal, silt, and clay. The coal had a gradation that would pass through a No. 16 sieve but not through a No. 100 sieve. The silt was local silt, wet-sieved through a No. 200 sieve. The split-hull barge was tested with all four materials. However, the hopper dredge was only tested with the silt. The sand and coal were generally very wet, but usually under no standing water at the time of disposal. The silt and clay were mixed with water to form a slurry, with a sample of the slurry being taken before each test to determine its bulk density. The slurry was pumped into the vessel and disposed as soon as possible to minimize settling within the test vessel.

Split-hull barge tests

Both stationary and moving disposal tests were conducted with the split-hull barge. The volume of each dump was 0.9 cu ft. At a scale of 1:50, this represents a disposal of approximately 4,000 cu yd of material. The water depth in the test facility varied from 2.0 to 6.0 ft, representing disposal in prototype depths of 100 to 300 ft. Figure 16 illustrates the basic behavior during convective descent after disposal of a load of clay material.

Normally one would expect surge speed to decrease with distance from the impact point. However, this is not always the case. With the density of the disposal material decreasing from the bottom of the vessel to the top, if the material leaves the vessel in a continuous fashion, the energy feeding the surge would be greatest at the initial impact and then decrease as the remaining disposal material entered the surge. Under such conditions the surge speed would decrease with lateral spread. However, it was observed that quite often material left the disposal vessel as distinct globs. In such cases, the surge temporarily accelerates as relatively dense globs of material impact the bottom and add additional energy to the expanding bottom surge.

Modeling this behavior is difficult since it requires a knowledge of how the material will leave the disposal vessel. However, as a result of insight gained from these disposal tests, such disposal operations were modeled by Johnson and Fong (1995) as a sequence of convecting clouds with varying characteristics.

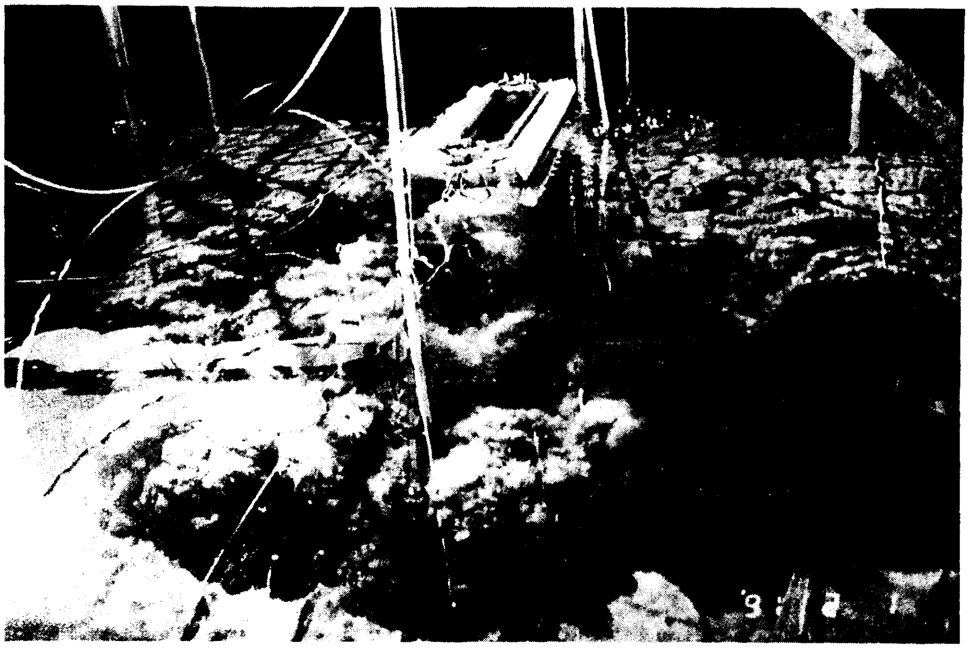

Figure 16. Model tests of open-water disposal from a stationary barge

After all disposal material had settled, bottom surveys were conducted. This was accomplished by measuring the thickness of the bottom deposit at the intersection of the grid lines painted on the bottom of the test facility. The deposition data were used to construct bottom deposition-contour plots. For the stationary tests, 95 percent or more of the material was deposited in approximately a circular pattern with a prototype radius of about 200 to 250 ft. Unlike the stationary disposal tests in which virtually all the material was quickly transported to the bottom, the moving tests also resulted in an upper water-column plume consisting of fine material sheared from the main body of descending material. If the water column had been stratified, it is probable that extremely fine material would have been trapped above the pycnocline for an extended period of time.

Johnson and Fong (1995) modeled such disposal operations by treating the disposal as a series of convecting clouds with different characteristics. Each cloud can be created at a different location due to the moving nature of the disposal operations and can possess varying bulk density and sediment characteristics.

Hopper-dredge tests

Initially, disposals of both sand and crushed coal were attempted with the model hopper dredge. However, in each case the disposal material bridged the bottom opening resulting in little of the material being disposed. Therefore, all remaining disposal tests from the hopper disposal vessel were conducted with a slurry of silty material. As with the split-hull barge tests, the data collected consisted of videotaping and taking suspended sediment samples at three vertical locations at three horizontal positions.

Conclusions

Several data sets consisting of descent and bottom-surge speeds, bottom-deposition patterns, and spatial representation of the suspended sediment in or near the bottom surge were collected. These data were later used at both the physical model scale and prototype scale for numerical model verification.

One of the most valuable uses of the physical model disposal facility was in allowing the dynamic placement processes of descent and bottom surge to be visually observed. As a result of those observations, it was concluded that the numerical disposal models existing at the time of those tests conducted by Johnson et al. (1993) did not adequately represent actual disposal operations. There were no instantaneous disposals of material that were uniformly distributed within the disposal vessel. In addition, moving disposal vessels tend to create upper water-column plume as a result of a shearing effect which can leave extremely fine material in the upper water column.

As a result of these physical tests, Johnson and Fong (1995) were able to significantly enhance existing numerical models to allow for the observed behavior of real disposal operation. Those modifications were concerned with representing the disposal operation as a sequence of small clouds convecting downward as a result of their negative buoyancy. A stripping of fines from each of the clouds results in the creation of small Gaussian clouds that are passively transported and diffused by the ambient environment. It was determined that with such modifications not only upper water-column suspended-sediment concentrations but also bottom deposition could be more accurately modeled in real disposals of dredged material.

STFATE Dredged Material Disposal Model[1]

An existing numerical model for computing disposal from instantaneous dumps (DIFID) was extensively modified by Johnson (1992) and Johnson and Fong (1995) to yield a more versatile, accurate, and robust disposal model called STFATE. To allow for disposal from hoppers or moving barges and for a more accurate representation of the disposal material, the concept of multiple convecting clouds was developed that allows for stripping of material during descent. Computation of the bottom surge was based upon energy concepts. The resulting model was subsequently verified using laboratory data collected by Johnson et al. (1993).

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1 This section of Chapter 5 was extracted from Johnson (1992), Johnson et al. (1993), and Johnson and Fong (1995).

Measured suspended-sediment data are presented in Tables 5 and 6 for comparison with numerical model STFATE results at increments of 1 ft (model) from the point of disposal for a representative test at 12 and 15 sec after disposal. Measured suspended-sediment values, shown in parentheses, were collected at approximately the vertical locations shown on the tables at about 12 to 15 sec after disposal.

The data in Tables 4 and 5 show that the computed concentration field changed significantly from 12 to 15 sec. This is because the bottom surge is still spreading and also because the material stripped during descent and from the top of the bottom surge has settled 0.3 ft (assuming a fall velocity of 0.1 ft/per sec).

Table 4
Comparison of Computed and Measured Suspended-Sediment Concentration (mg/ℓ) after 12 Sec[1]

	Horizontal Position Relative to Point of Disposal, ft							
Depth, ft	0	1	2	3	4	5	6	7
1.5	160	240	2 (1)	0	0	0	0	0
2.5	690	1,460	110 (352)	1	0	0	0	0
3.5	6,700	14,800	14,400 (17,074)	630	130	10	0	0
4.0	6,800	14,100	16,100 (13,907)	10,300	3,800	770	90	0
4.25	8,400	9,700	10,900	9,600	6,400	3,600	1,900	1,200

[1] Parenthetical entries represent concentrations measured 12 to 15 sec after discharge at the horizontal position so indicated. Other entries are values computed to occur at 12 sec after discharge.

STFATE application at Puget Sound

In 1985, the Puget Sound dredged disposal analysis (PSDDA) project was initiated to establish long-term disposal sites for material dredged within the confines of Puget Sound. To assist in determining the appropriate size and location of the disposal sites, an early version of STFATE (DIFID) was used to estimate the depositional pattern caused by the disposal of a single barge load of dredged material. In a simulation of 1,500 cu yd of material released in 400 ft of water, essentially all of the material was deposited within a 1,000-ft radius of the disposal point at the Port Gardner, WA, site.

The first phase of the Navy's homeport project at Everett, WA, required dredging and disposal of approximately 1 million cu yd of material at the Port Gardner site. Placement was completed in 1990. A detailed postdisposal

Table 5
Comparison of Computed and Measured Suspended-Sediment Concentration (mg/ℓ) after 15 Sec[1]

	Horizontal Position Relative to Point of Disposal, ft							
Depth, ft	0	1	2	3	4	5	6	7
1.5	3,480	5,100	31 (1)	0	0	0	0	0
2.5	710	1,640	270 (352)	3	0	0	0	0
3.5	8,700	18,300	20,100 (17,074)	11,900	4,000	830	110	0
4.0	7,100	13,400	17,100 (13,907)	15,000	9,000	3,800	1,100	210
4.25	11,000	18,100	23,800	25,200	22,000	16,700	11,900	8,400

[1] Parenthetical entries represent concentrations measured 12 to 15 sec after discharge at the horizontal position so indicated. Other entries are values computed to occur at 15 sec after discharge.

monitoring study of the site indicated that over 96 percent of the disposed material was within the disposal site. Some material, however, settled as far as 1,000 ft outside the disposal-site boundary (Nelson and Johnson 1992).

The enhanced version (STFATE) of the original short-term fate disposal model (DIFID) was later used to simulate disposal at the Port Gardner site for comparison with earlier DIFID simulations. Results indicated that material representative of the Navy project spread about twice as far as the material originally modeled by DIFID during the PSDDA site designation. A simulation of the combined effect of all disposals that took place during the Navy project accurately represented the well-defined deposition pattern found at the disposal site (Nelson and Johnson 1992).

Conclusions

From numerical model results compared with measured laboratory tests and field data from disposal sites, it can be concluded that STFATE accurately simulates the fate of material disposed in open water. Average computed and measured descent speeds from the laboratory tests compared to within 25 percent and average bottom-surge speeds compared to within about 10 percent.

All of the numerical model simulations allowed sediment to be stripped during descent. Computed results for the silt and clay deposits showed about 2 to 3 percent of the solids being stripped during descent. These results agree well with published estimated percentages of stripped material. When comparing computed and measured suspended-sediment concentrations collected by the sediment bottles, it should be realized that small differences in timing of sampling and location of the bottles are extremely important.

Results of the simulations (Johnson and Fong 1995) show that STFATE can be used to accurately simulate the fate of material during disposal operations. Descent and bottom-surge speeds, stripping, rates of dilution, total depositional areas, and suspended-sediment concentrations in the bottom surge are all reasonably reproduced. However, it is recommended that further attention be given to more accurately representing the effect of the torus (doughnut) shape of the bottom surge.

One area of additional research that is needed to make STFATE even more useful for addressing environmental issues lies in the area of uncertainty. Given the uncertainty in specifying characteristics of the disposal material at the moment of disposal, the manner in which material leaves the disposal vessel, and ambient conditions, an uncertainty analysis should be conducted to better define bounds on the accuracy of predicted water-column effects.

6 Numerical Simulation Techniques for Evaluating Long-Term Fate and Stability of Dredged Material Disposed in Open Water (LTFATE)[1]

The objective of this DRP research task was to provide a simulation technique for determining how a specified dredged material mound behaves over time. The methodology is intended for site-designation investigations and is based on long-term sediment transport simulations using local hydrodynamic boundary condition input data. The simulation technique provides a systematic and quantifiable approach to analyzing disposal-site stability based on local environmental conditions.

If material is eroded from a disposal mound and transported away from the designated location, the site is classified as dispersive. For locations predominated by strong wave and current regimes, sediment-transport calculations based on averaged wave and current data may easily show the site to be dispersive; however, if the local environmental conditions are not severe, it may take months or years before significant amounts of sediment are transported from the disposal site. The ability to identify long-term dispersive sites is especially important because eroded material could be transported into environmentally sensitive areas. Long-term dispersion investigations require knowledge of the local wave climate and current field at the site (Thevenot and Scheffner 1993).

Long-term fate and stability disposal-site analysis was accomplished using a numerically based sediment-transport prediction model, LTFATE, with long-term local boundary forcing functions. These conditions represent those forcings that entrain and transport sediment, including waves, tides, and storms. In

[1] Sources used to compile Chapter 6 are cited in the text.

many cases, these data are not available or are incomplete or too short in duration for long-term predictions. Tidal and storm surge elevations and currents can be determined through numerical modeling techniques. As discussed later in this chapter, these databases have been developed. However, the generation of arbitrarily long simulated realistic time sequences of ocean waves corresponding to specific locations must be performed. Unlike astronomical tides that can be predicted with great accuracy, waves cannot be precisely predicted. A viable approach for generating realistic wave field boundary conditions is to develop a wave simulation procedure that generates waves and currents statistically similar to those known to occur at the site (i.e., preserving seasonality, directionality, distribution, sequencing, and other characteristics). Details of this approach are given below.

Simulation of Wave Height, Period, and Direction Time Series

The simulation procedure for generating a long-term time series of wave characteristics requires an existing database from which the statistical parameters describing the intercorrelations of wave field parameters can be computed (Borgman and Scheffner 1991). The procedure is somewhat analogous to the computation of harmonic constituents for a tidal record. The 20-year record WES Wave Information Study (WIS) database (Corson, Resio, and Vincent 1980; Resio, Vincent, and Corson 1982) was selected as the source of wave-parameter statistics from which a matrix of multipliers was obtained that could then be used to generate time series of wave data that emulated the WIS 20-year hindcast data.

This statistical approach will enable the user to generate data series of any length (e.g., 31 days of January or several years) for any WIS station. Although the procedure is based on the WIS database, it is fully applicable to any database. The only limitation of alternate data sources is that they must be of sufficient length to resolve significant time-scale trends. For example, multiyear trends cannot be deduced from less than a year of data. The advantage of the procedure is that a finite length of data can be used to generate an infinitely long data series that is statistically similar to the original record and exhibits normal variations about its mean (Borgman and Scheffner 1991).

Theoretical considerations

Two criteria were required of the technique selected for simulating time sequences of wave data based on finite-length wave records: the synthetic record had to be realistic with respect to the statistical properties of the database and the methodology had to be computationally feasible with respect to both computer memory and computational speed.

Every simulation of random phenomena is artificial; therefore, differences between the simulated record and the actual data will exist. The adopted mathematical procedure was carefully selected to yield a synthetic data series that preserved those statistical features of the WIS data deemed most important. It was therefore necessary to explicitly identify those features that should be preserved as an aid in choosing between the inevitable compromises involved in the design of the simulation algorithm.

The following statistical properties, listed in their order of importance, were judged to be characteristics that should be preserved in a simulation of the WIS data:

a. Univariate probability law for the three wave parameters of height, period, and direction.

b. Temporal and spatial correlations within and between the wave parameters.

c. Nonstationary properties, such as seasonal variations.

A piecewise, month-by-month, multivariate, stationary simulation approach was selected by Borgman and Scheffner (1991) as the best means of generating realistic time sequences of wave data. This technique seeks to preserve the univariate probability laws and the first- and second-order moment properties that describe the intercorrelations of the data sequences. Higher order univariate moments are maintained to some extent by enforcing the univariate probability laws. Seasonal or nonstationary changes are imposed by simulating each month separately based on the WIS hindcast database for that month and then using a square-root interpolation scheme to force a smooth transition in the time series and intercorrelations from month to month. The statistical properties that may not be preserved are the third-order and higher moments between variables and between different time and space elements in the data.

An empirical transformation of the WIS data sequences to a multivariate normal representation is used to maintain the first-order multivariate and higher order univariate moments of the database. The approach was selected because multivariate normal sequences of data can be conveniently and rapidly generated and returned to the correct univariate distribution through inverse empirical transformations. This technique, referred to as the normal-scores transformation, forms the basis of the simulation approach.

Example application

In order to generate arbitrarily long time sequences of simulated wave data that preserve the primary statistical properties of the WIS data, two programs must be run. First, the height, period, and direction preprocessor (HPDPRE) is run one time to produce a data summary. The data summary produced by the preprocessor can be reused many times with new seed numbers each time, to obtain alternate simulations with the program height, period, and direction simulation (HPDSIM). Both programs can be run on 386 PCs with extended memory. This is possible because both the preprocessor HPDPRE and simulator HPDSIM are optimized to work with frequency-domain methods and other so-called "fast" algorithms. Emphasis has been placed on making the simulation program work rapidly because it will be run and rerun to obtain many simulated sets of wave conditions. Extended memory is not required to run HPDSIM.

The WIS station selected for demonstrating the capability of the simulation package was the Phase II Gulf of Mexico Station 27 (Hubertz and Brooks 1989), located just outside the entrance to Mobile Bay, AL. The simulated example was a generated synthetic data series for September 1956 through June 1958, with a starting random seed of 67676767 and is indexed as 1957. Tables 6 and 7 give the computed values of maximum, minimum, average, and standard deviation values for wave heights and periods, respectively. This comparison indicates that simulated and WIS data are similar with respect to both magnitudes and temporal trends, although expected differences between the two can be seen.

Table 6
Wave Height Comparisons for 1957

	Simulated Wave Height, m				WIS Wave Height, m			
Month	Max	Min	Ave	SD	Max	Min	Ave	SD
Jan	2.30	0.50	1.38	0.36	2.20	0.40	1.20	0.40
Feb	3.03	0.70	1.37	0.41	2.20	0.40	1.17	0.36
Mar	2.47	0.70	1.27	0.33	2.20	0.50	1.17	0.32
Apr	1.77	0.49	1.03	0.23	3.40	0.80	1.34	0.48
May	2.19	0.40	1.00	0.29	2.00	0.40	0.95	0.33
Jun	1.10	0.30	0.70	0.22	2.90	0.30	1.00	0.46
Jul	1.12	0.40	0.71	0.19	1.10	0.30	0.65	0.23
Aug	1.66	0.22	0.72	0.25	2.40	0.30	0.91	0.36
Sep	3.85	0.40	1.10	0.43	3.30	0.40	1.12	0.46
Oct	2.36	0.50	1.18	0.35	2.70	0.50	1.27	0.50
Nov	2.10	0.70	1.27	0.29	2.90	0.40	1.40	0.59
Dec	2.87	0.29	1.34	0.44	2.90	0.50	1.35	0.45
Jan-Dec	3.85	0.22	1.09	0.41	3.40	0.30	1.12	0.47

Table 7
Wave Period Comparisons for 1957

Month	Simulated Wave Period, sec				WIS Wave Period, sec			
	Max	Min	Ave	SD	Max	Min	Ave	SD
Jan	7.70	4.30	5.63	0.84	7.70	2.40	5.47	1.01
Feb	8.30	4.50	5.72	0.77	7.70	2.00	5.48	1.07
Mar	7.70	3.44	5.67	0.78	7.70	3.20	5.62	0.79
Apr	6.70	3.22	5.16	0.64	9.10	4.50	6.02	1.05
May	7.44	2.72	5.20	0.80	7.70	2.60	5.20	1.02
Jun	6.49	2.35	4.71	0.83	8.30	2.60	5.35	1.09
Jul	5.60	2.80	4.64	0.47	6.20	2.80	4.80	0.59
Aug	6.20	1.70	4.39	0.81	8.30	2.00	4.81	1.03
Sep	7.70	3.60	5.29	0.86	10.00	3.40	5.63	0.46
Oct	7.99	3.87	5.46	0.90	9.10	3.00	5.36	1.27
Nov	7.70	4.14	5.48	0.67	9.10	3.50	5.83	1.22
Dec	7.83	1.24	5.47	1.02	9.10	3.60	5.81	0.92
Jan-Dec	8.30	1.24	5.23	0.90	10.00	2.00	5.45	1.08

LTFATE Dredged Material Disposal Model

LTFATE is a numerical modeling system for systematically estimating the long-term response of a dredged material disposal site to local environmental forcings. The methodology is based on the development of databases of wave and current time series and the application of these boundary conditions to coupled hydrodynamic, sediment transport, and bathymetry change models. The approach was developed to provide an estimate of long-term material fate for use in determining whether an existing or proposed disposal site will be dispersive or nondispersive over periods of months to years.

LTFATE simulations are based on the use of local wave and current condition input. Local site-specific hydrodynamic input information is developed from numerical model-generated databases; however, user-supplied data files can be substituted for the database-generated files.

LTFATE has the capability of simulating both noncohesive and cohesive sediment transport. In addition, avalanching of noncohesive sediments and consolidation of cohesive sediments are accounted for to accurately predict physical processes that occur at the site.

Noncohesive mound movement

LTFATE uses the equations reported by Ackers and White (1973) as the basis for the noncohesive sediment transport model. The equations are applicable to uniformly graded noncohesive sediment with a grain diameter in the range of 0.04 to 4.0 mm. Because many disposal sites are located in relatively shallow water, a modification of the Ackers-White equations was incorporated to reflect an increase in the transport rate when ambient currents are accompanied by surface waves (Scheffner et al. 1995).

Cohesive mound movement

An algorithm developed by Teeter and Pankow (1989) was incorporated into LTFATE to account for transport of fine-grained materials such as silt (0.004 to 0.072 mm) and clay (0.00045 to 0.004 mm). They reasoned that because of the differences in cohesion and settling characteristics, fine-grained sediments are sometimes characterized as the algebraic sum of expressions for settling velocity, deposition, and resuspension. Consolidation calculations are based on finite strain theory, which is well-suited in cases of thick deposits of fine-grained material. It provides for the effect of self-weight, permeability varying with void ratio, a nonlinear void ratio/effective stress relationship, and large strains.

LTFATE Application at Offshore Disposal Sites

LTFATE was used to determine long-term fate of dredged material placed at two open-ocean disposal sites: Humboldt, CA (Scheffner 1992) and Charleston, SC (Scheffner and Tallent 1994). Time series of waves and currents necessary for conducting the investigations were developed in the manner of Borgman and Scheffner (1991).

Humboldt Bay, CA

This research pertained to a site-designation study of the potential dispersion characteristics of an interim offshore disposal site located seaward of the entrance to Humboldt Bay, CA. Water depths at the site (1 sq n.m.) varied from 49 to 55 m. Concern arose regarding whether material could effectively be deposited within the designated site and remain within those limits over time. The long-term transport model computes sediment transport as a function of a time series of both waves and currents.

Wave and current time series. The wave time-series component of the input was specified as a statistical simulation of the 20-year hindcast database of WIS, Phase III, Station 69 sea conditions. Station 69 is located immediately off Eureka, CA. A 1-year time series of waves was generated. Current information was collected by EG&G Oceanographic Services for the

U.S. Minerals Management Service. Current data were obtained at two mooring sites, in water depths of 60 m and 90 m, respectively. Current meters were deployed during four time periods between April 1987 and October 1989.

Raw (unfiltered) data for each of the time series were obtained in the form of northerly (U) and easterly (V) components. Separate analyses of each data series were performed to determine the average value and magnitude, defined as the square root of the sum of the squared U and V components. Since sediment is primarily transported by local currents, the computed total magnitude of local currents provides an indication of maximum anticipated erosion rates. The computed average values of the separate components, however, provide a measure of net movement. For example, although the velocity magnitude may be sufficient to transport material, the net transport effect may be zero if the magnitudes first flood, then ebb, in equal magnitudes but in opposite directions.

Sediment transport capability. The analysis approach used by Scheffner (1992) was based on coupled hydrodynamic and sediment transport models that compute the transport of noncohesive sediment as a function of the local waves, velocity, and depth. The resulting distribution of transport was used in a sediment-continuity model to compute changes in the bathymetry of the sediment mound. Bathymetry-change computations were made at every 3-hr time-step.

Empirical relationships for computing sediment transport as a primary function of depth-averaged water velocity, local depth, and sediment grain size were reported by Ackers and White (1973). These relationships were subsequently modified (Swart 1976) to reflect an increase in sediment-transport rate when the ambient currents are accompanied by surface wave fields. This additional transport reflects the fact that wave-induced orbital velocities are capable of suspending bottom sediments, independent of the sediment put in suspension by mean currents. The total amount of sediment put into suspension by waves and currents is then transported by the ambient current field.

The modified Ackers-White relationships were used to compute the transport of two uniformly graded noncohesive sediments with grain diameters D_{50} of 0.063 and 0.28 mm. Since these sediments contained approximately 25 percent noncohesive sand, the noncohesive formulation was appropriate for simulating the overall sediment-transport rate.

Long-term analysis of site stability was based on both a 96-day simulated time series of wave and current data and an 8-day simulated storm-surge hydrograph. Results of the 96-day simulation indicated that movement of material would occur only during periods of large current activity. Analysis of the prototype data indicated that currents required for this movement occurred at a frequency of approximately 20 to 30 days. However, these large currents do not occur in a consistent direction. In fact, the long-term mean depth-averaged currents are on the order of less than 5 cm/sec. As such, the computed net migration of the mound for either material was only about 3 ft. This does not imply that sediment does not move, but that the net movement considering ebb and flood as well as spring and neap tides is essentially zero. Conclusions of the study indicate that for both materials, the proposed disposal site is basically nondispersive.

Charleston, SC

Dispersion characteristics of dredged material placement operations at the Charleston, SC, Ocean Dredged Material Disposal Site (ODMDS) were investigated. Proposed inner harbor deepening would require the disposal of approximately 3 million cu yd of material in the approximately 5- by 9-km designated site, located in relatively shallow water (35 to 40 ft deep). The primary focus of the study was to determine if material deposited at the designated disposal site would migrate to live coral reefs that were recently discovered within the boundaries of ODMDS.

Wave and current time series. The wave time-series component was specified as a statistical simulation of the 20-year hindcast database of the WIS, Phase III, Station 117 sea conditions. Station 117 is located immediately off Charleston, SC. A 1-year time series of waves was generated. Analysis of the velocity patterns in the vicinity of the ODMDS began with an analysis of the multiple-depth National Oceanic and Atmospheric Administration (NOAA) velocity gauges from the region, since those data provided information on current variations with respect to depth. Results were then supplemented and enhanced by single-gauge Environmental Protection Agency (EPA) current data obtained 6 ft off the bottom within the boundaries of the disposal site. Depth-averaged currents were appropriate since the site was in relatively shallow water.

Sediment-transport capability. Modified Ackers-White relationships were again used by Scheffner and Tallent (1994) to compute the transport of uniformly graded noncohesive sediment with grain diameters D_{50} of 0.063 and 0.1 mm, representing silt-size sediments and fine sand to be deposited a ODMDS. The stability analysis was made by estimating mound response to long periods of exposure to the simulated wave and current fields. In addition to the normal-condition simulation, a storm-event (moderate northeaster or small hurricane) analysis was performed in an attempt to investigate single-event-related erosion of the mound.

The long-term simulation indicated that the mound is dispersive whenever the current magnitudes exceed approximately 1.5 ft/sec; however, normal conditions are not sufficiently severe to cause massive erosion. Results of the storm-surge simulation showed the mound to migrate approximately 155 ft, many times the migration rate associated with normal waves and currents. Since storm currents can be directed in virtually any direction, long-term erosion can easily be storm-dominated. Computed migration rates do not, however, indicate rapid and massive erosion that would affect areas far removed from the mound. Therefore, as long as the disposal mounds are located a reasonable distance to the northeast of the reef area, there should be no significant long-term effect to the reef area (Scheffner and Tallent 1994).

ADCIRC Model

A finite-element numerical 3-D circulation model (ADCIRC) was developed by the DRP for the specific purpose of generating long time periods of hydrodynamic circulation along shelves and coasts and within estuaries. The intent of the model is to produce long numerical simulations (on the order of a year) for very large computational domains (e.g., the entire east coast of the United States). Therefore, the model was designed for high computational efficiency and was tested extensively for both hydrodynamic accuracy and numerical stability. The theory, methodology, and verification of ADCIRC are presented by Luettich, Westerink, and Scheffner (1992).

ADCIRC was developed to (a) provide a means of generating a database of harmonic constituents for tidal elevation and current at discrete locations along the east, west, and Gulf of Mexico coasts of the United States, as well as the west coast of the United States and eastern north Pacific Ocean and (b) utilize tropical and extratropical global boundary conditions to compute storm-surge hydrographs along U.S. coasts. The database of storm and tidal surface elevation and current data was developed to provide site-specific hydrodynamic boundary conditions for use in analyzing the long-term stability of existing or proposed dredged material disposal sites. The overall intent of this research was to provide a unified and systematic methodology for investigating the dispersive or nondispersive characteristics of a disposal site. These goals can be realized through the use of hydrodynamic, sediment-transport, and bathymetry-change models. ADCIRC provides the tidal- and storm-related hydrodynamic forcings necessary for site-specific site designation.

ADCIRC development

A model for computing the important features of circulation patterns driven by tides, wind, atmospheric pressure gradients, and ocean currents must be broad in scope and size. To simplify seaward boundary conditions, yet include important flow details, the model must encompass large domains while providing a high degree of resolution in high-gradient regions as well as in nearshore areas. This means the model should allow for the simultaneous solution of flow in continental shelf regions, coastal areas, and estuarine systems. The model should solve the three-dimensional conservation equations (thereby resolving the vertical profile of horizontal velocity) instead of the widely used depth-integrated conservation equations. This is necessary since it is impossible to assume a relationship between bottom stress and depth-averaged velocity that is generally valid for stratified flows, Ekman layers, and wind-driven circulation in enclosed or semienclosed basins or in cases where wave orbital velocities or suspended-sediment concentration gradients are significant near the bottom.

The requirements of very large domains (a high degree of horizontal resolution in portions of the domain (Figure 17), and the resolution of rapidly varying vertical profiles of horizontal velocity) place strenuous demands on even the largest supercomputers. The goal in the development of ADCIRC was to bring together algorithms that are highly flexible, accurate, and extremely efficient. The algorithms that comprise ADCIRC allow for an effective minimization in the required number of degrees of freedom for a desired level of accuracy, show good stability characteristics, generate no spurious artificial modes, have minimal inherent artificial numerical damping, efficiently separate the partial differential equations into small systems of algebraic equations with time-independent matrices, and are capable of running months to years of simulation while providing detailed intra-tidal computations.

During development of ADCIRC, a novel technique was discovered that replaces velocity with shear stress as the dependent variable in the internal mode equations. The resulting direct stress solution (DSS) allows physically realistic boundary layers to be included explicitly in a 3-D model. This formulation of the internal mode equations should be invaluable for modeling coastal and shelf circulation, in which the bottom and surface boundary layers comprise a significant portion of the water column, and for modeling processes that are critically dependent on boundary layer physics such as wave/current interaction, sediment transport, oil-spill movement, ice-flow movement, energy dissipation, physical-biological coupling, etc.

ADCIRC was developed and implemented as a multi-level hierarchy of models. A 2DDI (two-dimensional depth-integrated) option solves only the depth-integrated, external model equations using parametric relationships for bottom friction and momentum dispersion. A 3DL (three-dimensional, local) option uses horizontally decoupled internal mode equations to solve the vertical profile of horizontal velocity and to evaluate bottom friction and momentum dispersion terms for the depth-integrated external mode solution. A 3DLB (three-dimensional, local, baroclinic) option includes baroclinic terms as a diagnostic feature. Finally, the 3DL and 3DLB options solve the complete internal mode equations for nonstratified and stratified flows, respectively.

ADCIRC achieves a high level of simultaneous regional/local modeling, accuracy, and efficiency. This performance is a consequence of the extreme grid flexibility, the optimized governing equation formulations, and the numerical algorithms used in ADCIRC. Together, these allow ADCIRC to run with order of magnitude reductions in the number of degrees of freedom and the computational costs of many presently existing circulation models. A user's manual for ADCIRC-2DDI has been prepared by Westerink, Blain, and Scheffner (1994).

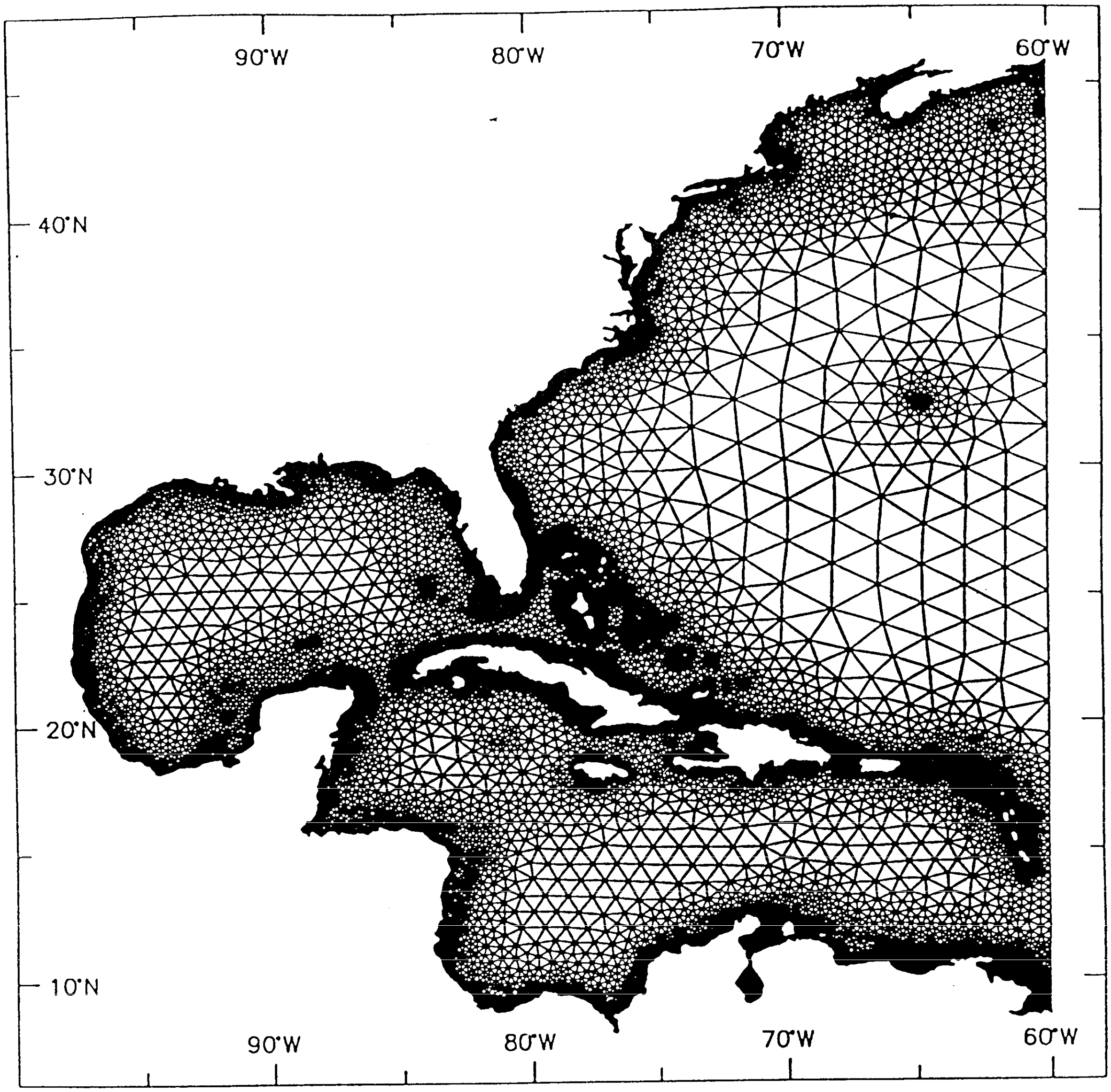


Figure 17. Example of domain size and grid spacing for ADCIRC (after Westerink, Luettich, and Scheffner (1993))

Tidal constituent database

Western North Atlantic and Gulf of Mexico. There has been a recent trend in coastal ocean tidal modeling towards using increasingly larger computational domains, which extend up to or beyond the continental shelf break and slope. Accurate tidal predictions can be conveniently obtained using large computational domains. Westerink, Luettich, and Scheffner (1993) and Scheffner (1994a) present results from a tidal model of the western North Atlantic, which encompasses the coastal ocean as well as the deep ocean. The computations were performed using ADCIRC-2DDI. Key features of the western North Atlantic tidal (WNAT) model are the definition of hydrodynamically simple open-ocean boundaries to facilitate the specification of boundary conditions, the use of a high degree of selective grid refinement to resolve the flow physics on a localized basis, and the coupling of the coastal ocean with a global tidal model.

The domain for the WNAT model encompasses the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. The WNAT model has an eastern open-ocean boundary that lies along the 60 °W meridian and is situated almost entirely in the deep ocean. The location of this open-ocean boundary was specifically selected to simplify the difficult task of specifying an accurate set of boundary conditions for a coastal-ocean tidal model. The WNAT model open-ocean boundary offers a variety of significant advantages. First, the boundary is geometrically simple and includes no discontinuities or corners. Second, the boundary lies almost entirely in the deep ocean where tides vary gradually. This avoids the difficulty of specifying complex and highly variable cross-shelf boundary conditions over most of the open ocean boundary. Furthermore, this open-ocean boundary is ideally suited for coupling with global tidal models, which should be most accurate in the deep ocean. Third, nonlinear tidal constituents will not be significant on this open-ocean boundary since they are generated on the continental shelf and are largely trapped on the shelf due to the out-of-phase reflective character of the continental slope.

The size of the resulting computational domain of the WNAT model exceeds 8×10^6 km^2 and is therefore very large in terms of coastal-ocean tidal models. It is clear that uniformly discretizing the entire domain with the resolution required in regions of rapidly varying flow would substantially increase the size of the discrete problem. In fact, in deep ocean regions that account for more than three quarters of the domain, a relatively coarse discretization should resolve all flow features of interest. However, on the continental shelf, propagation speed and wavelength of tidal waves decrease with decreasing bathymetric depth and therefore require an increasingly finer discretization. Flow also varies much more quickly in regions of rapidly varying topography, such as in the vicinity of the continental shelf break and the continental slope, as well as near the coastal boundary. Therefore, these regions should require a greater resolution than deep ocean regions.

In order to realize tidal computations on grids with a very high degree of grid flexibility, a generalized wave continuity equation (GWCE)-based finite-element (FE) shallow-water model was implemented. GWCE-based FE solutions to the shallow-water equations have been demonstrated by Westerink, Muccino, and Luettich (1992) to lead to highly accurate and robust hydrodynamic circulation predictions within the coastal and deep oceans.

Resolution requirements for the WNAT model were systematically examined by Westerink, Luettich, and Scheffner (1993) using the entire model domain. It was vital to establish the level of convergence achieved with the grid resolution used in the computational domain. Computations for a sequence of regularly discretized grids, ranging from a very coarse (1.6° ×

1.6°) mesh to a very fine (6' × 6') mesh are presented. These computations are compared to a sequence of irregularly graded grids with resolutions varying between 1.6° and 5' within each mesh. In the development of an optimal graded grid, the resolution requirements in regions of rapidly varying topography, as well as the resolution of the coastal boundary, were carefully considered. The final optimal-graded grid has a tidal response that is comparable to that of the finest regular grid in most regions. Computed cotidal charts are presented for eight astronomical constituents and comparisons are made between the computed results and field data at 77 stations within the WNAT domain.

The WNAT model grid-convergence studies demonstrate that convergence to solutions within 1- to 2-percent error in amplitude and 2° to 3° in phase have generally been achieved, with the exception of the Gulf of Mexico and Caribbean, where persistent errors occur in semidiurnal constituent phases. The latter problems appear to be associated with amphidromes whose locations shift readily.

Eastern North Pacific. Hench et al. (1995) presented results from a numerical tidal model of the eastern North Pacific that encompassed the coastal ocean as well as the deep open ocean. The simulations were performed using ADCIRC-2DDI, the same code used earlier by Westerink et al. (1993) for the entire western North Atlantic.

The size of the eastern North Pacific tidal (ENPACT) model is nearly 2×10^7 km^2 and would be computationally prohibitive to discretize in a uniform manner at the resolution required to resolve the rapidly varying flow features on the shelf. Therefore, a graded finite mesh was designed to minimize the size of the discrete problem, while still resolving the flow features of interest (Scheffner 1995).

The model was forced with five astronomical constituents on the open boundary derived from a state-of-the-art global tidal model. In addition, a realistic tidal potential forcing was applied to the interior of the domain. The simulations were intended to be entirely predictive, so no tuning or calibration procedures were performed.

Tropical storm database for the east and Gulf of Mexico coasts of the United States

Scheffner et al. (1994) and Scheffner (1994b) summarize results of a numerical storm-surge study conducted for the east and Gulf of Mexico coasts of the United States. They describe a database of surge elevations and currents produced from the numerical simulation of 134 historically based tropical storm events and their maximum water-level surge impact at 486 discrete locations along the east and gulf coasts and Puerto Rico. A visual indication of the spatial distribution of peak surge elevation is provided in the form of an atlas of storm track and maximum storm surges corresponding to a 246-station nearshore subset of the 486-location database.

The hydrodynamic model ADCIRC-2DDI was used for the storm-surge simulations. Blain et al. (1994, 1995) investigated the influence of domain size and grid structure on the response characteristics of a hurricane storm-surge model, and the optimum domain and grid were appropriately selected. Storm-surge elevations and velocities corresponding to each storm were computed over a very large domain encompassing the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. Previously, this domain was shown to accurately represent the peak storm surge as well as resonant modes associated with the storm-surge response. The generation of data contained in the atlas is based on use of the NOAA National Hurricane Center's hurricane database (HURDAT), the planetary boundary layer (PBL) hurricane model, and ADCIRC-2DDI.

Although the database was developed to provide input to a model that evaluates the long-term fate and stability of dredged material, the potential use of such a database goes far beyond the testing of disposal-site stability. The database can be used to provide offshore or nearshore boundary conditions for any type of coastal modeling or analysis requiring storm-generated elevation or current data, thus providing a benefit for all users requiring storm design criteria.

The accuracy, flexibility, and ease of applicability of this numerical approach of coupling with the National Hurricane Center's Hurricane Data Base (HURDAT), the PBL model, the tidal database, and the ADCIRC hydrodynamic model on a continental-scale, high-resolution grid has been demonstrated. Results imply that an application to real-time predictions of storm propagation should be pursued. The primary goal of the research has greatly exceeded original intent by representing a very comprehensive and realistic database of storm data which can be used for a great variety of applications in coastal engineering.

7 Numerical Simulation Techniques Combining Short- and Long-Term Fate Computations for Multiple Dump Fate (MDFATE)[1]

A dredging project which includes open water disposal of dredged sediment typically consists of numerous dredged material placements ranging from a few to more than a thousand. The operational duration of such projects can range from days to months. The life cycle of an offshore ODMDS may be many years.

A multiple dredged material placement model has been developed by Moritz (1994) to predict post-disposal bathymetry for ocean dredged material disposal sites. This PC-driven numerical simulation model for multiple dump fate (MDFATE) incorporates existing numerical models to simulate the overall (short- and long-term) behavior of dredged material placed within an open water disposal site. MDFATE spatially accounts for bathymetric change within an offshore disposal area, and can be used to assist with selection of the most efficient layout for a proposed disposal site or provide guidance for optimizing dredged material placement operations.

Overview of MDFATE

MDFATE defines an ocean dredged material disposal site in terms of a numerical grid and incorporates two existing models (STFATE and LTFATE) to predict or verify ODMDS bathymetry resulting from a series of disposal cycles or "dumps." In this regard, STFATE and LTFATE are used independently within the MDFATE simulation.

[1] Chapter 7 was extracted from Moritz (1994).

Discretizing an ODMDS

As a first step in simulating a disposal operation, MDFATE is used to produce a discretized representation (rectangular grid) of the ODMDS which is of interest. All that is required from the user is the ODMDS corner coordinates. Horizontal control is manifested in terms of the coordinate system actually used at the site. State plane (feet) and latitude-longitude (degrees) coordinates are currently supported. Up to 9,500 nodal points can be used to represent a given ODMDS in terms of an MDFATE grid. This is sufficient to represent a 9,000- by 9,000-ft ODMDS in terms of a 100-ft grid interval.

Bathymetric data are represented in terms of the elevation reference datum used at the site. Subsequent modification of the ODMDS grid's bathymetry is performed with respect to the datum established during the creation of the disposal area grid. MDFATE can either automatically generate the ODMDS grid bathymetry (flat or sloping) or overlay survey data (ASCII format) consistent with the actual site's coordinate system. Survey data are adapted to the grid domain by a multipoint polynomial interpolant scheme.

Simulating a disposal operation

Once a particular ODMDS grid has been created, MDFATE can be used to simulate a given disposal operation which may extend over a year and consist of hundreds of disposal cycles or dumps. A dump consists of one load of dredged material being released into open water from either a barge/scow or hopper dredge.

During MDFATE execution, the disposal operation is divided into separate week-long episodes over which long-term fate processes governing dredged material behavior on the seafloor are simulated using a modified version of the LTFATE model. Results are modeled in a cumulative manner. Long-term processes include self-weight consolidation, sediment transport by waves and currents, and mound avalanching.

Within each episode, a modified version of STFATE simulates short-term fate processes which govern each dump occurring inside the ODMDS grid of interest. Short-term processes are those which influence disposed dredged material up to the point at which all momentum imparted to the material from the dump activity is expended through convection, diffusion, and bottom friction.

MDFATE utilizes HPDSIM and the tidal constituent databases (portions of the LTFATE model) to generate wave and tidal information for every 3-hr interval during the disposal operation. This information is utilized by the modified STFATE model within MDFATE to simulate wave/current effects acting upon each dump as dredged material passes through the water column and comes to rest on the seafloor. STFATE produces a characteristic footprint for each type of dredged material type/disposal method involved in the disposal operation. The resultant disposal footprint is used to represent each dredged material placement.

MDFATE specification of-the disposal operation is performed through a menu-driven format in which the user specifies basic data defining (a) tidal and wave information, (b) volume of dredged material to be disposed, (c) duration of disposal, (d) disposal equipment characteristics, (e) dredged material properties, and (f) water column current. Positioning and control of the disposal vessel during material placement are specified according to one of the following options:

a. Within a specified radial distance of a pre-determined geographic location (i.e., coordinates defining a disposal buoy location). Dumps are placed in a random manner weighted in the direction of disposal vessel approach.

b. Along a pre-determined transect line based on beginning and ending coordinates.

c. Each dump location defined by user-entered coordinates.

d. Dump locations based upon pre-recorded coordinates for each load. Coordinates are contained in an ASCII data file queued by MDFATE.

The simulated disposal operation is concluded when all dumps for the disposal operation have been superposed and the long-term fate simulation has been completed for the specified time interval

MDFATE support options

Within MDFATE are a variety of viewing, sensitivity testing, and post-processing utilities. These options can be used to edit/update MDFATE grid bathymetry, develop two- and three-dimensional views of ODMDS bathymetry, quantify nominal sediment transport rates, calculate sediment volumes, and determine relative differences between grids.

MDFATE hardware requirements

The source code for the MDFATE program was written in FORTRAN and intended for use on an Intel 80486 CPU-based IBM or equivalent PC with a math co-processor, or PENTIUM-based PC. The disk operating system of the PC should be DOS 5.0 or higher.

A VGA monitor and 526 KB of uncommitted DOS-controlled random access memory (RAM) are required for MDFATE execution. Pre-existing resident software may compete with the MDFATE RAM requirements. Therefore, the CONFIG.SYS and/or AUTOEXEC.BAT files may require modification if resident software prevents MDFATE execution. Minimum hard-disk storage capacity required by MDFATE is 8 MB.

MDFATE software requirements

Software required to fully utilize MDFATE includes the DOS PC operating system and the MDFATE software package. Items included in the MDFATE package are:

a. MDFATE shell programs.

b. Short- and long-term modeling programs and data files.

c. Grid generation and editing programs.

d. Wave field and tide-generating programs.

e. Program installation for video and printing access.

f. Utility programs for viewing, volumes, transport rates, etc.

Prototype Application of MDFATE[1]

A prototype application of MDFATE was performed by Moritz (unpublished manuscript) where the final surveyed and predicted bathymetry within an actual open water dredged material disposal site were compared. Comparison of the actual site post-disposal and MDFATE-predicted bathymetry was based upon volume and spatial distribution assessments of dredged material placed within the Wilmington, NC, ODMDS, September 1990-April 1991.

Site description

The disposal site is located approximately 25 miles south of Wilmington, NC, at an approximate water depth of 40 ft. The site is rectangular in shape, having dimensions of about 8,500 ft by 8,400 ft. Although this disposal site is classified as dispersive, moderate temporal mounding of disposed dredged material has been documented (Boone and Payonk 1991). During non-summer months, the current at this ODMDS is dominated by a rotary tidal current with a mean depth-averaged amplitude of about 3.38 ft/sec.

Dredging and environmental data for this site were obtained for the period September 1990 through April 1991. The disposal site wave, current, and tidal data, and the volumetric quantities and placement location for each load of

[1] This section of Chapter 7 was extracted from Moritz (unpublished manuscript).

dredged material were used by MDFATE to predict bathymetric conditions resulting from the 7-month disposal operation. Additionally, the August 1990 pre-disposal and April 1991 post-disposal bathymetric surveys were used. The bathymetry survey interval was 250 ft. Horizontal and vertical uncertainty were estimated not to exceed ± 9.8 ft and ± 0.5 ft, respectively.

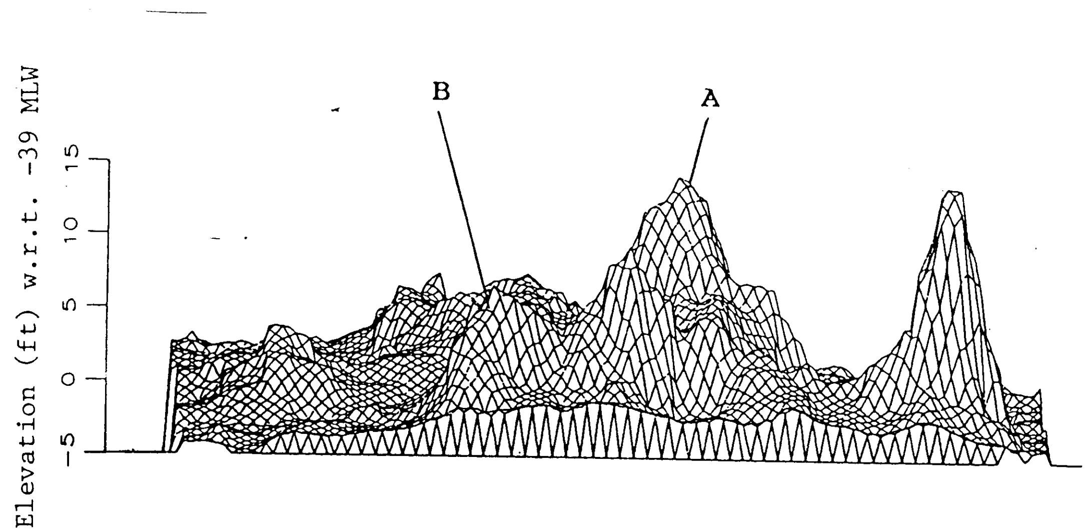
Dredged material description

Dredged material removed and placed using the hopper dredge *McFarland* was classified as clean sand (D_{50} = 0.10 mm) with an in-place (before dredging) density of 1,580 gm/ℓ. Dredged material which was removed using a mechanical dredge and placed using bottom dump scows was classified as silty-clay (D_{50} = 0.009-0.04 mm). To model the short-term fate of dredged material placed at the ODMDS, volumetric concentrations and void ratios for the dredged materials were estimated. The post-dredged (pre-disposal) volumetric concentration (solid/mixture) for the sand-based sediments was estimated to be 0.60, and its post-depositional void ratio was estimated to be 0.80. The post-dredged (pre-disposal) material volumetric concentration and post-disposal void ratio for the silt-clay material were estimated to be 0.40 and 1.7, respectively.

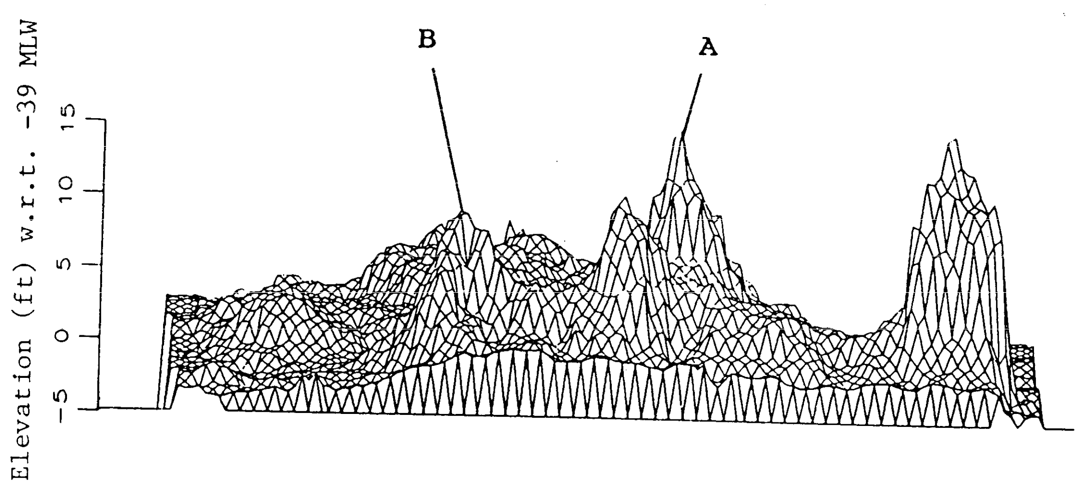
MDFATE short- and long-term simulations

Actual pre-disposal survey data taken at 250-ft intervals were discretized by MDFATE to reproduce the 8,500-ft by 8,400-ft disposal site in terms of a 100-ft-square element grid. MDFATE simulated the cumulative dredged material distribution for the entire dredging disposal operations. A total of 869 individual loads totaling 2,400,000 cu yd of dredged material was placed on the baseline bathymetry according to the recorded coordinate locations for each disposal event. Short- and long-term simulations were performed for the 7-month period under the environmental conditions appropriate to that time period.

A quantitative assessment of MDFATE and actual post-disposal bathymetry is shown in Figure 18. The simulated mound feature associated with the "A" location was slightly smaller in height (13 percent) and slightly larger in diameter (5 percent) than the actual case, and was located 500 ft northeast of the actual surveyed "A" mound location. The simulated "B" mound was somewhat smaller in height (35 percent) and diameter (8 percent) than the actual case, and was situated 420 ft southeast of the actual surveyed "B" mound location. Moritz (unpublished manuscript) believes the difference in spatial orientation could have been due to the residual current at the site differing from the assumed value, or disposal vessels being under way during material placement (vessels were assumed stationary during disposal).



a. Simulated post-disposal bathymetry



b. Actual post-disposal bathymetry

Figure 18. Cross sections of post-disposal survey for Wilmington, NC, offshore dredged material disposal site, April 1991 (after Moritz, unpublished manuscript)

Benefits of MDFATE

The manager of an ODMDS must simultaneously address the needs of obtaining regulatory approval for open-water disposal of dredged sediments, ensure environmental compliance, and maximize disposal site efficiency. In order to satisfy these constraints, the ODMDS manager must ensure that dredged material placed offshore does not accumulate in a fashion that would pose a navigational hazard, demonstrate that adverse impacts to significant resources do not occur, and attain maximum utilization of site volumetric capacity. Given these operational constraints, the proper management of many disposal sites requires a sophisticated methodology to quantitatively predict and assess the behavior of dredged material placed in ODMDS's.

MDFATE was developed by Moritz (1994) to bridge the gap between the modeling of individual disposal events or dumps and tracking a myriad of disposals that occur within a disposal area over the duration of a disposal site's operative cycle. With the flexible options of MDFATE, many aspects of open-water dredging and disposal operations can be examined and predicted at various levels of quantification. Thus, MDFATE should prove to be a valuable asset in managing ODMDS's.

Other potential uses of MDFATE include subaqueous capping of contaminated sediments, assessment of feeder berms/nearshore beach nourishment, and assessment of offshore pipeline/cable-burying techniques.

8 Field Techniques and Data Analysis to Assess Open-Water Disposal

At the initiation of the DRP, available field data were inadequate to predict the fate of dredged material placed in open water nearshore for wave attenuation to reduce shoreline erosion, as feeder beach material, and to simply reduce transportation costs to more distant disposal sites without increasing maintenance dredging costs by material returning to the navigation channels. Uncertainties existed about all of these aspects. Long-term site monitoring was required to (a) collect extensive, reliable field data to document the configuration and fate of disposed deposits, (b) improve monitoring and data-analysis techniques, and (c) develop an empirical methodology for predicting the overall response of the disposal deposit based on parameters readily available to planners and site managers.

To answer these questions, data were collected at 11 nearshore placement sites around the Atlantic, Pacific, and Gulf of Mexico coasts. Long-term data were collected on the erosive processes at each site, the fate of the placed material, and other site characteristics. All but one of these placement efforts were intended to be feeder deposits that would be moved shoreward by natural forces. There was a wide difference, however, in the actual berm responses. Results for all the sites are reported in Hands (1991) and Hands and Resio (1994) along with references to reports on each individual site. The following sections describe the monitoring efforts and results from the more intensely studied of these sites.

Monitoring Mobile, AL, Berms

Growing concern for environmental quality and proper use of resources has increased demand for beneficial uses of dredged material. Submerged mounds of dredged material are being placed nearshore for various purposes. It is crucial that the placed material not disperse too rapidly if there are adjacent sensitive resources that could be adversely impacted. Some beneficial uses of dredged material require that the material remain in the disposal site; a few uses even require material retention in specific design configurations. In other cases, dispersion can be beneficial. In all cases, the fate of the material remains a concern long after disposal is completed.

In 1987, the Corps initiated the national berm demonstration project (NBDP) off the Alabama coast. The purpose of the NBDP was to better understand the long-term fate of dredged material and ancillary benefits possible with its correct placement. The long-term fate of mounded material, its environmental impacts, and results from environmental monitoring at the NBDP site have been documented. Wave and bottom-current measurements obtained by McGehee et al. (1994) were used by Douglass, Resio, and Hands (1995) to investigate ways that natural forces can disperse material placed on the seafloor.

Descriptions of berms[1]

Three Alabama berms (Figure 19) were monitored for several years. Over 25 wide-area surveys were conducted, including side-scan, subbottom, and bathymetric surveys. Bottom samples and long-term measurements of the erosive processes were obtained. The largest of the three berms was planned as a retention site; two smaller berms closer inshore exhibited different degrees of dispersion and migration.

Sand Island Bar (SIB). The SIB was built in early 1987 using about 464,000 cu yd of entrance channel maintenance material (Hands and Bradley 1990). Prior to the major Mobile Harbor Deepening Project, the then 1.5-mile-long, 42- by 600-ft outer channel across the Mobile ebb-tidal delta trapped an average of 324,000 cu yd of material annually. To test a plan for returning this fine clean sand to the active zone of littoral transport, the 1987 maintenance-dredged material was placed along a 500-ft-wide corridor centered on the 19-ft contour. The resulting feature was a 6,000-ft-long, 6-ft-high bar that closely matched anticipated nearshore berm dimensions. The objective of the SIB was to save beach-quality sand from conventional deepwater placement and document what effect gulf waves might have on a berm placed well below the depth of previously observed dispersive deposits.

Sand Island Mound (SIM). The SIM was a preexisting, man-made mound included in the survey area with the SIB. This smaller (29,000 cu yd) symmetrical mound was apparently a product of recent gas well operations. The SIB and SIM are both composed of well-sorted fine-grained sand like the ambient materials on the outer Mobile ebb-tidal delta and are much more uniform than the heterogeneous mixture that went into the Mobile Outer Mound.

1 This section of Chapter 8 was extracted from Hands and Bradley (1990) and Hands et al. (1992).

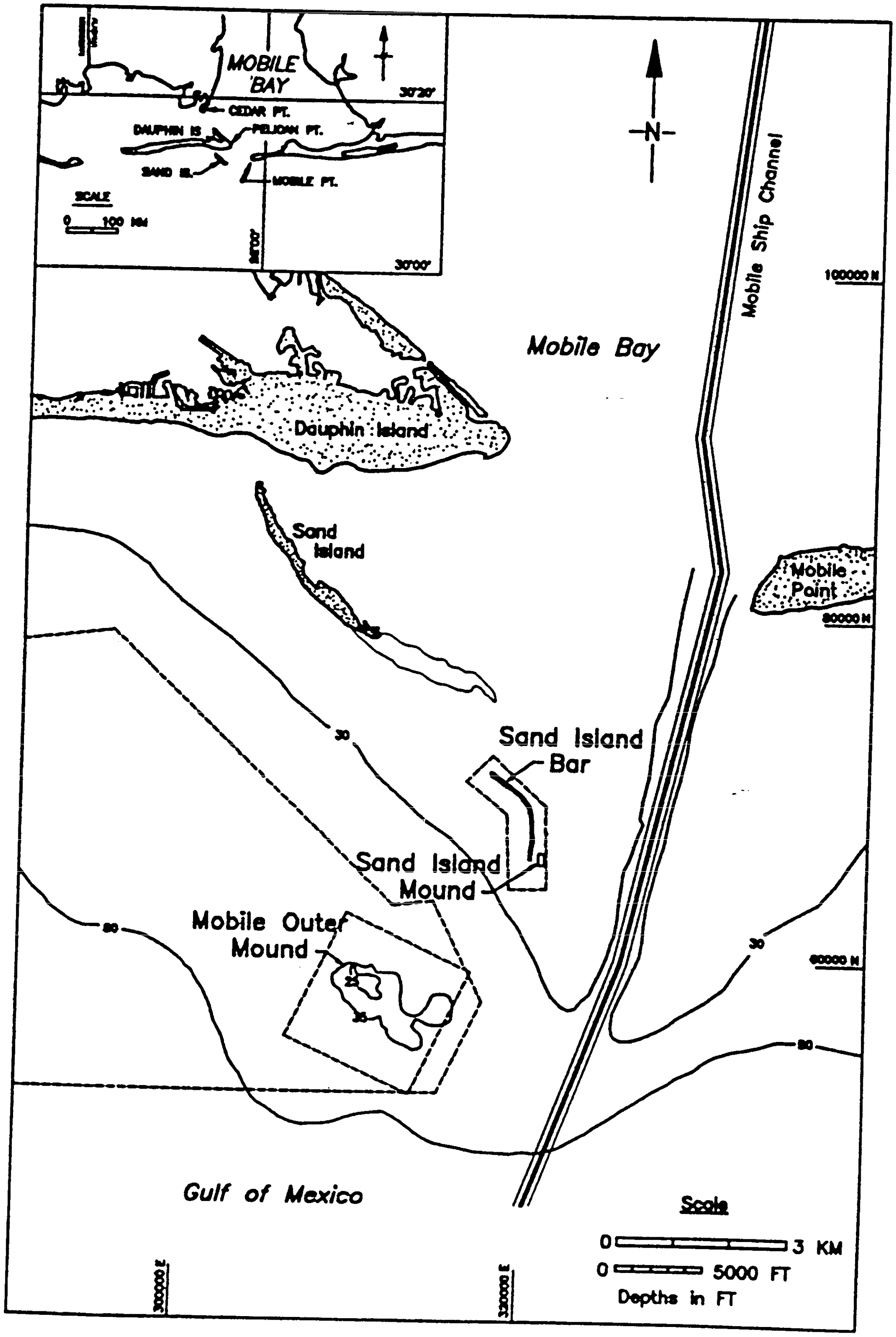


Figure 19. Berms of the NBDP monitored by the DRP

Mobile Outer Mound (MOM). Construction of the MOM began with initiation of the Mobile Harbor deepening project in February 1988 (Hands et al. 1992). About 17,000,000 cu yd of widely varying materials were excavated over a 27-month period to increase the authorized channel depths an additional 5 ft for about 35 miles from the gulf through Mobile Bay to the Port of Mobile. A mechanical dredge removed all of the new-work material, usually with a 50-cu-yd clamshell bucket, but switched to a smaller dipper bucket as needed to dig denser materials. All of the new-work material was carried to the MOM by four 6,000-cu-yd split-hull barges. The character of the dredged material varied from sand and silt to clay as work proceeded along the channel.

Field monitoring study[1]

A monitoring study was performed by WES to document short-term response (several years) of the MOM and SIB, the effect of the mounds on the local physical environment, and the environmental conditions that determined the fate of the placed material. Monitoring objectives at the MOM were to ensure compliance with local regulatory requirements, assess the mounding characteristics of fine-grained material, and document effects that such a large mound could have on incident waves and fisheries. The objective of monitoring the SIB in shallower water was to document the fate of beach-quality sand mounded at a depth below any previously observed feeder berm.

Monitored areas. The four areas shown in Figure 20 were selected for monitoring. Area 1 for study of the SIB (active berm) and Area 2 for the MOM (stable berm) are at about the same depth as the corresponding features but sufficiently remote to be unaffected by either feature. Area 3 was designated to document by comparison with Area 2 the reduction of the incident energy by the stable berm. To provide data on sediment suspension and transport, measurements were made at the crest of the active berm, Area 4, where most transport was expected to occur.

Sensors for waves and currents. Typical wave conditions range from near-calm to steep locally generated wind waves up to 10 ft in height, with periods in the range of 4-9 sec, to storm-generated swell with periods in the range of 10-12 sec. Waves shorter than 4 sec were judged to have no significant impacts on the mounds, and waves longer than 12 sec are rare in the gulf. During a hurricane, depth-limited or even breaking waves (i.e., on the order of 16 ft in height) may approach the active berm. The resulting conditions on the active berm would be extremely violent (McGehee et al. 1994).

While wave conditions represent a hazard on occasion, it was recognized that trawling activity represented the highest risk to any instrumentation in this region. Fishing trawlers drag large nets across the seafloor, which could snag

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[1] This section of Chapter 8 was extracted from McGehee et al. (1994).

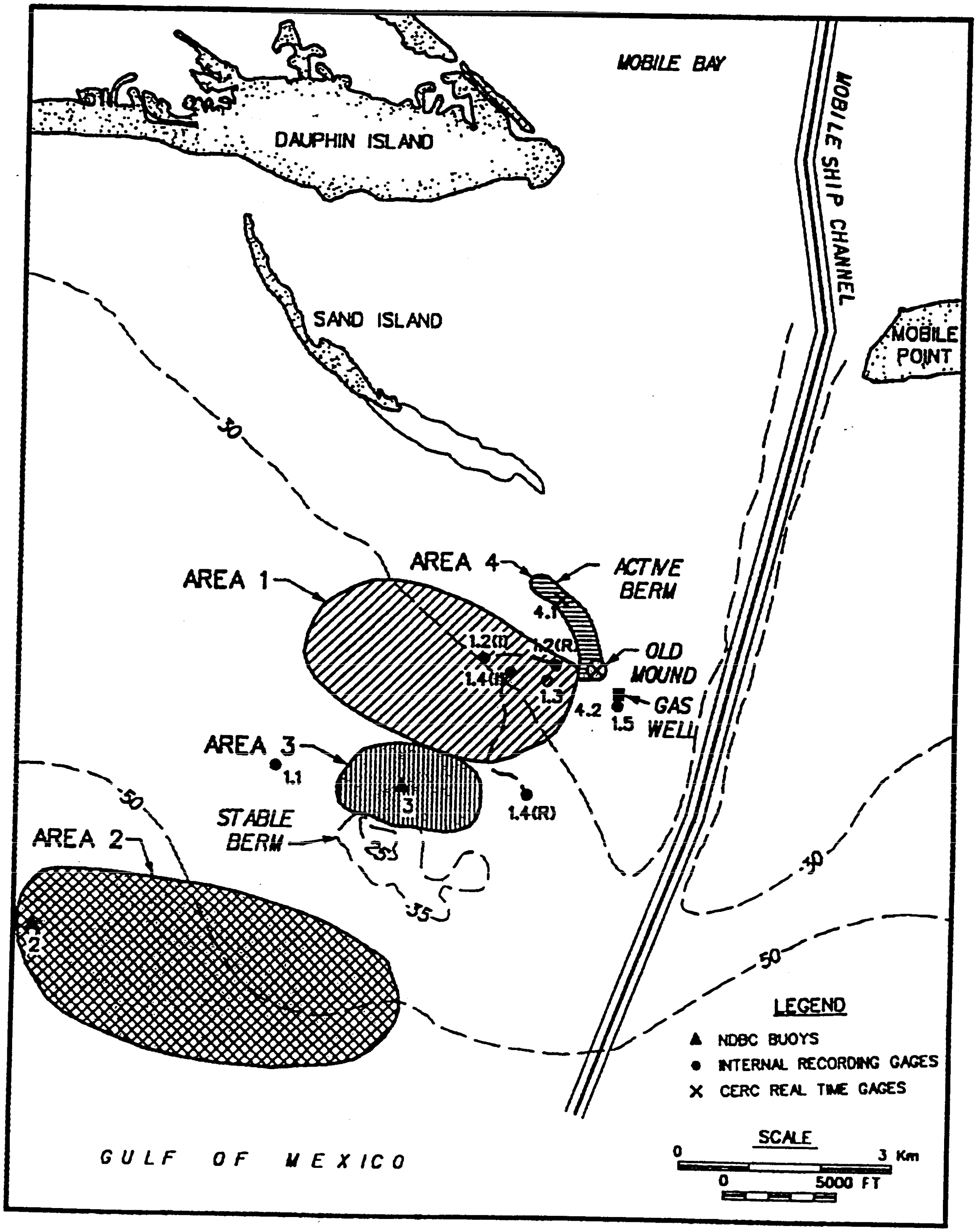

Figure 20. Instrumented sites for monitoring Mobile, AL, dredged material disposal sites

or remove unprotected instruments. Buoys marking a site have not proven an adequate defense, as they are routinely overrun, particularly when newly placed in a fishing area. Massive structural defenses interfere with the currents to be measured and potentially with the response of the mound.

WES has found that bottom-mounted pressure transducers are reliable rugged sensors that can provide relative water levels and nondirectional wave conditions when used singularly, as well as directional wave information when used in arrays. Another method of obtaining directional wave parameters is by measuring pressure P and the two horizontal components of the orbital velocity (u, v) with a current meter—the PUV gauge (Figure 21). Analysis of the current-meter signal also provides instantaneous and mean current data. An electromagnetic current meter is usually used since it has no moving parts to foul or clog. However, the depth-attenuated pressure and orbital-motion response of surface waves limits bottom-mounted PUV gauges to shallower depths for higher frequency waves. While suitable for the 10- to 15-ft depths of Area 4 and the 20- to 30-ft depths of Area 1, they were judged not adequate to resolve waves shorter than 6 to 8 sec in the depths near the stable berm.

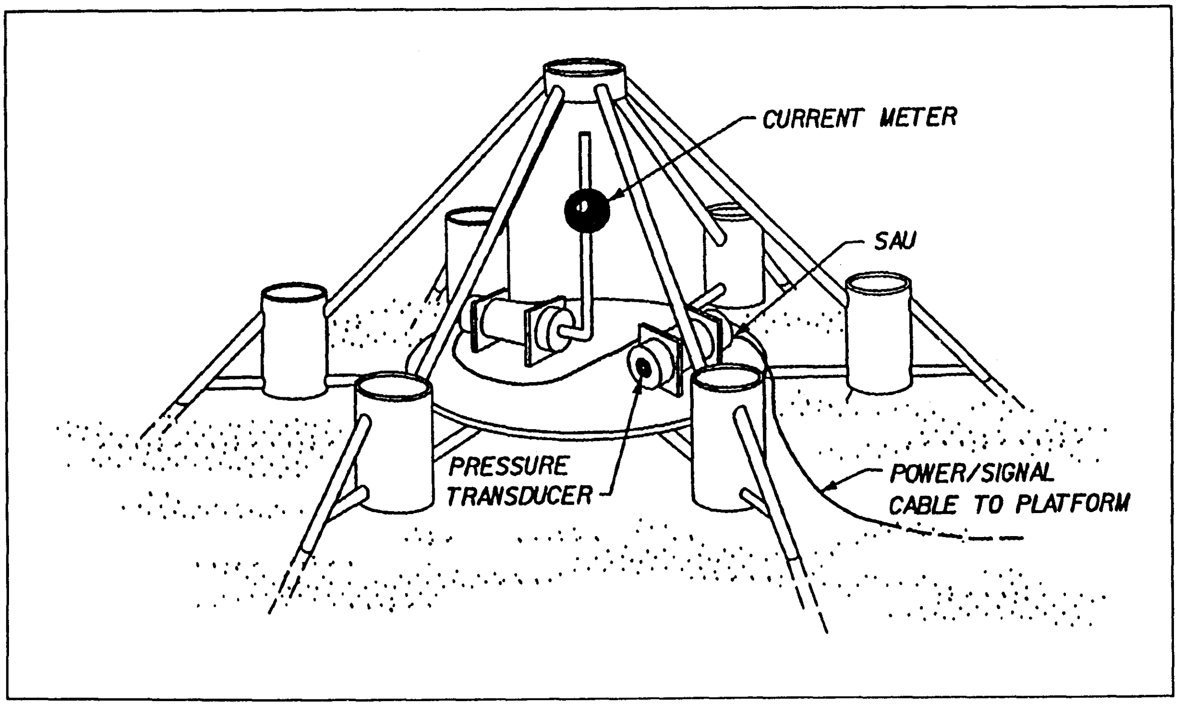

Figure 21. WES-developed PUV gauge used for monitoring waves and currents

Another approach to measuring directional waves is the pitch-roll-heave surface-following buoy. It is unaffected by pressure attenuation, but it is not as well-suited for shallow water since it violates the surface-following assumption in steep waves, and short moorings affect the motion in nonlinear ways. One of the first such systems developed by the National Data Buoy Center (NDBC) was available for deployment in August 1987. This buoy measures wind, atmospheric pressure, air and sea temperatures, and waves. Water depths of 40 to 50 ft made the NDBC buoy a logical choice in Areas 2 and 3.

Obtaining current measurements from a buoy is complicated by the motions of the buoy and the mooring. Separate bottom-mounted current meters in addition to the buoys were not within the monitoring budget. However, orbital velocities can be deduced using linear wave theory from the directional wave data. Tidal elevations and tide-induced mean currents do not vary significantly over distances on the order of miles (as long as the bathymetry changes are gradual), so these could be adequately represented at Areas 2 and 3 by the measurements at Area 1. On the other hand, currents can be significantly different on the top of the active berm because the steep slopes will directly affect the currents by deflecting incident flow, and its location in a potential breaker zone can result in setup or setdown that will affect the local hydraulic gradient. This was another consideration in selecting a PUV gauge for Area 4.

Analysis of field results[1]

Douglass, Resio, and Hands (1995) analyzed the actual field measurements obtained by McGehee et al. (1994) of waves and currents to assess which flow mechanisms are responsible for long-term landward transport of material from large submerged sand bodies. Near berms shown to be persistently migrating, gauges measured bidirectional currents at a sampling interval of 1 Hz over 17-min bursts repeated four to six times per day. Most gauges operated in this mode for months. Instruments were moved among seven stations over a period of 4 years. Data-retrieval history is shown in Figure 22. Three instrument stations were established offshore, two stations just seaward of and two on top of, the migrating sand berms (SIB and SIM). Elevations of the wave sensors above the seafloor ranged from 1.4 to 0.4 m.

Mechanisms for inducing berm movement. To begin assessing why berms move, a simple conceptual model of the basic mechanics of sediment transport was proposed by Douglass, Resio, and Hands (1995). This conceptual model included five fundamental mechanisms that could be evaluated against data. For simplicity, those mechanisms can be referred to as:

a. Dominant advection by mean currents.

b. Temporal organization of velocities on scales of wave periods.

c. Strongly correlated entrainment and advection on scales of hours.

d. Nonlinearities of wave oscillations.

e. Feedback between the berm and the flow field.

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[1] This section of Chapter 8 was extracted from Douglass, Resio, and Hands (1995).

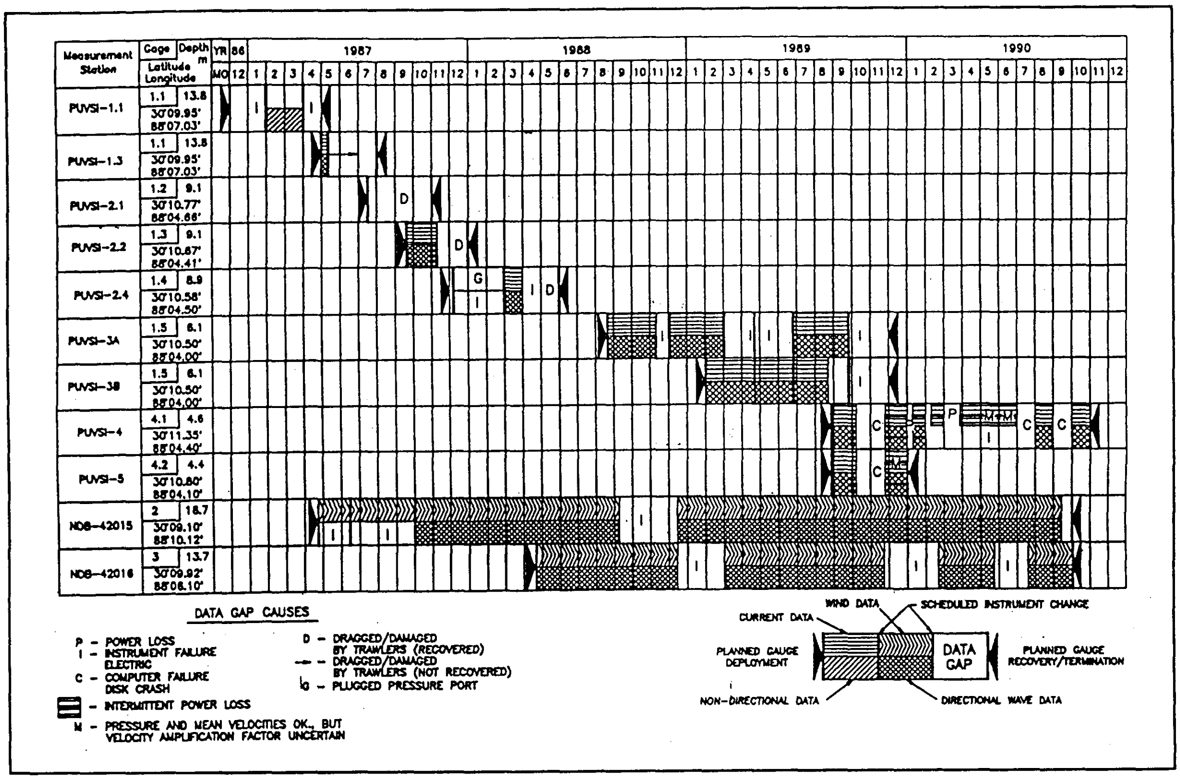

Figure 22. Data retrieval history for Mobile, AL, dredged material disposal mounds

Mean current speeds were small, and there was no constant or strongly dominant direction of mean flow. Because of the long duration of measurements and the simple pattern of berm movement, however, the first and third proposed mechanisms, a and c, could be eliminated as unimportant for berm movement at this site. No clear basis was found in the data to support the second mechanism, b. Differences in the characteristics of currents measured on and off berms were small and not clearly related to berm movement. Nonlinearity, perhaps in combination with a berm feedback mechanism, was seen in the data and appears to be the important movement mechanism. Both feedback and nonlinearity should be common to all wave-dominated placement sites, suggesting that dredged sand could be widely used as feeder deposits that would mitigate coastal erosion problems.

Berm migration. Though the completed stable berm (MOM) had been in place less than a year at the time of the report by Hands et al. (1992), fish surveys began in 1989. Both anecdotal and scientific data indicate a favorable habitat is provided by the MOM for several desirable fish species, in particular red snapper. Differences in wave heights on opposite sides of the MOM indicate substantial wave energy may be dissipated or scattered over this broad berm. It was too early to project the long-term stability of the MOM, but the dredged material mounded and remained onsite during the initial years of construction. Most of the placed material is expected to remain there for many years because of its mass.

Since the SIM and SIB were built earlier and monitored more frequently, their long-term fates are clearer than the fate of the MOM. They are both composed of a fine-grained sand and rose to peak elevations near -12 ft mean low low water (mllw) in early 1987. The main change during the first year was a flattening of scattered areas that rose above -13 ft mllw. The greatest erosion occurred on the southern end of the 6,000-ft-long SIB, where in a small area the berm eroded down to -18 ft mllw. This gulfward-extending tip of the SIB retreated about 300 ft northward. It is unclear where this relatively minor volume settled. The overall shape and size of the SIM and SIB remained essentially unchanged, and the concept of returning dredged material to the nearshore was verified in the sense that there was no evidence that material was being lost into deeper water. However, it was not confirmed that the deposit was actually feeding the active littoral system.

The SIM has continued to move slowly northward. The persistence of this landward migration over 3 years substantiated that the migration was significant and is likely to continue, although the rate may be declining. Moreover, on the northwesterly section of the bar where the elongated SIB is oriented nearly transverse to wave approach, a section of the bar also has migrated landward. Having traversed a flat area, the migrating section of the SIB now lies at the base of the steeply inclined face of the Mobile ebb-tidal delta. Shoals at the top of a delta marginal ridge are only a few feet below mllw. Preferential ebb-delta accretion is already evident leeward of the SIB. This is directly analogous to the concept of beach-erosion control through a combination of wave dissipation and direct nourishment by a nearshore feeder deposit.

Conclusions regarding berm movement. Preliminary analysis indicates the MOM is reducing wave energy to its lee. Conclusions by Douglass, Resio, and Hands (1995) regarding the dominant mechanisms affecting mound stability are based on analysis of the process measurements plus movement of the SIM and SIB toward the north-northwest. This motion is toward the coast and in the general direction of large wave propagation. Relative to the five hypothesized mechanisms of Douglass, Resio, and Hands (1995), the following conclusions were reached:

a. Related to the possibility that northward currents at on-mound sites are larger than at off-mound sites, it was found that mean currents were directed toward the offshore at both on-mound and off-mound sites. Furthermore, alongshore mean currents were somewhat larger than the onshore/offshore currents; so if mean currents play a dominant role in mound migration, the mound should not simply migrate shoreward as reported.

b. Concerning a positive correlation between sediment entrainment and northward currents, large waves were found more likely to be accompanied by mean currents in the offshore direction. This means that the observed correlation also fails to explain northward mound migration.

c. Concerning nonlinearities in currents, coefficients of landward skew were found to increase for larger waves. This could explain a tendency for northward sediment transport. Specific events with skew were the passage of a hurricane and southerly seas related to typical winter weather patterns. However, coefficients of skew at off-mound sites were equivalent to those at on-mound sites; consequently, this mechanism by itself would be expected to result in northward sediment transport at all depths along this entire stretch of coast.

d. Regarding the possibility that temporal organization of the currents is different at on- and off-mound sites, little or no difference was found.

e. Concerning the possibility that feedback between currents and transport exists that relates to large-scale deviations from an equilibrium profile, it is hypothesized that such a mechanism, with or without the landward skew in near-bottom orbital velocities, could explain observed mound migration. If verified, this concept could be used to design disposal mounds to maximize or minimize landward transport, depending on which berm benefits were appropriate for the specific site and materials under consideration. However, this concept was only speculation by Douglass, Resio, and Hands (1995) and would require additional study prior to acceptance. But, if such a feedback mechanism plays a role at the Mobile, AL, dredged material disposal mounds, it is probably a fairly universal mechanism.

Seabed Drifters[1]

With growing concern for environmental quality and the increased recognition of the ecological importance of coastal areas, it is vital that measurements and understanding of coastal processes be improved. Instruments like the electromagnetic and broad-band acoustic doppler current meters have improved the precision of current measurements. Pressure-gauge arrays effectively measure directional wave spectra. Increased public concern for the environment also permits better data collection at the low end of the technology spectrum. An example is the voluntary return of inexpensive drogues known as seabed drifters (SBDs) (Figure 23) that can be used to map current patterns.

SBDs have been used in oceanographic studies worldwide for decades. The purpose of a study by Resio and Hands (1994) at Mobile Bay, AL, was to investigate how SBD results might be better interpreted in terms of the likely fate of materials moving with coastal waters.

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[1] This section of Chapter 8 was extracted from Hands and Sollitt (1994) and Resio and Hands (1994).

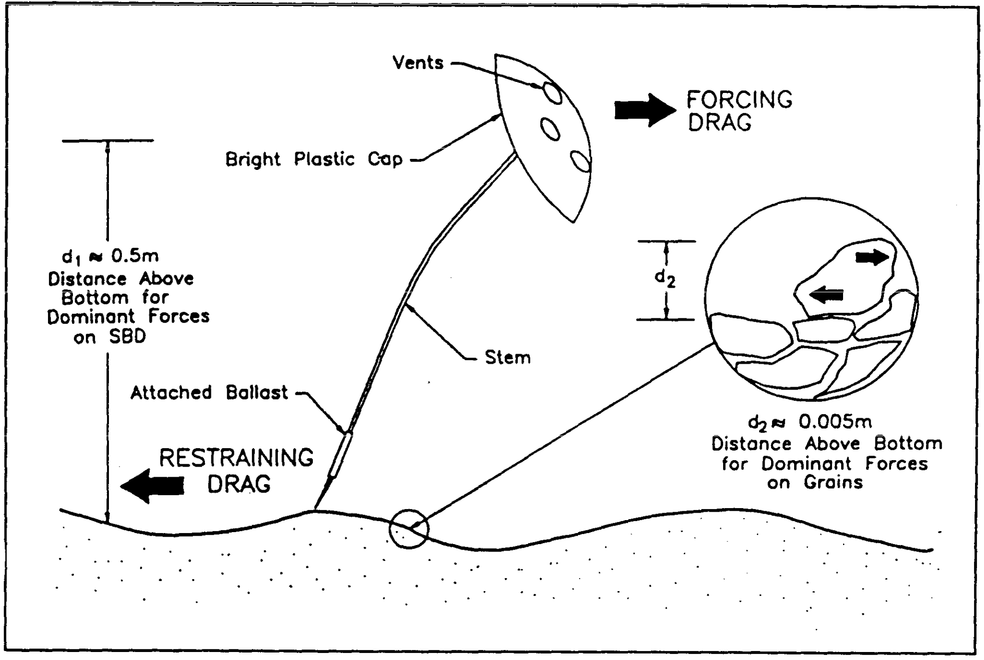

Figure 23. Differences in forces and scales on a seabed drifter and a sand grain

The standard SBD design used in Europe and North America is an umbrella-shaped plastic drogue consisting of a 7-in.-diam plastic cap with four 0.7-in. vents and a 22-in. plastic stem. The SBDs used in the Mobile Bay study were about 3.0 gm buoyant. Depending on the specific gravity of the plastics composing the SBDs, buoyancies have ranged form 2.8 to 6.5 gm in previous studies conducted by WES. The buoyancy is overcome by crimping a metal ferrule near the bottom of the stem. Further increasing the ferrule weight creates a resistance to the drag-induced motion, as later investigated by Hands and Sollitt (1994).

Interpreting SBD data

Attempts to interpret SBD patterns should begin with an analysis of the physical processes in the area of interest. Evaluation of the dominant processes will help develop the appropriate analysis for each situation.

In open-coast areas, wind-driven currents are usually the primary forcing process for SBDs. Because winds in coastal areas vary as a result of meso-scale effects (sea breeze/land breeze, etc.) and synoptic-scale effects (storms, fronts, etc.), the response of SBDs can be variable, depending on the conditions prevailing during the period following their release. Consequently, care should be taken to accumulate data from as many releases as feasible. The number necessary will increase with the variability of the driving forces, the scales and periods of interest, and the purpose of the study. The recovery pattern from a single release should be interpreted as a single, possibly representative case. A more typical study would include a dozen or more release episodes covering different conditions throughout the year. In areas where winds are variable (almost every coastal area), the climatology of all patterns from many returns should be considered in interpreting the climatology of circulation patterns. In areas such as the Mobile Bay region or Atlantic coastline, the expected transport during a given synoptic event (such as a frontal passage or storm) can produce motions on the scale of 100 km in a time span of only 2 or 3 days.

The probability that an SBD will be found varies with the location and time of year when it reaches shore. The chance that a recovered drifter will be returned can also depend on who finds it, when, and where. These site-sensitive uncertainties should be considered when interpreting the recovery patterns. For recoveries within Mobile Bay, the returns reflect differences in shrimping by numerous small boats. For offshore recoveries, the likelihood of recovered SBDs being returned appears to have been diminished if the SBDs were recovered by commercial fishermen and shrimpers in the course of their trawling activities.

Information from SBD recoveries contains both deterministic and random components. Normally, information is only available on the starting point, end point, and elapsed time, so caution should be taken in attempting to explain every recovery site in terms of a single deterministic process. The relative importance of random and deterministic components varies greatly among different release episodes. Sometimes SBDs can be recovered tens of miles apart on the same day following their release at the same time from the same location. Usually, this divergence should be interpreted as indicating the existence of important random motions or a secondary circulation pattern (such as possibly occurs in the western portion of the Mobile Bay study area). At other times, when there is a strong uniform response, the deterministic component predominates.

Combining SBDs with current-meter measurements and modeling provides more complete and useful documentation of large-scale current patterns than possible using either method alone. Consideration should be given to pilot SBD releases that would establish likely number of returns and indicate the spatial variability before selecting the number and location for instrument measurements. Because of their relatively low cost, SBD releases not only cover a wider area but also continue over a longer period than is usually feasible using other methods.

Correlating SBD weights to sand-movement threshold conditions

SBDs have long been used to track bottom currents and infer the transport paths of fine-grained sediment and plankton. However, a laboratory study by Hands and Sollitt (1994) quantified for the first time how prototype SBDs respond to the combined forces of waves and currents. Also investigated was the possibility of varying the ballast on the SBD stem so that the initial SBD motion occurs at the onset of sediment entrainment.

Large-scale laboratory tests were conducted using full-size SBDs and prototype waves. Tests in 11-ft water depths at Oregon State University included five monochromatic wave frequencies spanning a range from short deepwater waves to long intermediate- to shallow-depth waves. A long wave superimposed on four higher frequencies simulated a mean current superimposed on wind waves. Two sand sizes were used: one had a median diameter d_{50} of 0.21 mm; the other, 0.33 mm.

Acoustic current meters measured instantaneous velocities both near the seabed and at the elevation of the SBD cap where fluid motions exerted the principal drag. During each test, wave amplitudes were increased until sediment motion was initiated. Under this incipient motion condition, variously weighted SBDs were introduced to learn which weight would allow the SBDs to pivot on their contact points with the seabed while resisting net translation. This state of equilibrium was defined as the SBD threshold weighting corresponding to the particular incipient motion condition being tested. Lightening the SBDs below the equilibrium weighting allowed them to move to the next ripple or beyond during occasional wave passages.

Observed equilibrium conditions were compared to a well-known empirical predictor for initiation of sediment motion from a plane bed. Fall velocities of the variously weighted SBDs were measured and compared to their equilibrium threshold velocities. Measured threshold velocities and submerged weight of the SBDs were combined to examine the effect of flow on drag, friction, and inertial coefficients.

The developed relationship was used to estimate threshold weightings valid for different sand sizes, waves, and currents. An example by Hands and Sollitt (1994) showed how to select SBD weightings so that SBD movement begins coincidentally with movement of sand of a specified size. This method should be valid for a limited but useful range of field conditions.

For this study, precise laboratory data were collected on incipient motion of differently weighted SBDs and different grain sizes. The purpose was to find if adjustments to SBDs could effect a match between sediment and SBD initiation of motion. The data not only satisfied this objective, but provided additional insights into sediment transport. The general trend of several previous flat-bed threshold predictors was verified by these full-scale experiments. The effect of equilibrium bed forms was further quantified as approximately a 4-cm/sec drop in the required threshold velocity below that required for previously studied flat beds. At least for the grain sizes and wave conditions tested, this 4-cm/sec offset provided a good fit over a wide range of ripple sizes and types. The implication, important for feeder berm and sediment budget studies, is that sediment transport near the limit of the wave base may be more significant than previously thought because the seafloor is rarely planar, ripples usually form quickly when sediment begins moving, and (if biological reworking is not extensive) may persist through quiescent conditions until the next storm occurs.

Empirical Berm (EBERM) Fate Model[1]

Placement of dredged material offshore to nourish beaches has had a long history with mixed successes and failures. These accumulated records now provide a firm basis for empirically identifying where landward migrating designed active berms will renourish the littoral stream, thereby furnishing some benefits traditionally associated with more costly direct beach placement. At other sites where feeder berms are not practical, the dredged material may be used to provide other benefits. Designed stable berms may be used to improve fishery habitats or attenuate wave energy.

Verified predictors of long-term dredged material fate have been built into an easily used PC system called empirical berm (EBERM) fate. EBERM incorporates an expert system with results from past berm tests and detailed data on coastal bathymetry and wave climatology. EBERM will rank future placement sites dominated by open ocean waves and compare them to all well-documented earlier experiences. Ranking helps select placement depths to promote the desired dispersion or retention of placed materials. EBERM's user interface, graphical displays, and databases form a prototype system for effectively transferring information on coastal processes, bathymetry, and project performance to engineers and planners. EBERM standardizes the application of empirical criteria previously described by Hands (1991), which discriminate between active and stable berm sites.

EBERM architecture

EBERM architecture provides an evolving system that can keep abreast of continually improving states of knowledge on fate criteria, test cases, and environmental factors. The system is designed around modules that can be updated or replaced. A menu-driven interface guides the user. A nonproprietary graphics interface provides high-resolution color displays of bathymetry and various prediction results.

The wave database consists of three-dimensional discretization of wave heights, periods, and directions based on the latest WES Wave Information Study hindcasts. Wave transformations are handled by a modified steady wave transform that includes refraction, diffraction, directional/frequency spreading, wave/wave interaction, and wind effects. EBERM transforms the waves from deep water to proposed placement sites considering intervening winds and the bottom effects from system-resident databases.

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1 This section of Chapter 8 was extracted from Hands and Allison (1991) and Hands and Resio (1994).

EBERM fate criteria

EBERM's fate criteria consist of three empirical predictors. Hallermeier (1981) defined two limits bounding a buffer zone in which surface waves had a mild (neither strong nor negligible) effect on the bottom during a typical year. Suitable material for nourishment of the nearshore profile must generally be placed landward of the inner depth to ensure its inclusion in the annually very active littoral zone. Material placed in water deeper than the outer depth will usually remain stable. Material placed within the buffer zone between the inner and outer depths may or may not disperse.

Hallermeier's inner limit (HIL). The Hallermeier inner limit (HIL) is given as:

$$HIL = 2.28\ H_s - \frac{68.5\ H_s^2}{g\ T_a^2} \tag{7}$$

where

H_s = 12-hr significant wave height

T_a = average period of all waves with height $H_s \pm 0.05$ m

g = acceleration of gravity

Hallermeier's outer limit (HOL). The Hallermeier outer limit (HOL) is given as:

$$HOL = H_{50}\ T_a \sqrt{\frac{g}{5\ D_{50}}} \tag{8}$$

where

H_{50} = 12-hr median wave height

T_a = average period of all waves with height $H_{50} \pm 0.05$ m

D_{50} = representative grain size of the placed material in millimeters

Near-bed oscillatory peak speeds (NOPS). Although EBERM uses a spectral transform, a peak oscillatory speed u_{max} for each 3-hr wave condition can be estimated from linear wave theory as:

$$u_{\max} = \pi \frac{H}{T} \div \sinh \frac{2 \pi d}{L} \tag{9}$$

where

T = peak wave period

L = equivalent wave length at berm depth d

Fenton and McKee (1990) offer the following explicit solution for L that is exact at the shallow- and deep-water limits, and within 1.7 percent accuracy everywhere:

$$L = \frac{g T^2}{2 \pi} \left[\tanh \left(2 \pi \frac{\sqrt{d/g}}{T} \right)^{3/2} \right]^{2/3} \tag{10}$$

Use of EBERM

Cumulative distribution curves of u_{max} or NOPSs were found by Hands (1991) to be distinctly greater at active field sites than at stable field sites. Thus, the NOPS cumulative distribution field can be divided into active and stable berm regions (Figure 24). Feeder berms should be feasible for any proposed site with an NOPS distribution well within the active region. Stability would be indicated for sites with NOPS distributions below those of known stable reference sites. EBERM used the 90th percentile NOPS to compare to the sediment fall velocity as the third criterion to predict berm fate.

EBERM users need specify only the dredged material type (presently based only on the typical grain size) and the proposed placement site (input by latitude and longitude or by pointing to sites on EBERM-resident bathymetric maps). The user may specify wave conditions of interest or let EBERM employ resident wind and wave probabilities to assess berm fate. EBERM combines input and database information to evaluate the three fate criteria (HIL, HOL, and NOPS).

Combining these criteria gives an even clearer distinction between types of berm response and shows the compatibility between the proposed and reference sites and the multiple prediction criteria. If contemplated sites fall within the parameters of reference sites, EBERM offers a simple, verified prediction procedure to efficiently screen initial site possibilities. For cases where EBERM indicates uncertainty (the predictors are not consistent) or where the importance of the decision justifies further testing, numerical models are available to simulate detailed responses to specific events or long-term scenarios. Such a tiered approach to site selection can focus work on the best options,

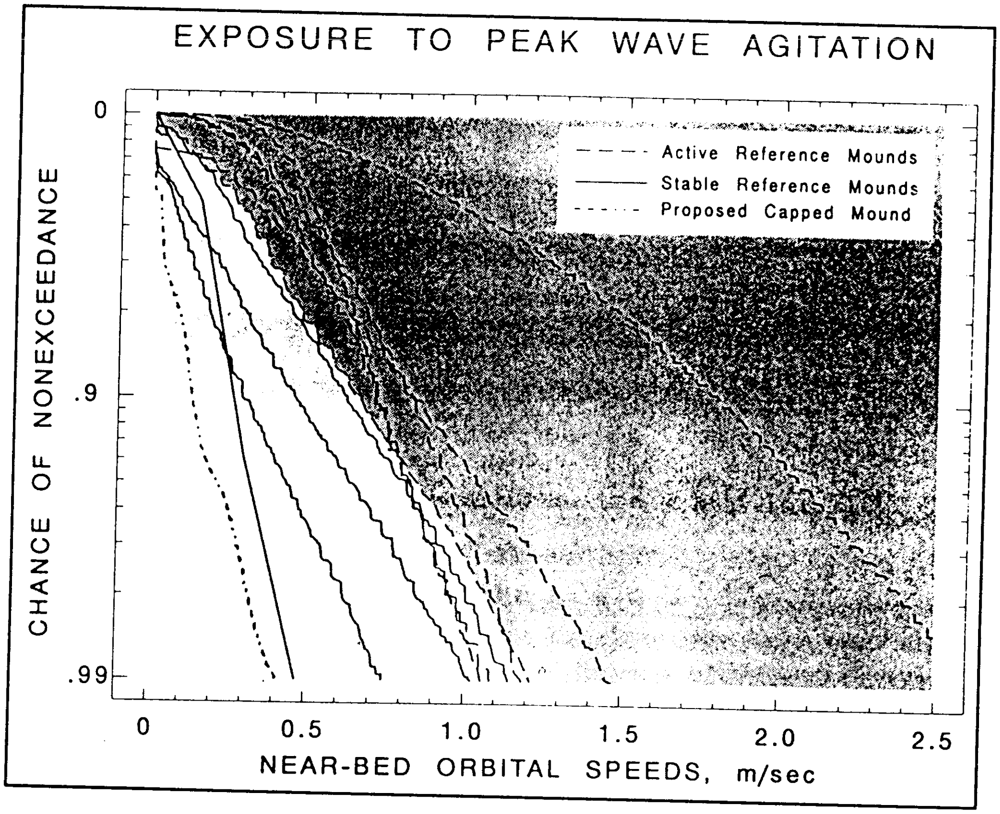

Figure 24. Frequency of near-bed oscillatory peak speeds (NOPS)

reduce the cost of baseline studies, and shorten future site-designation procedures.

9 Synopsis

Research was conducted under Technical Area 1 of the DRP, "Analysis of Dredged Materials Disposed in Open Water," to accomplish the following:

a. Improve understanding of the physics of the bottom boundary layer for both noncohesive and cohesive sediments in order to formulate better algorithms describing resuspension and transport of materials at open-water disposal sites.

b. Develop instrumentation to monitor suspended dredged material plumes during placement and resuspension of sediments from existing or potential disposal sites.

c. Enhance numerical-simulation technology for evaluating short- and long-term fate and stability of dredged material placed in open water.

d. Develop field techniques to assess potential migration of dredged material deposits such as berms placed in the nearshore littoral zone.

Calculation of Boundary-Layer Properties (Noncohesive Sediments)

The objectives of this research task were to (a) refine techniques for evaluating the potential of sands for beach nourishment, (b) develop numerical models to describe the longshore current, (c) formulate expressions for cross-shore movement of bars and berms, and (d) mathematically describe the physics of the bottom boundary layer at disposal sites and develop accurate and efficient algorithms to calculate shear stress, movable-bed friction factors, and sediment entrainment and transport for use by other related DRP numerical-modeling components pertaining to dredged material movement by waves and currents.

Evaluation of the potential of sands for beach nourishment

A methodology was developed by Dean and Abramian (1993) for predicting the equilibrium beach profile resulting from placement of an arbitrary volume of sediment with an arbitrary grain-size distribution on a profile of arbitrary shape and grain-size distribution, using certain fundamental assumptions, as follows. The volume of sand is assumed to be placed at a slope steeper than equilibrium in conjunction with a beach-nourishment project. The sand is well mixed at the time of placement. The sand will be reworked such that the volume removed from the placement cross section is sufficient to extend the nourished equilibrium out to a specified depth of limiting motion or to its intersection with the initial profile. The available sediment is sorted across the profile with a coarser fraction remaining in the berm and shallower water region and the finer sediment distributed offshore. The volumes of sediment removed and deposited are equal. The procedure can be considered as one of locally establishing segments of an equilibrium profile consistent with the local sediment diameter and of balancing sediment volumes.

Numerical model of the longshore current (NMLONG)

Kraus and Larson (1991) present mathematical formulation and verification of a numerical model of the longshore current (NMLONG). The model incorporates all known features of the wave and longshore current system that appear in research-type engineering models. The concept of placing dredged material in the nearshore as shore-parallel longshore bars or berms has been advanced as a beneficial use of dredged material for shore protection. It is necessary to know the properties of the longshore current profile over these bar and trough features both to understand the nearshore hydrodynamic environment and to estimate the longshore sand transport and evolution of such bars.

NMLONG calculates the longshore current across a barred profile under forcing by arbitrary combinations of waves arriving at an oblique angle to the shore. The governing equations are derived from the time-averaged and depth-integrated equations of motion. NMLONG was verified using three different laboratory and field data sets.

Cross-shore movement of bars and berms

The main objective of this research by Larson and Kraus (1992) was to develop criteria and a procedure for predicting the movement of material placed in the nearshore zone to act as a feeder berm. High-accuracy beach profile surveys were analyzed to determine the properties of natural longshore bars and their response to the wave climate. This understanding will enhance reliability for predicting behavior of artificial bars and berms placed in the nearshore zone. Analyses indicate that the criteria for predicting movement of berms nearshore based on readily available or estimated information has generality for all coasts exposed to energetic waves.

Wave/current bottom boundary-layer flow and movable-bed friction factors

A simple yet realistic model of the interaction between the turbulent wave and current boundary layers developed by Madsen and Wikramanayake (1991) included an enhanced formulation of a time-invariant continuous-eddy viscosity. The solution, which involved numerical integration, was simplified by development of an analytic approximation. These simplifications allowed a procedure whereby practical problems can be solved efficiently. Significant wave energy loss occurs in the wave/current bottom boundary layer due to bottom shear stress and movable-bed friction. To predict wave height in coastal areas, it is necessary to quantify the bottom shear stress. Wikramanayake and Madsen (1994a) developed a simple physically realistic model to predict the friction factor over a movable sand bed under field conditions.

Sediment transport by combined wave/current flow

Movement of sediment on the ocean bottom in coastal regions is nearly always governed by wave motion that exceeds the critical shear stress, and material then becomes transported either as bed load or suspended load by local currents. Wikramanayake and Madsen (1994b) extended the turbulent eddy-viscosity model to the case of suspended sediment under wave and current flow. The objective was to develop WCSTRANS as a predictive tool for sediment transport (bed load and suspended load) in the coastal zone. WCSTRANS was tested against prototype field data and provided good agreement with both bed and suspended loads. The model reproduced the shape of the wave-flux profiles of the field data despite use of a boundary condition not derived for the case of a rippled bed.

Calculation of Boundary-Layer Properties (Cohesive Sediments)

Entrainment, mass erosion, and surface erosion are erosion modes that must be better understood to make evaluations and predictions regarding movement of cohesive sediments from open-water dredged material disposal sites. This research was conducted to develop and verify (a) improved methods for assessing cohesive sediment erodibility, (b) PC programs for Corps field use to assist in disposal site management, and (c) methods for evaluating fluidization and transport of cohesive sediment.

Erosion of cohesive dredged material at open-water disposal sites

Cohesive sediments are a special class of sediments that exhibit interparticle cohesion and are generally composed of fine-grained sediments less than

0.074 mm in diameter. Erosion is related to breakage of electrochemical cohesive bonds and structural changes in fine-grained sediments. Cation exchange capacity (CEC) is a measure of the activity of the cohesive fraction of the sediment. Clay content and mineral type are the principal factors affecting CEC. In general, the greater the CEC, the more erosion resistant the material. Once mobilized, the fine particles are generally transported for long durations and distances due to their low settling velocities.

Natural cohesive sediments have a combination of elastic and viscous behaviors. Nonlinearity is an important aspect of those behaviors. Shearing breaks cohesive bonds, rearranges particles and aggregates, and alters microstructure. The material is weakened with respect to resisting imposed shear stress; however, this process is reversible, and the material recovers with time once shearing stops.

Open-water dredged material disposal site erosion depends strongly on bed shear stress, while shear stress is related to velocity profiles existing above the bed. For first-approximation (interim) estimates of material movement, Berger, Teeter, and Pankow (1993) developed a simple model to calculate velocity profiles over changing bed slopes to infer shear stress. Much more complicated conditions can be encountered in estuarine areas with tidally reversing flows, density stratification, suspended-sediment contributions, and combined current and wave effects.

Approaches to making boundary-layer calculations under estuarine conditions have been advanced by McAnally and Hayter (1992). These avenues include modified steady-flow equations, variable eddy-viscosity and mixing-length equations, and turbulence-transport equations. Interim recommendations by McAnally and Hayter (1992) for calculation methods are based on the specific situation and location under evaluation.

Because cohesive-sediment behavior depends on such a large number of sediment and flow properties and also is time-dependent, adjustment of erosion-process models is a difficult task, and results are unreliable without site-specific field and characterization data. Fortunately, the variation of cohesive-sediment conditions is not so wide in the coastal area. For a given coastal sediment composition, conditions having the greatest effect on mud erodibility at a disposal site are most likely to be sediment density or related parameters, clay content, and temperature.

Water wave attenuation by underwater mudbanks and mud berms

Naturally occurring underwater mudbanks are known to absorb water wave energy on the order of 30 percent to as much as 90 percent, even in the absence of any measurable wave breaking. Applications of wave/mud interaction modeling have been carried out by Mehta, Lee, and Li (1994) to simulate the degree of wave damping that will occur for a nearshore berm of given dimensions and mud rheology. This type of modeling can be used to develop guidelines for designing wave-energy-absorbing berms for future applications.

When subjected to wave action, bottom muds respond by oscillating at the forcing wave frequency. As a result of high viscosity, the oscillations attenuate much more rapidly with depth within mud than in the water column above. A high rate of energy dissipation within the mud causes the surface wave height to decrease rapidly with onshore distance. Under continued wave action, the long-term equilibrium water depth above a nearshore berm crest is that depth at which the wave-induced hydraulic shear stress amplitude is equal to the erosion shear strength of the mud. Until the berm erodes to equilibrium conditions, resuspension and transport will continue to occur.

The nearshore berm placed off Mobile, AL, causes significant wave energy reduction from the offshore to the inshore water regions. A wave/mud interaction model developed by Jiang (1993) was used by Mehta, Lee, and Li (1994) to simulate the inshore wave spectra at the Mobile berm site. Computations were done on a frequency-by-frequency basis. The simulations were found to be in very good agreement with field measurements at low frequencies, but the simulations were consistently lower than measured for periods smaller than 4 sec. This suggested that the source of these high-frequency inshore waves may have been at least partly different from that represented by the measured offshore wave spectrum, possibly from sea waves generated on the landward side of the berm and propagating oceanward.

Measurement of Entrainment and Transport (Noncohesive Sediments)

At the start of the DRP, the Corps had no capability to make direct measurements of sediment movement on the seafloor, in lake beds, or in the water column except by water bottle samplers at specific points in time and space. There were no accurate or complete field data sets for verifying algorithms used in sediment-transport simulation models. Instruments had to be developed and data collected to understand both short- and long-term movement of dredged materials disposed in open water.

Development of a plume measurement system (PLUMES) was initiated to obtain water-column concentrations of sediment plumes and to provide a means of tracking plumes below the surface that are not otherwise visible. The development of an acoustic resuspension measurement system (ARMS) was begun to provide a mechanism for obtaining accurate data regarding sediment resuspension and transport in and above the boundary layer of disposal mounds or potential disposal sites. Each of these systems was fully developed, laboratory calibrated, and tested in prototype field disposal operations during the DRP. PLUMES has been proven to be very effective in tracking plumes that could not be tracked by taking water samples. The determination of suspended sediment concentrations from PLUMES measurements is still experimental.

Plume measurement system (PLUMES)

Suspended-sediment clouds or plumes develop in open water at dredging sites and at disposal by both hopper dredges and barges. Environmental concerns often require an assessment of the extent, movement, and longevity of suspended-sediment plumes, using direct monitoring, numerical modeling, or both. The temporal and spatial distribution of turbidity from plumes and the ultimate fate of the suspended sediment in the plumes must be ascertained. PLUMES was developed to provide direct quantitative information on these issues (Kraus and Thevenot 1992).

PLUMES uses acoustic backscatter instruments to provide near-synoptic data on the three-dimensional spatial distribution of suspended sediments. The broad-band acoustic doppler concentration profiler (BBADCP) has five transducers on a single head. Data from the four transducers on the outside are used to calculate horizontal and vertical current velocities. The center transducer points straight down and measures acoustic backscatter intensity. Data from these measurements can be used to theoretically calculate suspended-sediment concentrations. The system, which can be mounted on the side of a survey boat or towed at depth in a towed body, consists of the following major items:

Broad-band acoustic doppler concentration profiler (BBADCP). The heart of the PLUMES system is the BBADCP. This is a multiple-beam doppler sonar system that can measure vertical profiles of 3-axis velocities and acoustic-backscatter strength by transmitting short acoustic pulses and processing backscattered acoustic signals from small particles in the water. The term "broad band" refers to the capability of the system to employ very short pulses and spread-spectrum techniques to achieve good vertical and temporal resolution.

In situ samplers. Backscatter intensity and acoustic losses depend on grain size and sediment type. Therefore, in most situations it is necessary to take suspended-sediment samples during the survey to use in analyzing acoustic intensity measurements. These samples can be taken either by water sample bottles or by continuously pumping out samples through a tube in the water.

Positioning system. The principal functions of a horizontal positioning system are to provide the location of a sediment plume as it moves with the current and disperses and to correct current velocities in deep water. The required degree of accuracy of the positioning system depends on the application. The PLUMES data acquisition system allows direct interfacing with a differential GPS receiver.

Data-acquisition system (DAS). DAS consists of hardware and software to operate PLUMES and to record, analyze, and display data. Measurements from the BBADCP can be viewed in real time. Screens on the control console of the PLUMES operating package display vertical profiles of backscatter intensity in the sediment plume, and the north-south and east-west current velocity vectors.

PLUMES has been laboratory calibrated and tested at several different field locations in both shallow and deep water on both coasts of the United States. In 1993 PLUMES was used in its deepwater configuration and towed at depth at a location off San Francisco, CA, in 3,000 m of water. After each barge release, the towed PLUMES system was lowered into the plume to a maximum depth of approximately 800 m. Plumes from the releases were monitored in excess of 6 hr. Even in rough weather with waves up to 5 m, PLUMES towed stably and produced good-quality acoustic data.

Acoustic resuspension measurement system (ARMS)

ARMS was developed to measure sediment resuspension and movement in the water column at existing and proposed dredged material disposal sites (Van Evra et al. 1992). In field conditions, depending on the character of the bottom material and the amount of energy being imparted to the area from wind, waves, and currents, there is a varying amount of sediment that is being resuspended into the water column off the seafloor. The manner in which this occurs determines the physical transport of bottom material at the site.

To measure in situ properties of the boundary layer above dredged material mounds in open-water disposal areas, an optimally arranged ensemble of specialized underwater instruments must be used. The instruments must be carefully mounted into specific positions on a rugged yet portable frame and interrogated at sampling rates frequent enough to allow observation of short-term as well as long-term physical processes.

Instrumentation. ARMS is an integrated ensemble of seven specialized underwater sensors designed to accurately measure in situ properties of the bottom boundary layer in open-water areas. The seven instruments that comprise ARMS are (a) an acoustic sediment-concentration profilometer, (b) four acoustic velocity sensors, (c) a pressure gauge, (d) a thermistor, (e) a transmissometer, (f) a multifrequency sediment-particle sizer, and (g) an optional video camera. ARMS was verified as a practical engineering tool in the laboratory and was deployed successfully in the field.

Deployment. The inherent stability of the tripod makes lowering ARMS a straightforward procedure. ARMS can be deployed at sites up to 100 ft in depth. It is optimal to place the tripod on a flat bottom that is clear of large debris, not only because the velocity meters protrude down through the middle of the space under the tripod, but also because measurements in unobstructed conditions are preferred. To guarantee this, if divers are not available to check before and after placement, inspection of the bottom with a drop video camera operated from the surface is required.

The ARMS central processing unit can be programmed for many different sampling routines to conserve battery power. The programs are written in a compartmented fashion, commanding the power-controller board to turn on instruments only when needed. Power-down periods allow longer deployment.

Numerical Simulation Techniques for Evaluating Short-Term Fate and Stability of Dredged Material Disposed in Open Water (STFATE)

Knowledge of the short-term fate of dredged material disposed in open water is an integral part of assessing environmental impacts of the water column. Mathematical models for predicting the short-term fate of material from individual disposal operations were initially developed by Koh and Chang (1973) and have since been enhanced by Johnson (1990). All these models suffer from a lack of verification at real disposal operations. Large-scale laboratory tests in a facility designed for simulating disposal from split-hull barges and hopper dredges to obtain verification data for numerical models were conducted by Johnson et al. (1993). Those tests resulted in development, calibration, and verification of the numerical model STFATE for computing water-column concentrations and bottom deposition resulting from open-water disposal of dredged material (Johnson and Fong 1995).

Scaling laws for dredged material disposal

A detailed investigation of scaling laws for the physical modeling of dredged material disposal is presented by Soldate, Pagenkopf, and Morton (1992) to determine the minimum size of the physical model necessary to avoid scale effects. Only undistorted models were considered because distorted models have inherent disadvantages. The range of various prototype parameters to be investigated included (a) water depth from 100 to 300 ft, (b) disposal volume from 4,000 to 8,000 cu yd, and (c) vessel speed from stationary to 2.0 knots. To ensure the Reynolds criteria were met, a length scale factor of 1-to-50 model-to-prototype was used in the physical model tests. The test facility had dimensions of 40 ft by 50 ft by 8 ft.

Physical model tests

Several data sets consisting of descent and bottom-surge speeds, bottom-depositional patterns, and spatial representation of the suspended sediment in or near the bottom were collected. These data were later used at both the physical model scale and prototype scale for numerical model verification.

One of the most valuable uses of the physical model disposal facility was in allowing the dynamic placement processes of descent and bottom surge to be visually observed. As a result of those observations, it was concluded that existing numerical disposal models did not adequately represent actual disposal operations. There were no instantaneous disposals of material that were uniformly distributed within the disposal vessel. In addition, moving disposal vessels tend to create a plume in the upper water column, the result of a shearing effect, which can leave extremely fine material in the upper water column. As a result of the physical model tests, Johnson and Fong (1995) were able to significantly enhance existing numerical models to allow for the observed behavior of real disposal operations.

STFATE model

An existing numerical model called DIFID was extensively modified to yield a more versatile, accurate, and robust disposal model called STFATE. STFATE was subsequently verified using laboratory data.

DIFID was used at Port Gardner, WA, to estimate spreading of dredged material released from barges in 400 ft of water for site-designation studies. Postdisposal monitoring indicated that some material settled as far as 1,000 ft outside the disposal-site boundary, contrary to predictions by DIFID. STFATE, the enhanced version of DIFID, was later used to simulate disposal at the site for comparison with earlier DIFID simulations. Results indicated that material representative of that Navy project spread about twice as far as the material originally modeled by DIFID during site designation. A simulation of the combined effect of all disposals that took place during the Navy project accurately represented the well-defined deposition pattern found at the site (Nelson and Johnson 1992).

Results of the simulations of the physical model tests by Johnson and Fong (1995) showed that STFATE can be used to accurately simulate the fate of material during disposal operations. Descent and bottom-surge speeds, stripping, rates of dilution, total depositional areas, and suspended-sediment concentrations in the bottom are all reasonably reproduced.

One area of additional research that is needed to make STFATE even more useful for addressing environmental issues lies in the area of uncertainty. Given the uncertainty in specifying characteristics of the disposal material at the moment of disposal, the manner in which material leaves the disposal vessel, and ambient conditions, an uncertainty analysis should be conducted to better define bounds on the accuracy of predicted water-column effects.

Numerical Simulation Techniques for Evaluating Long-Term Fate and Stability of Dredged Material Disposed in Open Water (LTFATE)

The objective of this research task was to provide a simulation technique for determining how a specified dredged material mound behaves over time (i.e., the long-term fate and disposition of mound material). The ability to identify long-term dispersive sites is especially important because eroded material could be transported into environmentally sensitive areas. Long-term dispersion investigations require knowledge of the local wave climate and current field at the site.

The approach selected for long-term fate and stability disposal-site analysis was use of a numerically based sediment-transport prediction model, LTFATE, using long-term local boundary forcing functions. These conditions represent those forcings that entrain and transport sediment, including waves, tides, and storms. In many cases, these data are not available or are incomplete or too short in duration for long-term predictions. The generation of arbitrarily long simulated realistic time sequences of ocean wave and current data corresponding to specific locations must be performed. Unlike astronomical tides that can be predicted with great accuracy, waves and currents cannot be precisely predicted.

Simulation of waves and currents

A viable approach for generating realistic wave and current field boundary conditions has been developed by Borgman and Scheffner (1991). The simulation procedure for generating a long-term time series of wave characteristics requires an existing database from which the statistical parameters describing the intercorrelations of wave field parameters can be computed. The procedure is somewhat analogous to the computation of harmonic constituents for a tidal record. The 20-year WIS database was selected as the source of wave-parameter statistics from which a matrix of multipliers was obtained that could then be used to generate time series of wave data that emulated the WIS 20-year hindcast data. This statistical approach will enable the user to generate data series of any length (e.g., 31 days of January or several years) for any WIS station. Although the procedure is based on the WIS database, it is fully applicable to any database.

LTFATE model

LTFATE is a numerical modeling system for systematically estimating the long-term response of a dredged material disposal site to local environmental forcings. The methodology is based on the development of databases of wave and current time series and the application of these boundary conditions to coupled hydrodynamic, sediment transport, and bathymetry change models.

LTFATE has the capability of simulating both noncohesive and cohesive sediment transport.

Noncohesive sediments.- LTFATE uses equations reported by Ackers and White (1973) as the basis for the noncohesive sediment-transport model. The equations are applicable to uniformly graded noncohesive sediment with a grain diameter in the range of 0.04 to 4.0 mm. Because many disposal sites are located in relatively shallow water, a modification of the Ackers-White equations was incorporated to reflect an increase in the transport rate when ambient currents are accompanied by surface waves (Scheffner et al. 1995).

Cohesive sediments. An algorithm developed by Teeter and Pankow (1989) was incorporated into LTFATE to account for transport of fine-grained materials such as silt (0.072 to 0.004 mm) and clay (0.004 to 0.00045 mm). They reasoned that because of the differences in cohesion and settling characteristics, fine-grained sediments are characterized as the algebraic sum of expressions for settling velocity, deposition, and resuspension.

LTFATE application at field sites

LTFATE was applied at the following two locations to determine long-term fate of dredged material placed in open-ocean disposal sites: the Humboldt Bay, CA (Scheffner 1992), and Charleston, SC (Scheffner and Tallent 1994). For these locations, time series of wave and currents necessary for conducting the investigations were developed in the manner of Borgman and Scheffner (1991).

Humboldt Bay, CA. The modified Ackers-White relationships were used by LTFATE to compute the transport of two uniformly graded noncohesive sediments at this site. Regardless of whether fine material (d_{50} = 0.038 mm) or sand (d_{50} = 0.28 mm) was assumed to be placed at the site, the proposed disposal site was found to be basically nondispersive for either material.

Charleston, SC. LTFATE simulations indicated that the disposal mound at Charleston, SC, is dispersive whenever the current magnitudes exceed approximately 1.5 ft/sec; however, normal conditions are not sufficiently severe to cause massive erosion. Results of storm-surge simulations showed the mound to migrate approximately 155 ft, many times the erosion rate associated with normal waves and currents.

ADCIRC model

A finite-element numerical advanced 3-D circulation model (ADCIRC) was developed for the specific purpose of generating long time periods of hydrodynamic circulation along shelves and coasts and within estuaries. The intent of the model is to produce long numerical simulations (on the order of a year) for very large computational domains (e.g., the entire east coast of the United

States). Therefore, the model was designed for high computational efficiency and was tested extensively for both hydrodynamic accuracy and numerical stability. The theory, methodology, and verification of ADCIRC are presented by Leuttich, Westerink, and Scheffner (1992).

ADCIRC achieves a high level of simultaneous regional/local modeling, accuracy, and efficiency. This performance is a consequence of the extreme grid flexibility, the optimized governing equation formulations, and the numerical algorithms used in ADCIRC. Together, these allow ADCIRC to run with order of magnitude reductions in the number of degrees of freedom and the computational costs of many presently existing circulation models. A user's manual for ADCIRC has been prepared by Westerink, Blain, and Scheffner (1994).

Tidal constituent databases have been developed by application of ADCIRC for the Gulf of Mexico, and the western North Atlantic and eastern Pacific coasts of the United States. Tropical storm databases have also been developed by using ADCIRC for the Gulf of Mexico and the east coast of the United States. Use of these databases goes far beyond testing of disposal-site stability.

Numerical Simulation Techniques Combining Short- and Long-Term Fate Computations for MDFATE

A multiple dredged material placement model has been developed by Moritz (1994) to predict post-disposal bathymetry for ocean dredged material disposal sites. This PC-driven numerical simulation model for MDFATE incorporates existing numerical models (STFATE and LTFATE) to simulate the overall (short- and long-term) behavior of dredged material placed within an open-water disposal site.

Simulating a disposal operation

Once a particular ODMDS grid has been created, MDFATE can be used to simulate a given disposal operation which may extend over a year and consist of hundreds of disposal cycles or dumps. A dump consists of one load of dredged material being released into open water from either a barge/scow or hopper dredge.

During MDFATE execution, the disposal operation is divided into separate week-long episodes over which long-term fate processes governing dredged material behavior on the seafloor are simulated using a modified version of the LTFATE model. Within each episode, a modified version of STFATE simulates short-term fate processes which govern each dump occurring inside the ODMDS grid of interest.

MDFATE utilizes HPDSIM and the tidal constituent databases (portions of the LTFATE model) to generate wave and tidal information for every 3-hr interval during the disposal operation. This information is utilized by the modified STFATE model within MDFATE to simulate wave/current effects acting upon each dump as dredged material passes through the water column and comes to rest on the seafloor. STFATE produces a characteristic footprint for each type of dredged material type/disposal method involved in the disposal operation. The resultant disposal footprint is used to represent each dredged material placement.

Prototype application of MDFATE

A prototype application of MDFATE was performed by Moritz (unpublished manuscript) where the final surveyed and predicted bathymetry within an actual open-water dredged material disposal site were compared. The comparison of the actual site post-disposal and MDFATE-predicted bathymetry was based upon volume and spatial distribution assessments of dredged material placed within the Wilmington, NC, ODMDS, September 1990-April 1991.

The simulated mound feature of the highest peak at the disposal site was slightly smaller in height (13 percent) and slightly larger in diameter (5 percent) than the actual case, and was located 500 ft northeast of the actual surveyed mound location. The simulated mound feature of the second-highest peak was somewhat smaller in height (35 percent) and diameter (8 percent) than the actual case, and was situated 420 ft southeast of the actual surveyed mound location.

Benefits of MDFATE

MDFATE was developed by Moritz (1994) to bridge the gap between the modeling of individual disposal events or dumps and tracking a myriad of disposals that occur within a disposal area over the duration of a disposal site's operative cycle. With the flexible options of MDFATE, many aspects of open-water dredging and disposal operations can be examined and predicted at various levels of quantification. Thus, MDFATE should prove to be a valuable asset in managing ODMDS's.

Field Techniques and Data Analysis to Assess Open-Water Disposal

At the initiation of the DRP, available field data were inadequate to predict the fate of dredged material placed in open water nearshore for purposes of predicting reduced shoreline erosion or beach nourishment due to feeder response. Long-term site monitoring was required to (a) collect data to document fate of disposal deposits, (b) improve monitoring and data-analysis techniques, and (c) develop an empirical methodology for predicting the overall response of nearshore berms based on parameters readily available to planners and site managers. Hands (1991) and Hands and Resio (1994) reviewed the processes and berm responses at 11 nearshore placement sites. The following summarizes results from the most extensively monitored of these 11 sites.

Mobile, AL, berms

In 1987, the Corps initiated a national berm demonstration project off the Alabama coast. The purpose of the project was to better understand long-term fate of dredged material and ancillary benefits possible with the correct placement of dredged material as berms or mounds in the nearshore littoral zone. Three Alabama berms were monitored for several years.

Sand Island Bar (SIB). The SIB was built in early 1987 using about 464,000 cu yd of entrance channel maintenance-dredged material. To test a plan for returning this fine clean sand to the active zone littoral transport, the material was placed along a 500-ft-wide corridor centered on the 19-ft contour. The resulting feature was a 6,000-ft-long, 6-ft-high bar that closely matched anticipated nearshore berm dimensions. The SIB was intended to be a feeder berm to return good beach material to the shoreline.

Sand Island Mound (SIM). The SIM was a preexisting man-made mound of about 29,000 cu yd of material. The mound was apparently a product of recent gas well operations. The SIB and SIM are both composed of well-sorted fine-grained sand like the ambient materials of the outer Mobile ebb-tidal delta and are much more uniform than the heterogeneous mixture that went into the Mobile Outer Mound.

Mobile Outer Mound (MOM). Construction of the MOM began with the initiation of the Mobile Harbor deepening project in 1988. About 17,000,000 cu yd of widely varying materials were excavated over a 27-month period to increase authorized channel depths an additional 5 ft for a distance of 35 miles. The character of the dredged material varied from sand and silt to clay as work proceeded along the channel. The MOM was intended to be a retention site to act as a wave attenuator to reduce shoreline erosion.

Field monitoring study

A monitoring study was performed by WES (McGehee et al. 1994) to document short-term response (several years) of the MOM and SIB, the effect of the mounds on the local physical environment, and the environmental conditions that determined the fate of the placed material. Monitoring objectives at the MOM were to ensure compliance with local regulatory requirements, assess the mounding characteristics of fine-grained material, and document effects that such a large mound could have on incident waves and fisheries. The objective of monitoring the SIB in shallower water was to document the fate of beach-quality sand mounded at a depth below any previously observed feeder berms.

Analysis of field results

Douglass, Resio, and Hands (1995) analyzed actual field measurements obtained by McGehee et al. (1994) of waves and currents to assess which flow mechanisms are responsible for long-term landward transport of material from large submerged sand bodies. Differences in wave heights on opposite sides of the MOM indicate substantial wave energy may be dissipated or scattered over this broad berm. The dredged material has mounded and remained onsite during early years following construction. Most of the placed material is expected to remain there for many years because of its mass and location.

Since the SIM and SIB were built earlier and monitored more frequently, their long-term fates are clearer than the fate of the MOM. They (SIM and SIB) are both composed of fine-grained sands and rose to peak elevations of -12 ft mean lower low water in early 1987. The SIM has continued to move slowly northward. The persistence of this landward migration over several years substantiated that the migration was significant and is likely to continue, although the rate may be declining. Moreover, on the northwesterly section of the bar where the elongated SIB is oriented nearly transverse to wave approach, a section of the bar also has migrated landward. Preferential ebb-delta accretion is already evident leeward of the SIB. This is directly analogous to the concept of beach-erosion control through a combination of wave dissipation and direct nourishment by a nearshore feeder deposit.

Several fundamental transport mechanisms were investigated and tested against the long-term wave, current, and bathymetric response data. The mean current over the mound was small and directed offshore. Furthermore, mean offshore currents tended to increase during storms and thus could not explain the persistent landward movement of the mounds. Shoreward skewness of wave oscillations is the lowest order mechanism capable of explaining the measured berm movement. This skewness and, therefore, feeder response, may be enhanced by the topography of the placed berm. The practical implications of these results include methodologies for assessing depths, orientations, and sizes of future disposal mounds.

Seabed drifters

SBDs have been used in oceanographic studies worldwide for decades. The purpose of a study by Resio and Hands (1994) at Mobile Bay, AL, was to investigate how SBD results might be better interpreted in terms of the likely fate of materials moving with coastal waters.

In open-coast areas, wind-driven currents are usually the primary forcing process for SBDs. Because winds in coastal areas vary as a result of meso-scale and synoptic-scale effects, the response of SBDs can be variable, depending on the conditions prevailing during the period following their release. Consequently, care should be taken to accumulate data from as many releases as feasible.

New techniques are given for understanding SBD recovery patterns. Procedures are established for resolving deterministic and random components of flow based on the dispersion of bundles of SBDs. As shown in the real recovery data, the relative importance of deterministic and random components can vary widely, but display predictable spatial and/or seasonal patterns. Understanding these variations and patterns is valuable in explaining transport variations and predicting the spread of materials on the seafloor. Conclusions are validated by comparisons with other data and model results.

Combining SBDs with current-meter measurements and modeling provides more complete and useful documentation of large-scale current patterns than possible using either method alone. Because of their relatively low cost, SBD releases are able to not only cover a wider area but can also be continued over a longer period than is usually feasible using other methods. Consideration should be given to pilot SBD releases that would establish likely number of returns and indicate the spatial variability before selecting the number and location for instrument measurement.

Seabed drifter weights

A laboratory study by Hands and Sollitt (1994) quantified for the first time how prototype SBDs respond to the combined forces of waves and currents. Also investigated was the possibility of varying the ballast on the SBD stem so that the initial SBD motion occurs at the onset of sediment entrainment.

Tank tests were conducted using full-size SBDs and prototype waves. Tests in 11-ft water depths included wave frequencies spanning a range from short deepwater waves to long intermediate- to shallow-depth waves.

Observed equilibrium conditions were compared to empirical predictors for initiation of sediment motion from a plane bed. The fall velocities of variously weighted SBDs were measured. The measured threshold velocities and submerged weight of the SBDs were combined to examine the effects of flow on drag, friction, and inertial coefficients. A method was devised to select SBD weightings so that SBD movement would begin coincidentally with movement of sand of a specified size.

Empirical berm (EBERM) fate model

Verified predictors of long-term dredged material fate have been built into an easily used PC system called empirical berm (EBERM) fate by Hands and

Allison (1991) and refined by Hands and Resio (1994). EBERM incorporates an expert system with results from past berm tests and detailed data on coastal bathymetry and wave climatology. EBERM will rank future open-ocean, wave-dominated placement sites in comparison to all well-documented earlier experiences. Ranking helps select placement depths to promote the desired dispersion or retention of placed materials. EBERM's user interface, graphical displays, and databases form a prototype system for effectively transferring information on coastal processes, bathymetry, and project performance to engineers and planners. EBERM standardizes the application of empirical criteria previously described by Hands (1991) that discriminate between active and stable berm sites.

EBERM's fate criteria consist of three empirical predictors. Hallermeier (1981) defined two limits bounding a buffer zone in which surface waves had a mild (neither strong nor negligible) effect on the bottom during a typical year. Suitable material for nourishment of the nearshore profile must generally be placed landward of the inner depth to ensure its inclusion in the annually very active littoral zone. Material placed in water deeper than the outer depth will usually remain stable. Material placed within the buffer zone between the inner and outer depths may or may not disperse. The three empirical predictors are (a) Hallermeier's inner limit (HIL), (b) Hallermeier's outer limit (HOL), and (c) the near-bed oscillatory peak speeds (NOPS).

Cumulative distribution curves of NOPS were found by Hands (1991) to be distinctly greater at active field sites than at stable field sites. Thus, the NOPS cumulative distribution field can be divided into active and stable berm regions. Feeder berms should be feasible for any proposed site with a NOPS distribution well within the active region.

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes research conducted by the Dredging Research Program, Technical Area 1, "Analysis of Dredged Materials Disposed in Open Water." Goals of Technical Area 1 were as follows:

a. To establish a better understanding of boundary-layer properties of both cohesive and noncohesive materials and develop short- and long-term numerical approximation for determining the fate and disposition of dredged materials disposed in open water.

b. To develop field instrumentation to track suspended sediment plumes and monitor nearshore berms and disposal mounds for resuspension and migration of the dredged material.

Fundamental knowledge on the boundary-layer flow properties of both cohesive and noncohesive materials was used to better formulate numerical expressions describing movement of these materials under wave and current conditions. The plume measurement system PLUMES was developed to track suspended-sediment plumes in open

(Continued)

14. SUBJECT TERMS

ADCIRC	Dredging Research Program	STFATE
ARMS	LTFATE	
Dredging	PLUMES	

15. NUMBER OF PAGES 124

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