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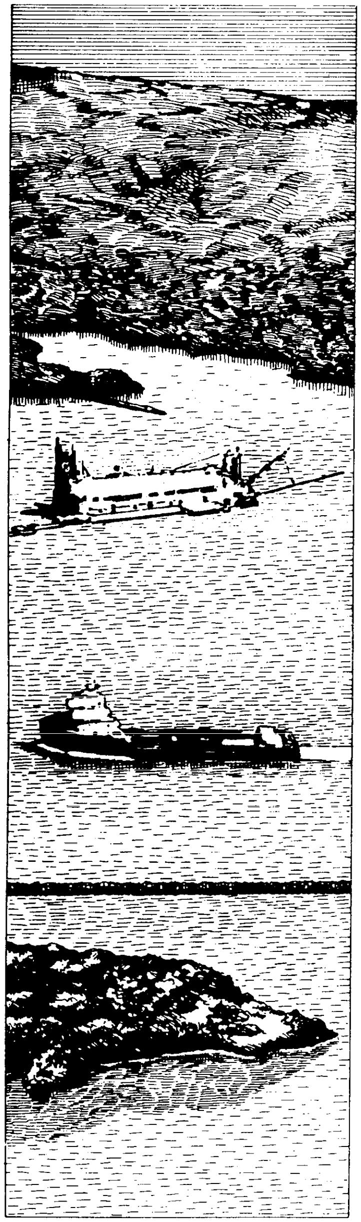

DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-95-10

DREDGE PLANT EQUIPMENT AND SYSTEMS PROCESSES; SUMMARY REPORT FOR TECHNICAL AREA 3

compiled by

Lyndell Z. Hales

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

November 1995
Final Report

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

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US Army Corps of Engineers
Waterways Experiment Station

Dredging Research Program Report Summary

Dredge Plant Equipment and Systems Processes; Summary Report for Technical Area 3 (TR DRP-95-10)

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 Cops field operating Division and District offices. Implementation of 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 conducted under DRP Technical Report Area 3, "Dredge Plant Equipment and Systems Processes," developed new technologies and enhanced existing dredge systems to achieve economic load during dredging operations. Improvements included more effective eductors and a single-point mooring system for direct pumpout of hopper dredges onto beaches. Technology for dredge production and process monitoring was improved, and designs for hopper-dredge dragheads were modified to increase production.

SUMMARY: Research conducted under DRP Technical Area 3 improved the following equipment, systems, or processes: (a) eductors with more efficient sand-bypassing features and water-injection dredging to fluidize shoals and permit transport by density of natural currents; (b) dredging equipment for nearshore/onshore placement, including a direct pumpout capability for hopper dredges; (c) technology for monitoring and increasing dredge payloads for fine-grain sediments, including an automated load monitoring system and an electrical resistivity method; and (d) draghead desigin enhancements for more efficient production, including water jets and blades to loosen compacted sediments.

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

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Technical Report DRP-95-10
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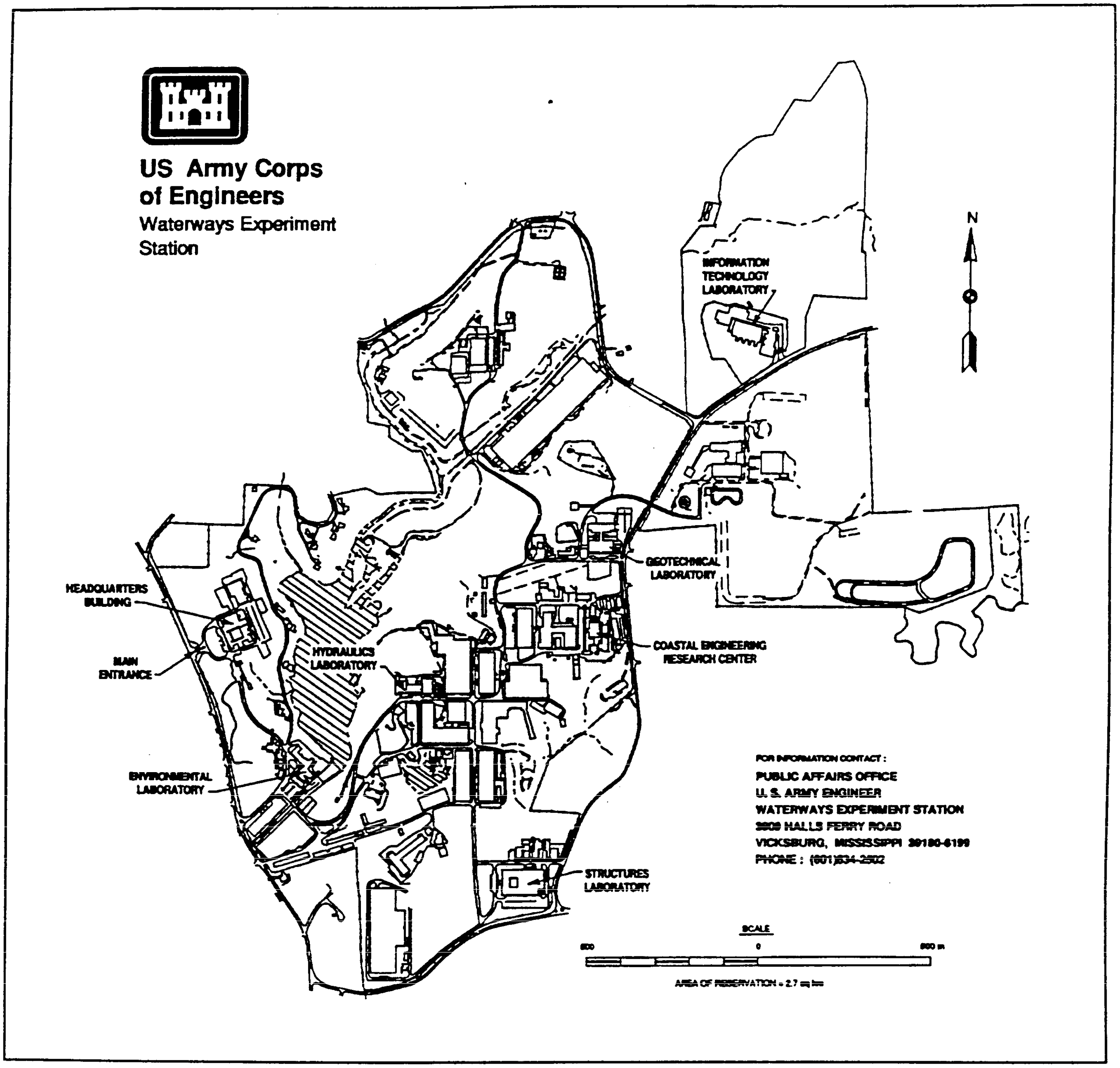

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Preface

This report summarizes research conducted by U.S. Army Engineer Waterways Experiment Station (WES) Dredging Research Program (DRP) Technical Area 3, "Dredge Plant Equipment and Systems Processes." The DRP was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Technical Monitor for Technical Area 3 was Mr. Gerald Greener, HQUSACE. Chief Technical Monitor for the DRP was Mr. Robert H. Campbell (retired), 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 3 reports.

Technical Area 3 studies were conducted by or under the supervision of the following WES personnel:

CERC--Mr. James E. Clausner, Principal Investigator, Coastal Structures and Evaluation Branch (CSEB), Engineering Development Division (EDD); Mr. Peter J. Neilans, Coastal Processes Branch (CPB), Research Division (RD); Mr. Timothy L. Welp, Prototype Measurement and Analysis Branch (PMAB), EDD; Mr. Darryl D. Bishop, CSEB; and Mr. Gregory L. Williams, CSEB. Additional supervision was provided by Ms. Joan Pope, Chief, CSEB; Mr. Bruce A. Ebersole, Chief, CPB; Mr. William L. Preslan, Chief, PMAB; Mr. Thomas W. Richardson, Chief, EDD; Mr. H. Lee Butler, Chief, RD; Mr. Charles C. Calhoun, Jr., Assistant Director, CERC; and Dr. James R. Houston, Director, CERC.

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Environmental Laboratory (EL)--Dr. Michael R. Palermo, Environmental Restoration Branch (ERB), Environmental Engineering Division (EED). Additional supervision was provided by Dr. Norman R. Francingues, Chief, ERB; Dr. Raymond L. Montgomery (retired), former Chief, EED; Dr. John W. Keeley, Director, EL; and Dr. John Harrison, former Director, EL.

Instrumentation Services Division (ISD)--Mr. Monroe B. Savage, Operations Branch (OB); and Dr. Cary B. Cox, OB. Additional supervision was provided by Mr. Leiland M. Duke (retired), Chief, OB; and Mr. George P. Bonner, Chief, ISD.

Mr. Martin was the Technical Area Manager for Technical Area 3.

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.

Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
gallons per minute	63.094578	cubic centimeters per second
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	2.54	centimeters
kips	454.0	kilograms
knots (international)	0.514444	meters per second
miles (US nautical)	1.852	kilometers
miles (US statute)	1.609347	kilometers
miles per hour	0.4470	meters per second
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
tons (force)	908.0	kilograms
yards	0.9144	meters

Summary

This report summarizes research conducted under the Dredging Research Program (DRP) at the U.S. Army Engineer Waterways Experiment Station (WES). Under DRP Technical Area 3, "Dredge Plant Equipment and Systems Processes," new technologies were developed and existing dredge systems were enhanced to achieve economic load during hopper-dredging activities. Improvements include design and field verification of a debris-resistant eductor for sand bypassing at tidal inlets, the conceptual and recommended design of a single-point mooring system for direct pumpout of hopper dredges onto the beach, better technologies for hopper-dredge production and process monitoring, and design modifications to hopper-dredge dragheads to increase production.

"Improved Eductors for Sand Bypassing" developed a debris-resistant DRP eductor (jet pump) and conducted comparison field tests with this new eductor, an existing eductor design presently in use at Indian River Inlet, DE, and two different designs of submersible pumps. The design of a fluidizer system for inducing sand transport to the eductor site also was provided. A water-injection dredging demonstration was conducted to determine the effectiveness of this method of fluidizing shoaled sediments and allowing density or natural currents to transport the material to deeper water regions.

Under "Dredging Equipment for Nearshore/Onshore Placement," a direct pumpout (DPO) mooring system was designed so hopper dredges can respond to national emergencies (such as hurricanes) with the ability to quickly place sand on the beach as needed. Significant amounts of material dredged by the Corps could also be used for beneficial purposes such as wetland development if less-expensive means were available to deliver the material to an appropriate site. The DPO is transportable by truck, rail, or barge to the assembly site. Logistics requirements for transportation, deployment, and retrieval were developed.

"Technology for Monitoring and Increasing Dredge Payloads for Fine-Grain Sediments" evaluated diffusers, hydrocyclones, and inclined plates to assist in obtaining the economic load of a hopper dredge by increasing fine-grain sediment load in the hopper. Economic load is the load in a hopper dredge that corresponds to the minimum unit dredging cost, and is achieved by often very inefficient overflowing techniques. An automated load monitoring system

(ALMS) was developed to determine the average density in a dredge hopper by measuring the level of dredged material in the hopper and the dredge draft. An electrical resistivity method was developed and installed aboard the dredge *Wheeler* for determining the actual vertical density profile in the hopper.

"Improved Draghead Design" evaluated modifications to hopper-dredge draghead design to maintain an optimum production rate in varying bed-material types. These physical tests in the laboratory of a prototype-size section of a hopper-dredge draghead (to avoid scale effects) considered the effectiveness of water jets and blades as enhancement devices to scarify compacted sediments for better entrainment by the suction-dredge draghead. A draghead fitted with uniform slots to increase hydraulic efficiency and induce more dredging capacity also was evaluated.

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 dredges an average annual 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 minimal 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. 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 in which many distinct products were generated and annual and one-time direct and indirect benefits are quantifiable.

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 3

Objectives of Technical Area 3, "Dredge Plant Equipment and Systems Processes," included (a) improvement of debris resistance of eductors (jet pumps) for sand bypassing and evaluation of the concept of water-injection dredging, (b) conceptual design of a single-point direct pumpout facility for Corps hopper dredges, (c) improved technologies for hopper-dredge production and process monitoring, and development of methods to increase hopper-dredge payloads, and (d) design of modifications to hopper-dredge dragheads to increase production. Solutions were developed for deficiencies existing in four major areas of concern pertaining to physical enhancements to dredge-plant equipment for improving systems processes:

a. Improved eductors for sand bypassing and water-injection dredging.

b. Dredging equipment for nearshore/onshore placement.

c. Technology for monitoring and increasing dredge payloads for fine-grain sediments.

d. Improved draghead design.

Report Organization

Chapter 2 of this report presents (a) results of controlled comparison field tests of eductors (jet pumps) and submersible pumps, (b) operational comparison field tests of the DRP and Indian River Inlet eductors, (c) development of design guidance for fluidizer application for channel maintenance and sand bypassing, and (d) investigations of water-injection dredging (WID) as a concept for fluidizing sediments for transport by density currents away from the dredging site, at applicable locations.

Chapter 3 provides conceptual and recommended designs for a single-point mooring system for direct pumpout (DPO) of Corps hopper dredges (including the buoy, swivel, floating and underbuoy hoses, and mooring hardware) and transportation and installation procedures.

Chapter 4 discusses (a) practices and problems associated with economic loading and overflow of dredge hoppers and scows, (b) results of laboratory testing of methods to increase hopper dredge payloads, including diffusers, hydrocyclones, and inclined plates, and (c) results of laboratory and field investigations of technologies for hopper dredge production and process monitoring, such as the automated load monitoring system (ALMS) for determining average density in a dredge hopper and electrical resistivity methods for directly determining actual density in the vertical direction in a dredge hopper.

Chapter 5 describes laboratory studies to determine the effectiveness of water jets, blades, and uniform slot modifications to a hopper dredge draghead for increasing dredging production when operating in compacted sediments.

Chapter 6 is a synopsis of technical reports pertaining to products and technology developed by the DRP to enhance the operational aspects of Corps dredge plant equipment and systems processes.

2 Improved Eductors for Sand Bypassing, and Water-Injection Dredging[1]

While conventional dredges are used in the majority of sand bypassing at tidal inlets, fixed bypass plants have been used in the United States since about the 1930s. These early fixed bypass plants used conventional dredge pumps operating through a suction snout from a pivoting turret attached to the updrift jetty. In the 1970s, WES investigated using eductors (jet pumps) for sand bypassing (McNair 1976), culminating in an instruction report on eductor bypass-system design (Richardson and McNair 1981). During the late 1970s and early 1980s, a limited number of eductor-based bypass plants operated on the U.S. east and gulf coasts. However, debris often reduced production rates, and difficulties in deploying and retrieving the eductors limited their effectiveness. One objective of this research area was to evaluate a new design for an eductor to improve operational characteristics. Another objective was to determine the feasibility of WID for flushing shoaled sediments away as fluidized density currents.

Eductors and Submersible Pumps

One goal of the DRP was to design an eductor (referred to as the DRP eductor for the remainder of this report) that would maintain good performance in removing various types of debris and would be easily deployed and retrieved when used as a part of a fixed bypass plant. As the eductor investigations progressed, it became apparent that other options for fixed plant bypassing should be evaluated. Submersible pumps (small centrifugal pumps placed directly in the sediment to be bypassed) appeared to offer several positive features that made them potentially attractive as eductor alternatives for sand bypassing.

[1] Chapter 2 was extracted from Clausner (1992b), Clausner et al. (1993, 1994), and Williams, Clausner, and Neilans (1994).

Fluidizers are perforated pipes through which water is pumped under pressure and released through orifices, causing the overlying sand to liquify and flow down mild slopes toward the eductor or pump. This is a method of improving bypassing with fixed eductors to increase the area over which sand is trapped. To complement the eductor research, the DRP also investigated fluidizer hydraulics to expand the area of eductor influence.

Eductors

Eductors are hydraulic pumps with no moving parts. They operate by using a supply (motive) water pump to provide high pressure flow at the eductor nozzle. As the jet contacts the surrounding fluid, momentum is exchanged in the mixer as the jet slows while it accelerates the surrounding fluid, entraining additional fluid into the jet. As the surrounding fluid is entrained by the jet, it pulls in additional fluid from outside the eductor. Placing an operating eductor in saturated sand allows it to bypass a sand/water slurry. Often some of the supply water is diverted to fluidizing nozzles to increase the flow of sand to the eductor. In the diffuser, the excess jet velocity is converted to allow operation with appropriate hydraulic conditions (Clausner et al. 1994).

Figure 1 is a schematic of an eductor installed at Indian River Inlet (IRI), DE, in 1990. This bypassing plant uses a single eductor deployed from a crawler crane to mine the updrift fillet. Between February 1990 and August 1991, this plant bypassed over 200,000 cu yd[1] and successfully performed its mission. The eductor used at the IRI bypass plant was designed and manufactured by Genflow America and had nozzle, mixer, and diffuser dimensions nearly identical to the refined DRP eductor. As such, it provided an excellent baseline for evaluating improvements made in the DRP eductor shown in Figure 2. An application of the IRI-type eductor at Nerang River entrance, Australia (Clausner 1989), has operated with considerable success, except for periods of debris clogging. The IRI installation is far simpler than the Nerang application.

One advantage of eductors over conventional centrifugal pumps is that they are essentially immune from blockages in the discharge line. A brief explanation is that as the discharge line starts to clog, the pressure against which the eductor is working increases. This reduces the amount of material the eductor is entraining, thus reducing the potential for clogging the pipe. This is true even when the eductor is used in a hybrid combination with a centrifugal pump.

WES investigations in the 1970s were based on a commercially available eductor with a single side-suction tube. This type eductor is susceptible to clogging of the side-suction duct by debris. The Genflo eductors used at the

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

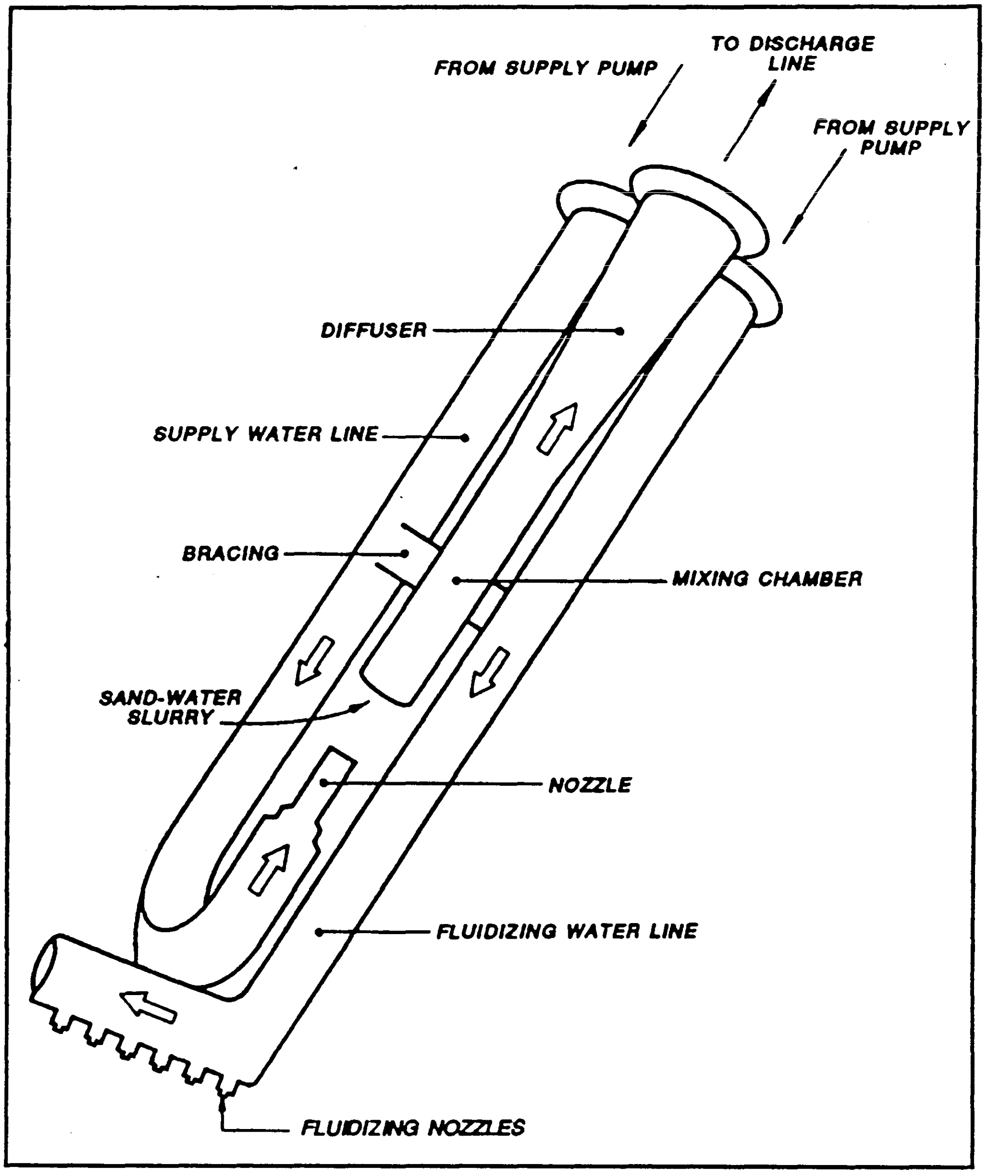

Figure 1. Schematic of IRI eductor

Nerang River entrance and at the IRI bypass plant have an open annular suction, providing less opportunity for a single small piece of debris to clog the unit. A shroud can be added to reduce the risk of a hemispherical sand bridge forming around the entrainment zone and to reduce the risk of sand feeding back into the eductor nozzle when the eductor is turned off. However, the open annular-suction eductor proved to be susceptible to debris, particularly sticks and logs, that could form a filter layer above the eductor. This tangle of sticks both reduced performance and made retrieval of the eductor difficult at the Nerang bypass plant.

The standard method of handling debris at a plant with fixed eductors (i.e., eductors that are not readily removed) is to backflush, blocking the discharge

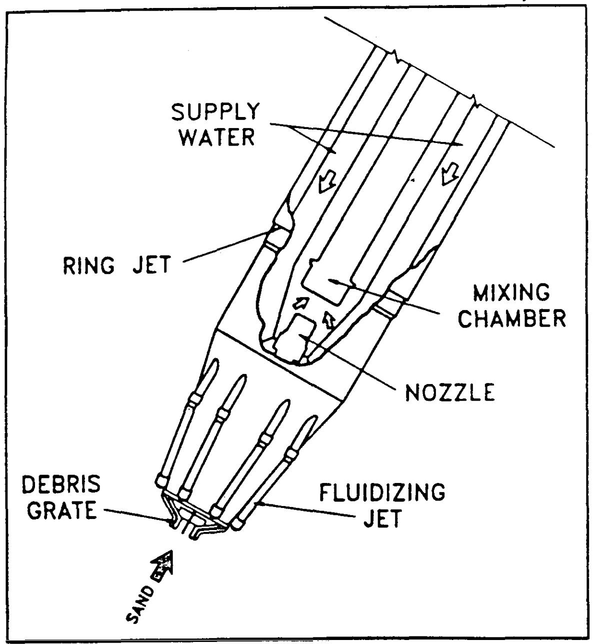

Figure 2. Schematic of DRP eductor

line and thus forcing the supply water out through the suction duct and, hopefully, also flushing out the debris. However, in areas with considerable amounts of debris, the backflushing requirement can become so frequent that the operation becomes impractical. The ability to operate effectively in areas with debris is important and was the driving force behind the DRP eductor development.

The DRP eductor was designed to reduce the impact of debris and deployment problems. A number of mechanical and hydraulic devices were considered to solve the problems. The final configuration selected was designed to have the best combination of debris resistance, ease of installation, and simplicity of design and operation.

The DRP eductor was developed under contract to Genflo America. Included in the contract were conceptual design, detailed design, construction, controlled comparison field tests, and full-scale performance field tests. Some of the design features of the DRP eductor include:

a. A smooth cylindrical outer shape to prevent debris (logs and sticks) from jamming in the eductor framework and making retrieval difficult.

b. A series of fluidizing nozzles around the perimeter of the tip to fluidize the sand for removal and to allow heavy debris to sink below the eductor.

c. A grate over the entrance to prevent debris from entering the suction chamber.

d. A ring jet to reduce pullout forces.

Submersible pumps

Submersible centrifugal pumps are typically single-stage vertical pumps with discharge diameters that range from 4 to 12 in. (Figure 3). Pump sizes are usually based on discharge-line diameters. Submersible pumps differ from conventional dredges in that the submersible pump is placed directly

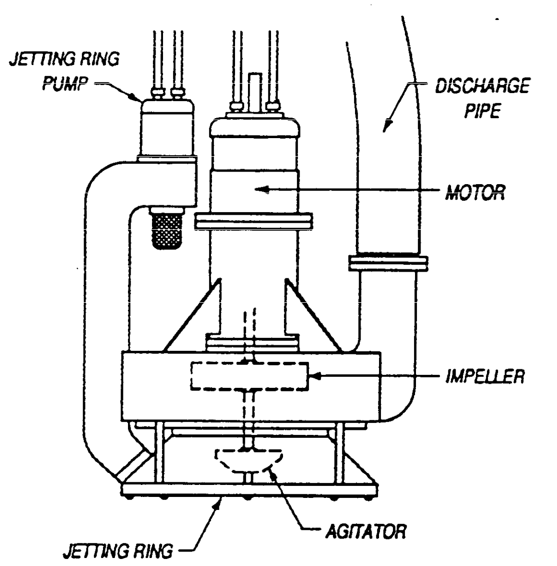

Figure 3. Submersible pump with jetting ring

in the material to be removed.

Submersible pumps are powered by hydraulic or electrical motors, usually requiring a diesel power source for the hydraulic pump or a generator. The power requirements for most of the submersible pumps used in dredging applications are in the 70- to 250-hp range. The pumps range from a few feet up to 8 ft in height and weigh from under 500 lb to over 4 tons. They can be deployed from various platforms such as at the end of a crane or the boom of a backhoe. Obviously, the smaller and lighter the submersible pump, the greater the number of deployment options. Submersible pumps (depending on the deployment method) can be easily maneuvered into areas of limited access. Some submersible pumps have an external agitator on the end of the impeller shaft that assists the material flow into the pump. In addition, an option to add a jetting ring or small cutterhead to improve material flow to the impeller is available on a number of submersible pumps.

A primary advantage of submersible pumps over eductors is that they do not require a clean water source. In coastal inlet sand-bypassing operations, eductors are often combined with booster pumps to optimize production and efficiency and to allow the discharge to be pumped from one to several thousands of feet downdrift. Often the supply pump and booster pump are placed in a common pump house adjacent to the inlet that is used as the clean water source. Submersible pumps typically used for bypassing operations often have higher discharge pressures than eductors and therefore may not require booster pumps, depending on the distance the material must be pumped.

Some of the major areas of concern for submersible pumps are the life of the pump seals and overall reliability of the mechanical components, motor, and other parts, with much of the concern due to the abrasive nature of the material being pumped. Manufacturers recommend checking the pump impellers for wear every 80 hr of operation.

One disadvantage of submersible pumps is that they tend to dig vertical-sided holes. This operating characteristic can be a particular problem in cohesive material because it makes the pump susceptible to collapse of the hole, which can bury and choke the pump and may result in the loss of the unit. Most submersible pumps are not designed for burial and self-starting unlike an eductor, where the water supplied under pressure provides sufficient energy and dilution water to the eductor. Clean fine sand is the optimum material that submersible pumps can transport.

Controlled field tests of eductors and submersible pumps

The objectives of these controlled field tests were to determine the production rate of the DRP eductor, the IRI eductor, and two commercially available submersible pumps[1] under conditions similar to those in a coastal environment. Tests were conducted in clean sand and in a series of different debris combinations similar to those expected on open-ocean coasts (Clausner, Welp, and Bishop 1992; Clausner et al. 1994).

Test location. Tests were conducted at Standard Gravel Company's Enon, LA, sand pit where site characteristics were very similar to coastal bypassing locations. The site encompassed an area approximately 300 ft by 450 ft with clean sand (mean diameter 0.3 mm, less than 5 percent fines) in excess of 25 ft thick. The test site layout was essentially the same for both the eductor and submersible pump tests.

Test conditions. Based on past experience with eductors, several different combinations of debris were selected. Logs and sticks are often found in coastal areas, as are stones both from naturally occurring materials and core stones washed out or left over from jetty construction. Garbage and ice bags (plastic products) are commonly found, as are more sturdy but still flexible items such as swim fins, rubber tires, etc. Aluminum beverage cans also are commonly found in the coastal zone. Finally, kelp is common along Pacific coastal areas. The following combinations of materials were selected for testing:

a. Clean sand, mean diameter of 0.3 mm and less than 5 percent fines.

b. Sixteen cubic feet of cut wood that varied in length from 1 to 3 ft and in diameter from 1 to 6 in. Prior to the tests, the wood pieces were soaked in water, which produced a negative buoyancy and allowed them to sink to the bottom of the crater during the test.

c. Sixteen cubic feet of stone riprap ranging in size from 2 to 18 in. with a mean diameter of 7 in.

d. Sixty garbage-bag-sized plastic liners (weighted with sand) and 15 "swim fins" fabricated from 3/4-in., 4-ply conveyor belt cut into 9- by 24-in. rectangular pieces.

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[1] H&H Pump Company, Model PF50x8 (8-in. discharge) and Toyo, Inc., Model DP-150B.

e. Approximately 500 aluminum beverage cans (punctured to sink) were tested in one eductor trial with no apparent effect on production (small pieces of shredded cans were observed), so use of this debris was discontinued.

f. Kelp was obtained from San Diego, CA, Department of Parks and Recreation, but test runs with this debris were discontinued due to the kelp's increasing rate of deterioration and negligible effect on production rates. Had fresh kelp been constantly available, it likely would have had an impact on production.

Eductor tests. The DRP and IRI eductors had very similar performance in clean sand, about 400 cu yd/hr. Production was relatively constant throughout each 30-min test period for all tests of both eductors in clean sand. These relatively constant production rates are due to the fact that eductors are self-metering. As they pick up more material, their ability to pick up additional material is reduced, and the reverse is true as they pick up less material. The eductors consistently pumped slurries of 35 to 42 percent solids by weight in clean sand.

Eductor performance was reduced substantially in debris. The DRP eductor was considerably better in stone (296 versus 239 cu yd/hr) and slightly better at bypassing garbage bags and swim fins (249 versus 217 cu yd/hr). The IRI eductor was superior in wood (379 versus 316 cu yd/hr). In the tests with debris, production rates at the beginning of the tests were nearly the same as in clean sand. As the test progressed, debris would accumulate around the eductor at the bottom of the crater and cause a reduction in percent solids to below 30 percent, thus reducing production rates. Production dropped from rates of 300 to 400 cu yd/hr to rates of only about 100 to 200 cu yd/hr at the end of the 30-min test period.

Submersible pump tests. Of the two submersible pumps, the Toyo pump had consistently higher production in clean sand and all types of debris, while the H&H pump had the lowest production of any unit (i.e., eductor or pump) tested. It should be noted that the H&H pump had only an 8-in.-diam discharge pipe while the eductors and Toyo pump had 10-in.-diam discharge pipes. Had a 10-in.-discharge coupling that attaches directly to the pump housing been available for the H&H pump, an increase in production rate of up to 15 percent was conceivable. This could have potentially raised production rates for the H&H pump to 292, 112, and 247 cu yd/hr in sand, stone, and garbage bags and swim fins, respectively. The H&H pump could produce slurries with 60 percent solids for short periods of time, but generally averaged around 30 percent solids in clean sand. The ability to capture very high percent solids made the H&H pump more prone to plugging of the discharge line than any of the other units.

The Toyo pump had the highest overall production of any unit tested, nearly 500 cu yd/hr, with percent solids often exceeding 45 percent by weight. The wood and the garbage bags with swim fins had an appreciable impact on production, reducing it to 285 and 380 cu yd/hr, respectively. The Toyo pump's external agitator, combined with an inlet shroud, apparently assists in metering solids into the pump more effectively than the H&H combination and thus contributes to its better performance and reduced risk of line plugging.

Conclusions from controlled field tests. In clean sand, performance of the DRP eductor and the IRI eductor are about the same. Performance in debris is a function of the type of debris. The grate and fluidizers on the DRP eductor allow better production in stone and garbage bags/swim fin debris than the IRI eductor; however, the DRP eductor grate is more prone to clogging with wood than the IRI eductor. The IRI eductor is more susceptible to stones entering into the suction chamber, thus reducing performance. For fixed plants where the eductor cannot be moved, production in a particular debris type can be optimized by selecting the correct combination of intake, grate, and fluidizer. Even with the proper design, production will be considerably lowered as debris accumulates. To achieve maximum production, the ability to move the eductor to a new location and/or remove the accumulated debris from the crater is required.

The H&H pump, as tested, was not well-suited to the types of debris tested. It was very susceptible to both rocks and wood. A rock guard, relatively easily fabricated (and also available from the manufacturer), could help solve these problems, though possibly reducing performance somewhat. The Toyo pump performed the best overall and was only bettered by the IRI eductor when pumping wood debris.

Submersible pumps have been used successfully around locks (Neilans et al. 1993). These applications have been relatively small, aperiodic jobs removing fine sand with considerable amounts of silt where initial cost and the low number and simplicity of components have been of prime importance. Submersible pumps are not recommended by Clausner et al. (1994) in coastal sand bypassing applications. The high amount of operator adjustments required to maintain high solids contents and the potential for line plugging when dredging medium and coarser sand makes them less desirable than eductors.

Operational field tests of eductors

Field tests comparing production of the DRP eductor and the IRI eductor were conducted at the existing IRI eductor location at the Indian River Inlet, DE, sand-bypassing plant. The IRI site is not ideally suited to fully test the design features of the DRP eductor. The IRI bypassing plant is neither fixed (the condition for which the DRP eductor was designed) nor does it have a significant debris problem. However, the IRI site had a number of attractive features including compatible hydraulics (pressure, flow rate, pipeline diameters), adaptable deploying crane, and existing instrumentation. Both eductors were tested and data collected on several different parameters. These data were then used to calculate hourly production rates that were used for comparison between the two eductors. Operational field tests to compare the DRP eductor and the IRI eductor are detailed in Williams and Clausner (1994) and Williams, Clausner, and Neilans (1994).

The operational field tests were intended to test the DRP eductor in actual working conditions and compare its performance with that of the existing IRI eductor over an extended period of time. Because the DRP eductor was specifically designed to operate in high debris conditions, two fundamental design differences (fluidizer arrangement and an inlet grate) existed that had the potential to affect production performance. Another objective of the tests was to determine the deployment capabilities of the DRP eductor. The IRI bypass plant operates with a crawler crane that strategically places the eductor in locations most desirable for bypassing. The DRP design was intended to be deployed from a fixed location, most likely from a pier, similar to the bypass plant at the Nerang River entrance.

Test location. The operational field tests were conducted at Indian River Inlet, DE, located on the Atlantic coast approximately 10 miles north of Ocean City, MD. The shallow meandering inlet at the site was improved in the late 1930s to provide a more reliable conduit of fresh water for the bay. Soon after construction, the 500-ft-wide twin-jettied inlet began to show the classic updrift accretion and downdrift erosion pattern associated with a net sediment transport in one direction. Since then, periodic beach nourishment has been required to protect the highway bridge approach on the north side of the inlet.

It was concluded that a fixed sand bypass plant was the most economical means of protecting the bridge. The final design selected consists of an eductor employed from a crawler crane along a 500-ft-long stretch of the beach just south of the south jetty. Slurry discharge from the eductor flows to a booster pump and is then pumped across the highway bridge to the north side of the inlet. Typical discharge pipeline length from booster pump to discharge point is 1,500 ft.

Test conditions. Several parameters were measured during the eductor tests to be used in examining eductor performance: (a) time, (b) slurry velocity (feet per second), (c) percent solids (by weight) of slurry, (d) production rate (cubic yards per hour), (e) specific gravity of slurry, (f) motive-pressure (pounds per square inch), (g) pressure at booster pump intake (pounds per square inch), (h) booster pressure (pounds per square inch), (i) supply suction (pounds per square inch), and (j) accumulated production (yards).

Raw data were collected continuously with 30-sec averages reported. These 30-sec averages were used to calculate both 1- and 5-min averages of all parameters. Each parameter was examined to provide insight into the relation between eductor performance, system components, pressures, and material properties. The most direct way to compare eductor performance is to study the respective DRP and IRI production rates. Average daily production rates were calculated by summing the accumulated volume (cubic yards) of material bypassed during each test run and dividing by the duration (hours) of pumping for each test run. This average production rate is therefore more easily utilized in inter-comparison of eductor performance.

Conclusions from operational field tests. The DRP eductor performed slightly better than the IRI eductor by about 11 percent without considering other factors. This increased production is probably most directly related to the perimeter fluidizer arrangement on the DRP eductor, which may have more effectively entrained sand for entry to the pump and to the suction chamber geometry.

A qualitative factor not included in the production analysis is the ease with which each eductor setup could be maneuvered. Bypass plant staff were more familiar using the crane to manipulate the IRI eductor system as opposed to the larger, heavier, and more awkward DRP eductor/deployment truss/roller combination. It is probable that a slight additional increase in production may have been realized for a more easily maneuvered DRP eductor. For permanent use at a bypass plant like Indian River Inlet, the present DRP eductor could be made easier to handle by making some modifications. These would include removing the deployment truss/roller combination and modifying the upper end of the DRP eductor to accept the supply and discharge pipes by adding a curved steel pipe section similar to that used on the IRI eductor.

It should be reiterated that the intent of the DRP eductor design was for use in areas with large amounts of debris. The Indian River Inlet site is not indicative of an area with significant debris, so the true effectiveness of the DRP eductor in high debris areas was not determined during these tests.

Fluidizers

Fluidization is a process in which fluid is injected into a granular medium (typically sand) causing the grains to lift and separate. Over the last decade, research on fluidization of sand at tidal inlets and harbor mouths has been undertaken to use fluidization for maintenance of navigable waterways and for use in sand bypassing (Clausner 1992b). The design objective for a fluidization system is primarily to create a trench of a given cross section and length. To obtain a trench, complete fluidization must be achieved. The two basic parts of the design are a hydraulic aspect to attain full fluidization and a geometric element to obtain a desired trench geometry. Basic research has helped define these two crucial aspects.

Use of fluidizers to augment sand bypassing

The best use of a fluidizer pipe in sand bypassing is to increase the fluidized zone of a fixed bypassing system. The quantity of sediment that a fixed system can bypass is limited by the sand supplied by littoral transport. In particular, an eductor creates a crater of fairly limited extent, and an operator must wait until the crater refills with sand supplied by littoral processes before pumping again. A fluidizer pipe, used in conjunction with a fixed slurry pump, can create a long trench (typically 100 to 400 ft) that traps sand across a portion of the littoral zone, supplying additional slurry to the pump crater (Figure 4).

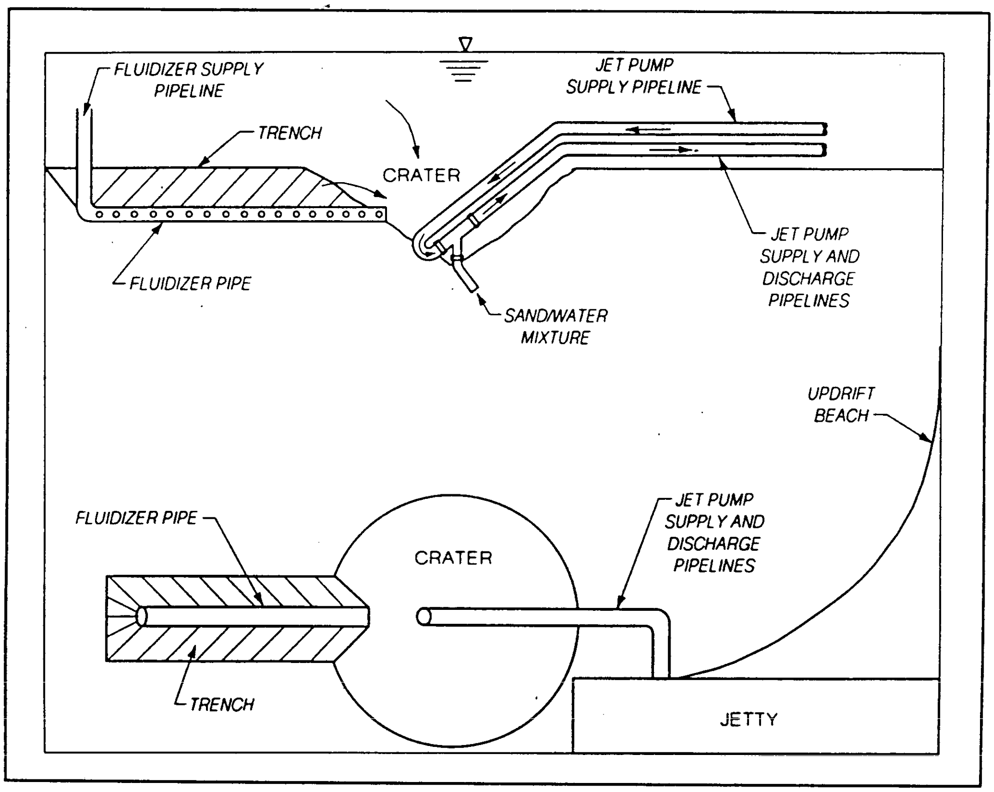

Figure 4. Fluidizer pipe used in conjunction with a fixed slurry pump; hatched area indicates fluidized zone

The basic components required for the fluidizer system include:

a. One or more fluidizer pipes sloping toward the jet pump crater.

b. Water supply pipelines to each fluidizer pipe to carry clear water.

c. Pumps to provide clear water to the fluidizer pipes.

d. Intake facility to ensure that pumps carry clear water to the fluidizer to avoid clogging of holes.

e. Supply pump for the jet pump.

f. Supply pipeline for the jet pump.

g. Discharge pipeline from the jet pump.

h. Booster pump and discharge pipeline to deliver slurry to some distant discharge point.

Use of fluidizers for channel maintenance

The trench created by removing slurry from the fluidized region above a fluidizer pipe can be used to stabilize and maintain a navigable channel. If the pipe is placed sufficiently deep or if two or more pipes are placed parallel to each other, the trench dimensions that can be achieved may satisfy the navigation requirements of small shallow-draft vessels.

Once fluidized, slurry in the fluidized region must be removed for the trench to form. For channel formation and maintenance, the slurry may be removed by either of the following two mechanisms:

a. Pumping the slurry out of the trench and placing it on a downdrift beach, as in bypassing.

b. Gravity flow of the slurry to carry the sediment out of the trench, either in the seaward or landward direction; a strong ebb current will assist in sediment flowing in a seaward direction.

For channel maintenance, the fluidizer pipe (or parallel pipes) is extended along the center line of the navigation channel. The configuration for a channel maintenance system can take on various forms depending on the slurry removal mechanism.

Fluidizer design procedure

The detailed procedure for designing a fluidizer system has been given by Weisman, Lennon, and Clausner (in preparation), including a family of design curves for choosing the appropriate flow rate based on the relative depth of burial of the pipe with respect to pipe diameter, and relative particle size with respect to trench dimensions. All experiments and field experience thus far have been limited to fine to medium sand. There is no experience with either finer or coarser material. If the fine material is noncohesive, fluidization should work. However, if some cohesive materials are present, there may be difficulty in achieving full fluidization and trench formation (i.e., the side slopes may not slump). Clearly, it takes much larger flow rates to fluidize medium sand compared to fine sand. There may be a practical limitation to sediment size such that the flow rate requirements to achieve full fluidization become uneconomically large.

Limitations also may exist due to pipe slope. If the fluidizer pipe is placed on a 1-percent slope to provide for flow of the slurry to a jet pump, then the downstream end of the pipe may require extremely deep burial if the pipe is long. A 1,000-ft-long pipe would require 10 ft deeper burial at the end. This may have significant implications where clay or rock layers underlie sands.

The design of any coastal study, including design of fluidization systems, should begin with an office phase followed in most cases by a field investigation. The office phase should review existing data and begin the design process. Parameters that can be estimated without a field program should be approximated, and a 1- to 3-year field investigation should be conducted if reliable wave data are unavailable. Field data should be reviewed, final parameter values selected, and the design implemented. At the conclusion of the data-acquisition phase, information should include:

a. Estimates of direction and volume of littoral drift.

b. Available information on the sediment type, size, layer thickness, and areal distribution.

c. Historical records of morphology and shoreline location.

d. A historical survey. This may help identify the geomorphology of the site, providing insight into the nature and nonhomogeneity of the materials encountered.

e. Information on coastal structures and their impact.

f. Seasonal variations in littoral transport rates.

g. Waves, currents, and tides.

Frequency of operation

Although the frequency of operation criteria can be estimated, it will actually be determined during operation, being triggered by accumulated depth of sediment in the trench. The duration of operation will be determined by how long it takes to achieve the design elevation of the bottom of the fluidized trench. This will probably be constrained by how fast the jet pump can remove the slurry for sand-bypassing operations; hence, the two systems should be sized/designed together. It is likely that the fluidizer pipe will operate more intermittently than the jet pump. Recent experience with the fluidizer pipes in the Oceanside, CA, bypass system indicates that regular (periodic) operation (once every few weeks) is needed to reduce clogging. Designers should anticipate clogging and provide for measures to clear clogged fluidizer pipes.

Water-Injection Dredging

WID is a dredging concept new to the United States where shoal sediment is fluidized, causing it to flow by density or riverine currents to deeper areas where it does not affect navigation. WID is based on a simple concept: vessel-mounted pumps inject water directly into the sediment voids through low-pressure jets mounted on a long horizontal pipe. This fluidizes the sediment, creating a gravity-driven density current that can flow down very mild slopes. The density current transports shoal material to deeper water where it can settle without impeding navigation or else can be carried farther away by stronger natural currents (Figure 5). Because the dredging equipment is simple to operate with minimal crew or other support and because there is no need to actively transport the dredged material to a disposal site, WID offers a potentially low-cost alternative to traditional dredging for appropriate locations (Clausner 1993, Clausner et al. 1993).

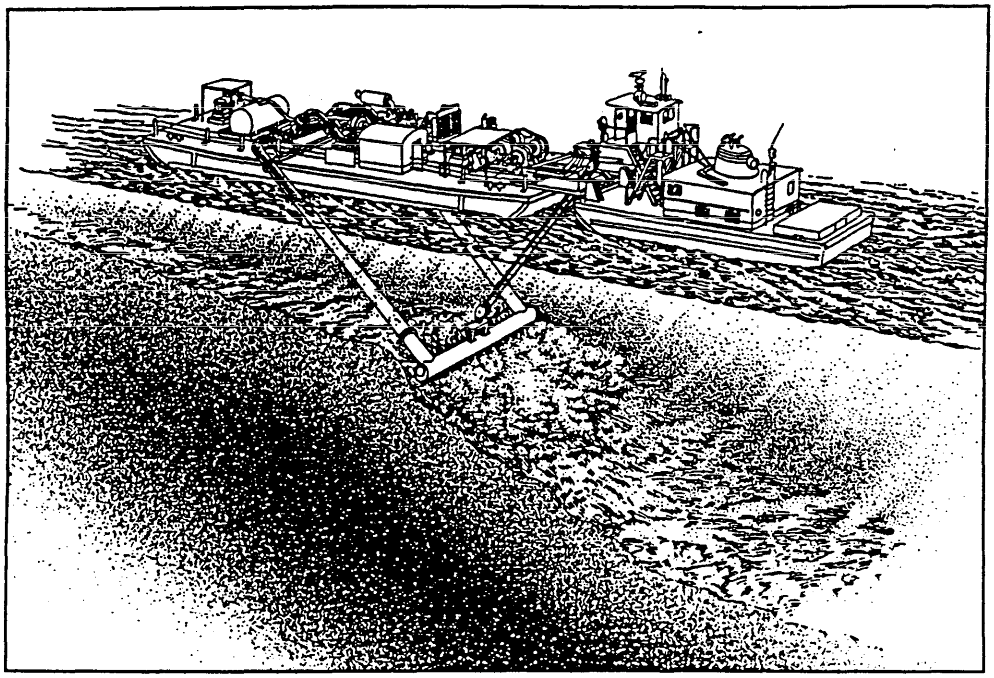

Figure 5. Sediment fluidization and transport by WID

WID demonstration

Objectives and site locations. The DRP's mission of investigating new dredging technologies led to the first prototype field demonstration of WID in the United States. Conducted at two sites on the upper Mississippi River where crossings and point bar shoals had developed, the demonstration was a combined effort that involved WES, the Corp's St. Paul and Rock Island Districts, and two contractors (Gulf Coast Trailing (GCT) and HAM Holland and Dredging International of Belgium).

The WID demonstration was conducted to meet several objectives. The primary objective was to verify the accuracy of the contractors' predictions on production rate, transport distance and direction, and suspended-sediment distribution in the water column. The secondary objective was to determine if the technology worked in conditions found on the upper Mississippi River (moderate currents, medium-sized sand substrates, and two types of shoal typically found there--crossings and point bars). A third goal was to introduce the technology in an area with strong environmental concerns so that those concerns would be addressed during the demonstration.

Many of the concerns from the resource agencies were based on the fact that the WID process was new to the United States, and the agencies were not satisfied with the limited data available on suspended-sediment levels and sediment transport distances. The monitoring plan was designed to provide data to address those concerns about sediment movement onto sensitive biological regions. The two sites selected for the WID demonstration and environmental monitoring were at Lower Zumbro on the Mississippi River between Minnesota and Wisconsin and at Savanna on the Mississippi River between Illinois and Iowa. Characteristics of the two sites are given in Table 1.

Water-injection dredge. GCT designed and constructed a water-injection dredge for these demonstrations consisting of components already owned by GCT. The dredge that was constructed, the BT-208, is not self-propelled. The BT-208 requires a 700-hp (minimum) pushboat for propulsion. An operating crew of three is needed--dredging supervisor, winch operator, and mechanic. The pushboat requires a crew of two. Dredge characteristics are presented in Table 2. The WID barge can dredge in water depths from 7 to 42 ft. Dredging is done in both directions, with the injection head in direct contact with the bottom.

Advantages of WID over other more conventional methods of dredging include lower cost for mobilization/demobilization, quicker response time for project start-up, potentially lower operating cost, potentially higher production

Table 1
WID Demonstration Site Characteristics

Feature	Lower Zumbro (Minnesota/Wisconsin)	Savanna (Illinois/ Iowa)
River mile	744.2	539.2
Type of dredge cut	Crossing	Point bar
Bottom material	Sand (D_{50} = 0.3 mm)	Sand (D_{50} = 0.4 mm)
Dredge cut dimensions	750 ft by 150 ft	700 ft by 200 ft
Dredging depth/datum	11 ft LCP[1]	11 ft LOP[2]
Average thickness of material removed	1.5 ft	2 ft

[1] Lower Control Pool elevation = 659.8 ft.
[2] Low Operating Pool elevation = 583.0 ft.

Table 2
Water-Injection Dredge Characteristics

Component	Description
Barge hull	87 ft long, 28 ft wide, 3-ft draft
Pump power	Caterpillar D398, 750 hp
Pump	Goulds 30- by 24- by 32-in., 30,000 gpm at 18 to 20 psi
Pump intake	4-ft-square opening in bottom of dredge hull, covered with grate, 4-in.-square openings
Water-injection head	36 ft wide, 36-in. diameter (20 3.5-in.-diam jets)
Propulsion	NCS pushboat *Lyon*, 700-hp, twin-screw, 7-ft draft

rates than dredges with comparable horsepower (under certain soil and bathymetric conditions), and potentially quicker project completion time. Other advantages result because the injection head merely rides on the surface of the sediment as opposed to actively digging. Thus, WID allows safer operations with respect to reduced chance of damage to docks, pipelines, and quay walls. Also, restrictions on navigation are less with WID because of the absence of discharge pipelines, spuds, swing wires, etc.

Monitoring program

Nearly all measurements taken as part of the monitoring program were obtained using a short-range microwave system for navigation and positioning. Therefore, at least 90 percent of the measurements had position accuracy better than ± 5 ft. Bathymetry was the primary monitoring tool and was used to determine production rates, assess the ability of WID to clear the dredge cut, and determine where the fluidized sediments were transported.

Water samples were collected and analyzed for total suspended solids to measure the amount of sediments in the water column above background levels resulting from the WID process. Samples were collected a variety of distances from the dredge, ranging from about 30 to 3,200 ft. The samples were generally collected 1 to 2 ft above the bottom and 1 to 2 ft below the water surface. During more intense monitoring episodes, water samples were collected from three or four depths spaced throughout the water column simultaneously from three vessels on a cross-river transect.

Results

A summary of the WID demonstration performance is presented in Table 3. Production rate varies depending on a number of factors. In sand, multiple passes over the same area are needed to initiate the density current. The

Table 3
Summary of WID Performance

Parameter	Lower Zumbro	Savanna
Dredging date	27-29 Jul 92	5-7 Aug 92
Total dredging time	18.25 hr	21.85 hr
Volume removed (in cut)	2,500 cu yd	5,500 cu yd
Volume removed (outside or below cut)	2,500 cu yd	1,500 cu yd
Average production rate (in cut)	130 cu yd/hr	250 cu yd/hr
Average production rate (all material moved)	275 cu yd/hr	340 cu yd/hr
Average fuel consumption		
Pushboat overall	23 gal/hr	23 gal/hr
Pushboat during operations	29 gal/hr	29 gal/hr
Dredge	40 gal/hr	40 gal/hr

dredge is most effective when the water-injection pipe is constantly in contact with the bottom. Therefore, high spots on the bottom must be removed prior to getting good production.

Contractor-predicted production rates and sediment transport distances and directions were reasonably close to actual values. In general, the actual values were lower than predicted as the result of differences between surveys used for estimating production and actual site bathymetry at the time of the operation (Clausner, Welp, and Sardinis, in preparation).

The contractor predicted about 250 cu yd/hr at Lower Zumbro and achieved an average in the cut of about 125 cu yd/hr and 250 cu yd/hr overall. Contractor predictions were based on bathymetry taken months prior to the operation and did not show an area of material just downstream of the cut that had to be removed to access the deeper area downstream. Also, unknown to the contractor before arriving onsite, the Mile 744.2 daymarker restricted access to deeper water.

At the Savanna point-bar site, the contractor predicted about 450 cu yd/hr, based on limited bathymetry and grain-size data. Actual production rates of 250 cu yd/hr in the cut and 350 cu yd/hr overall were measured. The inability to work at an angle to the currents reduced production; also, some of the Savanna material may have been coarser than 0.4 mm. A plateau at the 12- to 13-ft depth may have also been a contributing factor to the lower production rate.

Transport distance and directions agreed very well with contractor predictions, with the vast majority of the material staying within 200 to 400 ft of the limit of dredging.

Conclusions regarding WID

This demonstration of a patented WID technique new to the United States successfully met planned objectives. WID appears to have potential at other sites. Application in sand with diameters greater than 0.2 mm will be very site-specific, requiring nearby deeper water and a smooth downslope gradient. WID is not generally suitable for crossing shoals where sand-sized material above 0.2 mm has to be moved more than a few hundred feet. The propulsion and steering influences on the dredge's ability to work at an angle to the current need to be considered. Also, the draft of the WID vessel or barge/pushboat combination needs to be considered when working in shallow areas. The lack of pipelines and swing wires greatly increases mobility of a WID vessel and reduces to a minimum the disruption of normal navigation traffic. Based on the contractor's experience, WID provides much higher production rates in fine sand and silt. (In other tests in Louisiana, production rates of over 1,500 cu yd/hr in sand with D_{50} of 0.18 mm or less were achieved.)

Routine use of WID in areas where in-water disposal is not normally practiced will require additional considerations. For example, the amount of material now removed by dredging and placed upland in a given reach of the upper Mississippi River is generally a very small fraction of the material transported by the river. However, keeping the material in the system with WID may change surrounding areas and impact future dredging requirements over the long term. Some level of periodic monitoring may be needed to assess such situations.

3 Dredging Equipment for Nearshore/Onshore Placement[1]

At the beginning of the DRP, the Corps of Engineers did not have the capability for direct pumpout (DPO) of hopper dredges in open water. The Corps desired this capability to be able to respond to national emergencies (such as hurricanes) where the ability to quickly place sand on the beach is needed. Significant amounts of material dredged by the Corps could be used beneficially if easier and less expensive means were available to deliver the material to a site where it could be used. For example, clean sand could be placed on eroding beaches or fine-grained materials could be used to nourish wetlands. The Corps desires to increase beneficial uses of dredged material by lowering the delivery cost, making cost-sharing a more attractive option to local sponsors.

Equipment used to perform DPO of hopper dredges was not designed for this purpose; existing equipment was adapted to meet the specific need. With increasing opportunities for beneficial uses of dredged material, the Corps desired a commercially available mooring system able to provide open-ocean DPO for the U.S. hopper dredge fleet. The DRP contracted with SOFEC, Inc., to develop a detailed preliminary design of a single-point mooring system for DPO of hopper dredges (including the buoy, swivel, floating and underbuoy hoses, and mooring hardware) and to conceive the transportation and installation procedure.

DPO Concept

DPO is a method of removing dredged material from hopper dredges, where the dredge moors to an anchored floating structure, buoy, or multiple buoy berths. An underwater pipeline extends from the DPO facility (assumed to be a buoy for the remainder of this section) to shore. A hose is connected

[1] Chapter 3 was extracted from Clausner (1992a) and SOFEC, Inc. (1992a,b).

from the DPO buoy to the hopper-dredge discharge manifold. The dredge mixes the dredged material with water to form a slurry and pumps the slurry from its discharge manifold through the floating hose to the anchored floating DPO buoy and on through the underwater pipeline toward shore (Clausner 1992a).

Design Criteria

The mooring system design was based on three Corps hopper dredges, the *Wheeler*, *Essayons*, and *McFarland*. Design loads and system analysis were based on the displacement and draft of the largest of these vessels, the hopper dredge *Wheeler*. Because the *Wheeler* is one of the largest hopper dredges in the United States, the mooring system design is applicable to most of the U.S. hopper-dredge fleet. The *Wheeler* is 408 ft long and has a 78-ft beam and a 29.5-ft draft. The Naval Facilities Engineering Command calculated the mooring loads for a single-point mooring generated by the *Wheeler* under a variety of wind, current, and wave conditions (Chisholm 1990). The maximum design mooring load was determined to be 100 kips.

Operational weather conditions were chosen to fit the maximum operating environment for the dredge. The mooring was designed for the operational and survival conditions of Table 4. The system was designed for operation in a water depth of 30 to 45 ft; however, operation is possible in water depths up to 75 ft with a slight reduction in capabilities. The distance of the mooring system from shore is limited by the hopper-dredge pumping capacity. The shallow slopes along parts of the east and gulf coasts will often require the dredge to operate in water depths very close to its maximum draft of approximately 30 ft.

Table 4
Design Environmental Conditions[1]

Parameter	Operational	Survival
Significant wave height, ft	6	10
Wind velocity, knots	30	30
Current velocity, knots	2	2

[1] Directions of the environmental forces were chosen to be consistent with nearshore conditions; current parallel to the shoreline and wind and waves perpendicular to the shoreline.

The following operational criteria were also required for the mooring design:

a. Transport by truck or rail.

b. Rapid assembly.

c. Installation with a minimum of crane support and diver assistance.

d. Recoverable and reusable.

Mooring

A catenary anchor leg mooring (CALM) concept was selected because of its ability to be transported in truck-size packages and assembled quickly. Also, the CALM system proved to be the least costly of alternatives to fabricate. The system is anchored by four anchor chains that are arranged 90 deg apart. Each anchor chain is an approximately 600-ft-long, 2-in.-diam oil rig quality stud link, with an anchor suitable for sand and clay connected to the end. Anchors may either be 10,000-lb Navy Navmoor or 6,000-lb Bruce International anchors. The oval-shaped CALM buoy is 24 ft in diameter and has a 28-ft-diam skirt that extends beyond the buoy. A turntable mounts on top of the buoy. The mooring hawser and floating discharge hose connect to the turntable.

The CALM system provides a very compliant mooring that is the most adaptable to water depth changes of any of the alternatives studied. The system can be designed to be disassembled for truck transport and then reassembled at the side of a pier. Installation and retrieval of the system can be accomplished with the assistance of chain-handling boats. A minimal amount of diver or surface swimmer work would be required. A CALM system is inherently a wave rider and should require very little preparation for most storms other than the possible need to disconnect the floating and under-buoy hoses.

DPO Buoy System

Description

The DPO mooring buoy (Figure 6) is a capsule-shaped buoy that is 28 ft long by 11 ft 6 in. wide by 7 ft 6 in. deep. Although not the conventional shape for a mooring buoy, the shape was chosen to facilitate towing the buoy and placement on flatbed trucks. The buoy can be disassembled into four components: buoy hull, fluid piping, fluid swivel, and mooring table.

The buoy hull serves as the foundation for the fluid piping. Slurry from the dredge enters the buoy through a floating hose connected to the fluid piping just above the water at the outer edge of the buoy. Piping is designed to contain a minimum amount of bends to reduce areas of high abrasion.

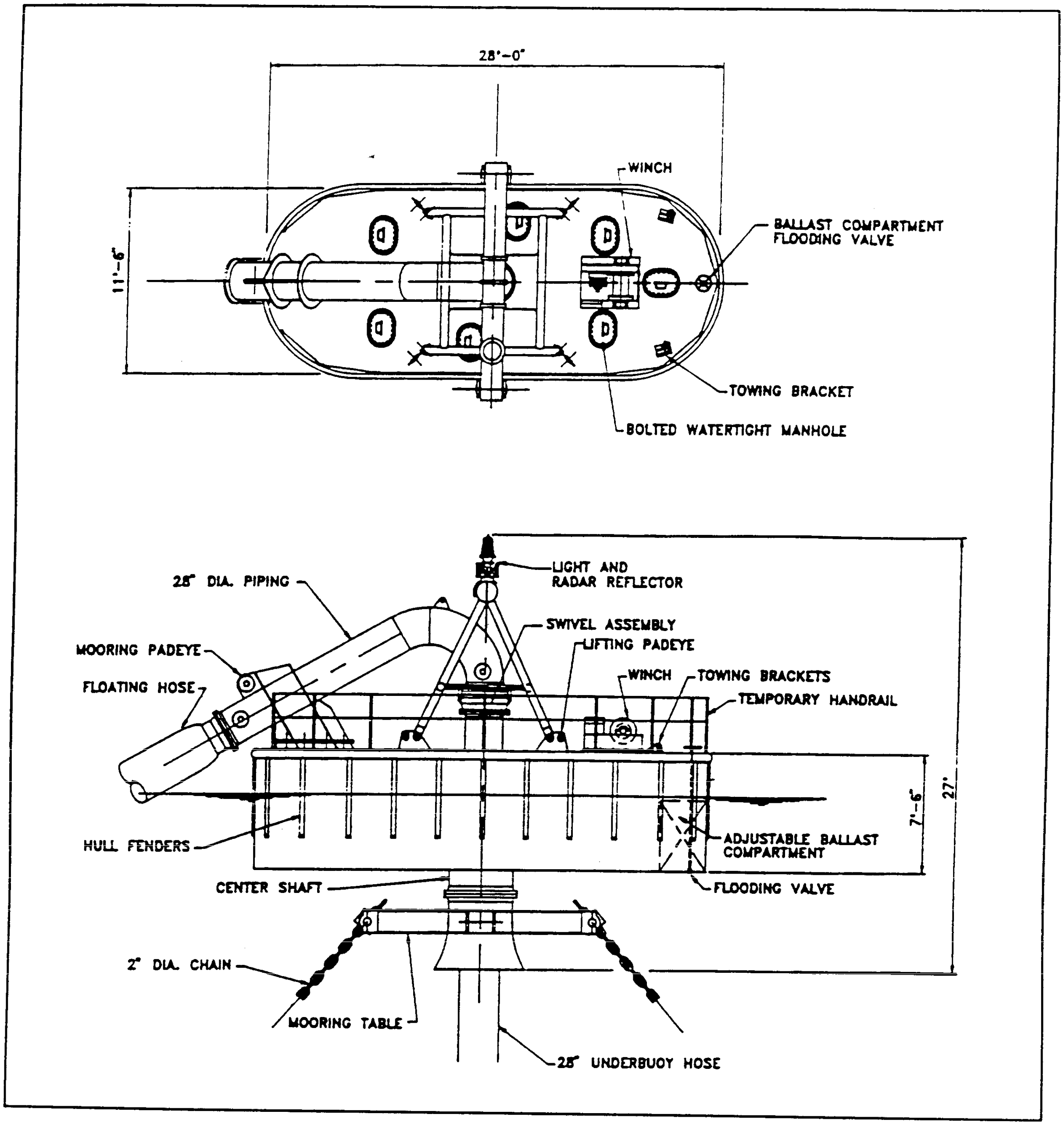

Figure 6. DPO mooring buoy

Slurry travels through the piping to a fluid swivel. Slurry leaves the buoy through an underbuoy hose that is connected to the fluid swivel and leads to a submerged steel pipeline that carries the slurry to the discharge area on shore.

The fluid swivel is an in-line swivel currently used by the dredging industry. It contains bronze bushings that reduce the need for seals or the need for extensive maintenance that roller bearings would require. The lower end of the fluid swivel contains a quick-release flange to assist in connecting the underbuoy hose.

Near the fluid piping/floating hose connection, a mooring pad eye provides for connection of a mooring hawser. The hawser transfers the mooring forces from the dredge to the buoy.

The buoy is designed for a 28-in. pipeline. As a general rule, dredges with discharge pipe diameter within ±2 in. of the shore-discharge pipeline can efficiently use the shore-discharge pipeline. Thus, this DPO buoy design is suitable for use with dredges having discharge pipe diameters ranging from 26 to 30 in. This range of diameters covers most of the U.S. dredge fleet with DPO capability.

The buoy rotates about a shaft that runs through the center well of the buoy. The center shaft contains two permanently lubricated bronze bushings located at the top and bottom of the center well of the buoy. A 48-in.-diam flange is located at the bottom of the center shaft. This flange provides the mechanical connection between the buoy and the mooring table.

The mooring table extends below the buoy and provides locations for connecting the mooring chains to the buoy. The mooring table also provides a bell fairing to reduce chafing of the underbuoy hose. Floating and underbuoy hoses for this mooring system are standard commercially available hoses currently used in the dredging industry. Figure 7 shows the installed mooring system during the DPO process.

Transportation

The DPO CALM system can be transported by truck, rail, or barge to the assembly location. Figure 8 shows the buoy packaged for transport by truck.

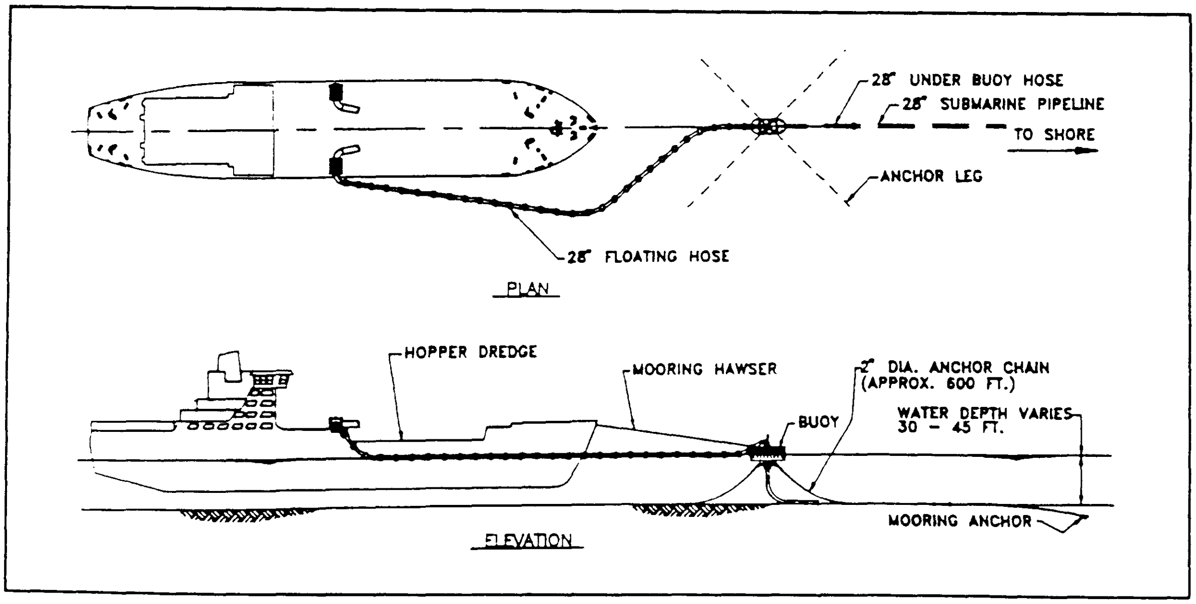

Figure 7. DPO system general arrangement

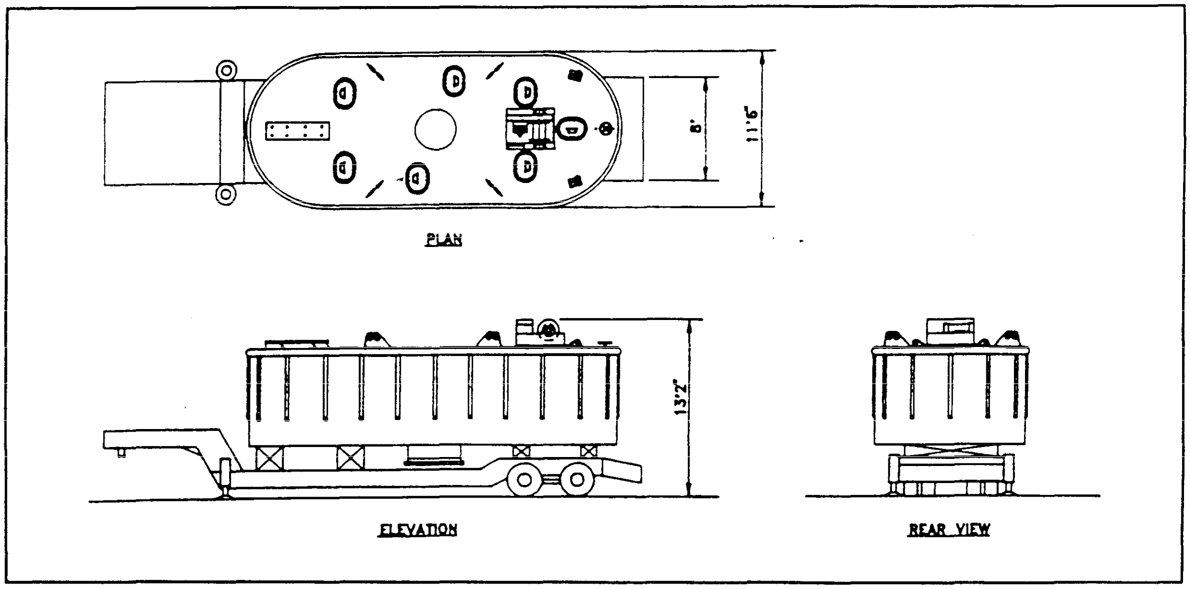

Figure 8. DPO mooring buoy truck-transportation configuration

Components of the system can be consolidated and transported on standard flatbed tractor-trailer rigs. The entire system can be transported by as few as seven trucks. For ocean transport, the entire system can be arranged on a standard 60- by 120-ft cargo barge.

Assembly

The DPO CALM system is assembled by attaching the mooring platform to the 48-in.-diam flange located at the bottom of the buoy (Figure 9). The fluid swivel is then attached to the buoy top deck, followed by the attachment of the piping to the fluid swivel and to the buoy deck at the outer edge of the buoy. The buoy is then lifted into the water by a shore-based crane. For short tows, the floating hose can be attached to the piping before towing.

Assembly requires 300 ft of dock space adjacent to a 250- by 300-ft staging area. Minimum crane lifting capacity required for assembly and launch is 60,000 lb at 20 ft. The buoy can be assembled and installed onsite in 1 week. Additional dock space, a second crane, and appropriate personnel can reduce the total time for assembly and installation by 1 or 2 days.

Installation

Once the buoy is assembled, a tow tug is connected to the towing pad eyes on the buoy deck opposite the piping. The capsule shape of the buoy allows the buoy to be towed at greater speeds and provides a more stable tow than a conventional cylindrical buoy. While the buoy is under tow to the installation location, an anchor-handling tug is used to install the four mooring chains and

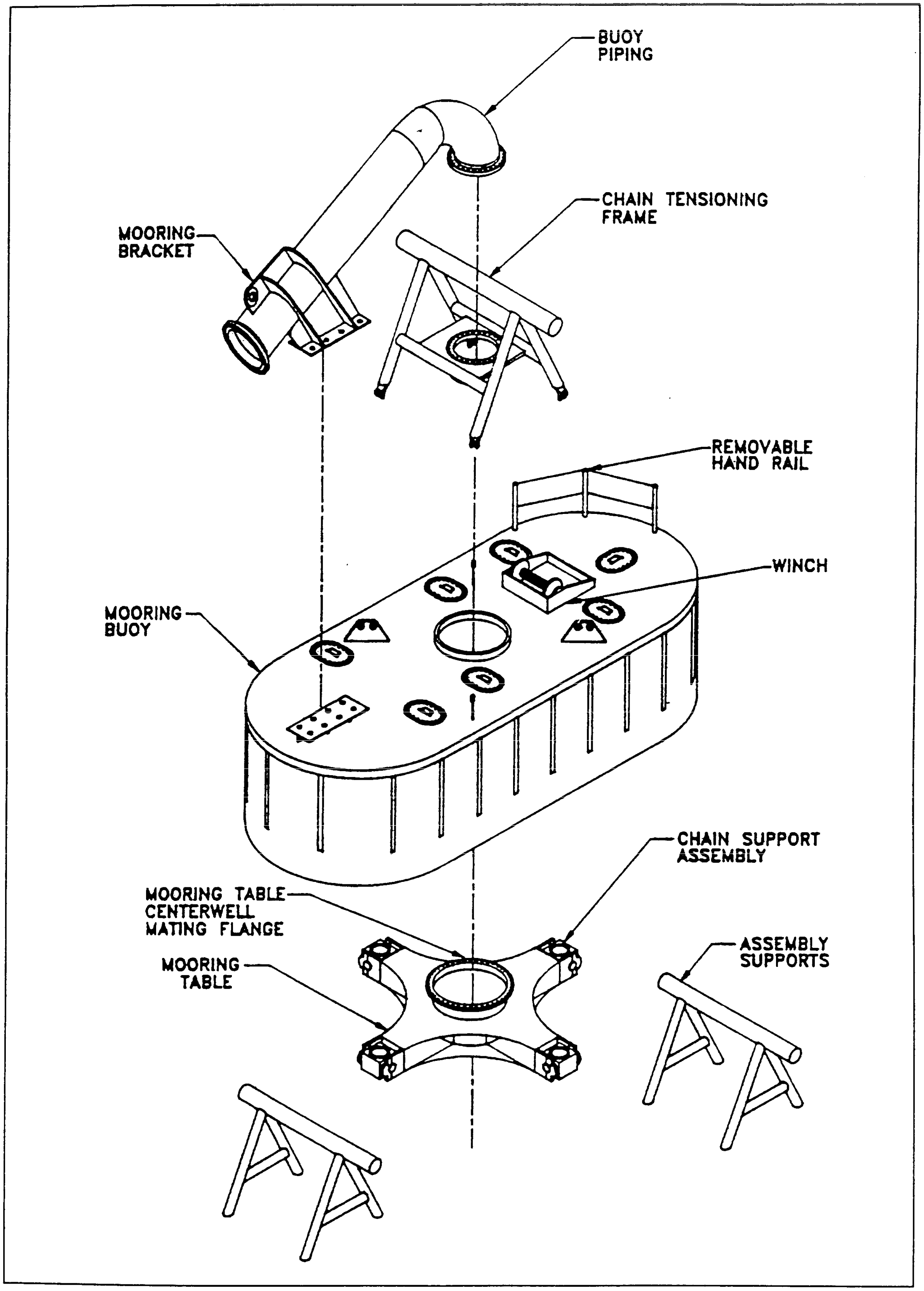

Figure 9. DPO mooring buoy assembly

the mooring anchors. The crew of the tug will tension the chains to set the anchors before buoy arrival. Chains will be laid close to the pipeline/underbuoy hose connection. Pickup buoys will be attached to each mooring leg.

As the chains are being installed, the pipeline will be assembled on the shore, floated into position, and lowered to the seafloor. Any pipeline stabilization required will be undertaken while the buoy chains are being attached. When the buoy arrives at the installation location, the chains are attached to the mooring platform and tensioned until the proper chain catenary is achieved.

The underbuoy hoses are then pulled through the guide on the mooring platform and connected to the lower end of the fluid swivel. If the floating hoses were not installed at the shore, the connection is made between the floating hoses and the buoy piping. The hawser is connected to the mooring pad eye to complete the system installation. More details pertaining to the DPO buoy system are presented in SOFEC, Inc. (1992a).

Logistical Requirements for DPO Buoy System

Information pertaining to DPO system time and resource analysis requirements for transporting the system to the site, assembly, installation, and retrieval was developed by SOFEC, Inc. (1992b).

Transportation requirements

Transportation analysis of the DPO CALM system was based on the use of over-the-road trucks. This method of transport provides the most extensive coverage of the geographical areas of the Nation. The system was not analyzed specifically for rail or barge transport on the premise that truck transport dictates a more stringent weight criterion and cube requirement.

To minimize overall system life cycle cost, it is assumed that the system will be primarily working on station or held in storage at a staging yard. The fleet of trucks required for shipping the system are required temporarily. Therefore, maximum utilization of rental trucks is envisioned. As part of the initial contract, each component will be provided with the requisite support blocking/frame to facilitate truck shipment. In addition to the system components and their support blocking/frame, the material requiring transport includes the material-handling equipment (i.e., slings, shackles, spreader bars, come-alongs, air compressors, air hose, air tools, drifts, assembly stands, etc.).

It is recommended by SOFEC, Inc. (1992b) that the DPO CALM system and support equipment be configured to ship on the type of rental truck trailer most commonly available in the freight forwarding industry and referred to as a "40 ft float." The specification description of the "40 ft float" trailer is a 40-ft-long, maximum 56-in.-high, fixed bed platform style, two-axle, kingpin trailer with a gross capacity of 40 tons and an actual usable payload capacity of approximately 25 tons.

Vehicle requirements, both number and type, for transport of the DPO CALM system are controlled by the following factors: total component weight and weight distribution per vehicle; total component cube per vehicle with specific limitations on overall height and width; and contingency planning constraints. The first two items are self-explanatory; however, contingency planning constraints will be further explained. Contingency planning constraints encompass the possibility of a vehicle breakdown or delay, space limitation at the assembly staging area, limited rental fleet availability in a particular geographic area, or overall system transport costs.

The following scenario presents an example of a contingency planning constraint. Assume for a specific deployment that the DPO CALM system was configured and shipped using the minimum transportation cost (i.e., minimum number of rental trucks) as the primary constraint. Enroute to the staging area, the truck carrying the majority of the load-handling equipment and assembly tools has mechanical problems and is delayed. At the staging area, deployment of the system is halted with the concurrent cost of an idle crew, crane, and loaded rental trucks. Per the example, it is recommended by SOFEC, Inc. (1992b) that the trucks be loaded, as much as possible, with complete subassemblies and supporting material-handling and assembly equipment.

To meet highway height restrictions, the buoy hull will require a low-boy style trailer. Low-boy trailers with sufficient length and capacity are not normally readily available in the majority of truck rental fleets. Two alternative solutions for this problem are available.

a. Alternative 1. A low-boy style trailer can be purchased as part of the contract and dedicated to the transport of the buoy hull.

b. Alternative 2. Conversely, the design of the buoy could incorporate attachment rails for a tandem-axle assembly and a fifth-wheel kingpost assembly, with the additional purchase of the tandem-axle assembly.

A cost-benefit analysis and life-cycle analysis should be conducted to indicate the optimum solution for transport of the buoy hull.

The shipping configuration, listed in the desired order of arrival at the assembly/deployment staging area and encompassing shipping segregation of CALM components into complete subsystems and requisite support equipment, is presented in Table 5.

Of the seven trucks, only Trucks 4 and 5 will require a permit for transport. Each vehicle will require a wide-load permit. All vehicles are within maximum weight limits. A typical industry procedure in shipping heavy freight on trucks is for the truck supplier to supply the tie-down chains or nylon straps, normally per the customer's preference, upon request by the customer. The

Table 5
DPO CALM Shipping Configuration

Truck	Load	Weight, kips	Height/Width, ft
1	Three underbuoy hoses (35 ft) Hose-handling frame Two leg-chain slings Three nylon slings Buoy piping assembly Four shots of anchor chain Hose hardware, air compressor Assembly tools, impact wrenches Standard tool kit, two spar buoys	45	14/8
2	Two marine anchors with pins Seven shots of anchor chain Two half shots of anchor chain One short shot of anchor chain Anchor chain connecting links Four anchor pendant buoys Assembly tools, hammers, pliers Come-alongs	46	10/8
3	Two marine anchors with pins Seven shots of anchor chain Two half-shots of anchor chain One short shot of anchor chain Anchor chain connecting links Four anchor pendant buoys Assembly tools, hammers, pliers Come-alongs	46	10/8
4	4-part heavy-lift sling assembly Towing bridle, two buoy stands Mooring table, buoy-lift frame Air compressor, assembly tools Impact wrenches, standard tool kit Buoy rigging and blocks Anchor tensioner with rigging Four half-shots of anchor chain Two short shots of anchor chain	46	10/12
5	Buoy hull	44	12/12
6	Four floating hoses (35 ft) Three shots of anchor chain Hose hardware	35	12/8
7	Three floating hoses (35 ft) Three shots of anchor chain Mooring hawser assembly Chain stopper assemblies Hose hardware	35	12/8

truck tractors, drivers, and, depending on trucking company or distance of shipment, assistant drivers, are provided by freight forwarding companies.

Assembly and marine installation

Staging area. The DPO CALM assembly and marine deployment staging area shall be located along a dock or similar structure that can support the use of heavy equipment and has a channel with a minimum depth of 12 ft for marine deployment and tow of the CALM buoy. The staging area should encompass an obstacle-free well-drained flat area capable of supporting heavy trucks. Approximate dimensions of the staging area would be not less than 250 ft by 300 ft. A 300-ft frontage on the water is desired.

Staging-area equipment. A mobile rental crane or a fixed crane with sufficient capacity and boom length is required onsite during buoy and component unloading, assembly, deployment, recovery, disassembly, and loading for transport. Minimum crane capacity during buoy assembly and launch is 60 kips at a 20-ft radius. The following cranes meet these criteria: 60-ton wheeled rough terrain crane, 50-ton hydraulic truck crane, 50-ton lattice boom crawler crane, or port stevedoring cranes over 100 tons. Crane manpower requirements are two personnel (operator and rigger/oiler).

Assembly and marine deployment. The DPO CALM assembly and marine deployment event summary are given in Table 6.

The primary constraint at the staging area is material-handling capacity. Therefore, the addition of another lesser capacity cherry-picker type crane with an additional rigging and assembly crew would accelerate offload and assembly. SOFEC, Inc. (1992b) recommends that the minimum staging-area water-access frontage be increased to 400 ft. The staging-area jobs include offloading the trucks, assembling the four major components (i.e., four anchor leg assemblies, the buoy assembly, the underbuoy hose assembly, and the floating hose assembly), and loading them for marine shipment. Primary time constraint at the marine site is the installation of the anchor legs. To benefit from a gain in time at the staging area, a second anchor-handling vessel is employed to emplace the second opposing anchor leg system in a staged schedule with the first anchor-handling vessel. Estimated time saved is 1 to 2 days.

Buoy recovery

The recovery operation is essentially the reverse of the deployment operation. More time will be required to carry out the recovery operation due to the time required to accomplish the following functions:

a. Perform maintenance on the system components, tools, and equipment.

b. Account for components, tools, etc., and replace lost items.

c. Bundle the numerous shots of anchor chain.

Table 6
DPO CALM Assembly and Marine Deployment Event Summary

Description	Resource	Time
Day 1		
Unload buoy piping, air compressor, tools, marker buoy, underbuoy hose, and hose hardware. Assemble underbuoy hose for tow.	Staging-area Crew + crane	5 hr
Tow underbuoy hose to marine site.	Tow vessel	Travel
Connect underbuoy hose to end of pipeline, mark, and drop.	Tow vessel + pipeline constructors	1 hr
Transfer two complete anchor leg assemblies with marking buoys to anchor-handling vessel and pre-position remaining anchor components at staging area site.	Crane + staging-area crew + anchor-handling vessel	6 hr
Assemble shots of anchor chain into anchor leg assemblies.	Anchor-handling vessel	2 hr
Day 2		
Transfer chain-tensioner assembly to anchor-handling vessel. Unload anchor chain to staging-area site. Set up mooring table and buoy stands for buoy assembly. Unload air compressor, tools, slings, marking buoys, towing bridle, and hardware. Erect buoy on mooring table, make up joint and launch buoy. Unload remaining anchor chain. Assemble remaining anchors. Unload seven floating hose sections and mooring hawser assembly.	Staging-area Crew + crane	10.5 hr
Anchor-handling vessel sails to marine site.	Anchor-handling vessel	Travel
Install two opposing anchor legs.	Anchor-handling vessel	6 hr
Day 3		
Load two anchor-leg assemblies onto the anchor-handling vessel and assemble the anchor legs.	Staging-area Crew + Crane + Anchor-handling vessel	4 hr
Anchor-handling vessel sails to marine site.	Anchor-handling vessel	Travel
Install two opposing anchor legs.	Anchor-handling vessel	6 hr
Complete assembly of the buoy components on the floating buoy. Test and confirm the function of the safety, navigation, and rigging equipment on the buoy.	Staging-area Crew + crane + buoy crew	4 hr

(Continued)

Table 6 (Concluded)

Description	Resource	Time
Day 4		
Tow buoy to marine site.	Tow vessel + buoy crew	Travel
Install buoy at marine site.	Tow vessel + buoy crew	8 hr
Assemble floating hose string for tow. Consolidate equipment in the staging area for inventory and storage/transport.	Staging-area Crew + crane	8 hr
Day 5		
Tow floating hose string to marine site.	Tow vessel + buoy crew	Travel
Install floating hose string. Install underbuoy hose string. Trim buoy. Adjust chain angles as required. Deploy mooring hawser. Ensure proper operation of buoy equipment. Recover and stow marker buoys and installation equipment.	Tow vessel + buoy crew	5 hr
Complete staging area clean up and equipment accountability/storage.	Staging-area Crew + crane	4 hr
Days 6 and 7		
Contingency days for equipment failure/delay, extensive travel times to the marine site, or weather delay.		

d. Remove the individual hose sections from the water.

e. Sort the system components, tools, equipment, and shipping frames/blocking into the shipping configuration.

f. Load the trucks.

Marine recovery is accomplished in the following sequence:

a. Recover the floating hose ring.

b. Release the underbuoy hose and four anchor chain legs. Tow the buoy to the dock.

c. Recover the underbuoy hose string.

d. Recover the four marine anchors and anchor chain legs.

Anticipated time for marine recovery is 5 days.

Dock/staging-area activity will include removal of the system from the water, disassembly, inventory, maintenance/replacement, packing, and preparation for shipment. Anticipated elapsed time for dock/staging-area activity is 7 to 10 days. The loading of the system onto trucks for transport is anticipated to require 4 days, assuming the use of one crane. Crew complement for the recovery operation is equivalent to the assembly and installation operation.

Emergency buoy recovery

In the event of an emergency such as extremely severe weather, the DPO CALM system can be released for expedient towing to shore for disassembly later or for reinstallation onsite at some later date. The towing bridle is recovered from the support vessel, and each leg of the dual-leg towing bracket is attached to its respective buoy-towing bracket. The support vessel utilizes the towing bridle as its primary mooring line during the remainder of the buoy-recovery operation. Total estimated elapsed time is 0.25 hr.

The buoy handrail system is deployed as desired. The winch air-supply hose is rigged from the support vessel to the onboard buoy winch. The chain-tensioning blocks are transferred to the buoy and rigged. A pelican hook is attached to the hook block. Four short choker slings and four anchor pendant buoys with shackles are transferred to the buoy. Total estimated elapsed time is 0.50 hr.

The underbuoy hose string is released from the buoy hose swivel by:

a. Removing the quick-lock pins.

b. Rotating the rotating bar socket by hammering on the hammering lug provided, causing the five locking lugs to disengage, and releasing the lower swivel assembly and underbuoy hose to drop through the buoy hull center well to the seafloor.

Total estimated elapsed time is 0.25 hr.

The mooring hawser assembly is pulled, hand over hand, onto the buoy hull deck and secured. Alternatively, the mooring hawser assembly could be released from the buoy and secured on the support vessel. Total estimated elapsed time is 0.25 hr.

The support vessel will maneuver the buoy hull into position over each individual chain-support assembly to align the chain-tensioning tackle for chain release. The support vessel captain should plan his method of maneuver to arrange to have the up-current chain leg be the last chain to be released. The first chain-support assembly is selected and the support vessel holds the buoy on station.

The chain legs will be released in turn. The sequence of events is as follows:

a. The diver locates the short sling at a chain link slightly above the chain stopper and attaches the pelican hook.

b. The buoy crew raises the anchor chain to gain access to the chain-stopper halves and removes the chain-stopper halves to the support vessel.

c. The diver threads the anchor pendant buoy up through the chain-support assembly and attaches it to the end link of the anchor chain.

d. The diver clears the area. The buoy crew deploys the anchor pendant buoy assembly clear of the buoy.

e. The buoy crew trips the pelican hook and releases the anchor chain leg.

f. The buoy hull is maneuvered into position over the next chain-support assembly, and the process is repeated until all four anchor chains are marked and released.

Total estimated elapsed time to release all four anchor chains is 1 hr.

The buoy crew secures the chain-tensioning rigging, the winch air hose, and the buoy handrails. Estimated elapsed time is 0.50 hr.

The buoy is ready for tow to shore. Total estimated elapsed time onsite is 2.75 hr. The buoy crew consists of four personnel, one of whom is the diver. The support vessel crew is as required by the vessel, but a minimum of three personnel will always be necessary.

4 Technology for Monitoring and Increasing Dredge Payloads for Fine-Grain Sediments[1]

Dredge hoppers and scows are commonly filled past the point of overflow to increase the load. Some Corps Districts routinely allow overflow to increase the load, while others do not because of actual or perceived environmental and/or economic reasons. Overflow with hopper dredges is beneficial when sand is the predominant material because the settling velocity is high enough for the sand to rapidly settle in the hopper during the short filling time. Overflowing when dredging silt and clay with conventional equipment and procedures is questionable because the sediment particle sizes are smaller and settling velocities are lower, which tend to cause the solids to stay in suspension longer and be discharged back overboard without settling in the hopper.

The cost efficiency of a hopper dredge is typically judged by its ability to move dredged sediment from the project area to the disposal area with a minimum of pumping and traveling time. The ideal hopper load for accomplishing this is referred to as the economic load. Several devices have been tested in a scale-model hopper at WES to determine the effectiveness of techniques for optimizing the payload when dredging fine materials and for obtaining the economic load. Two new devices were designed, fabricated, tested, and evaluated by the DRP for effectiveness in providing data to dredge personnel for the purpose of increasing dredge efficiency.

[1] Chapter 4 was extracted from Palermo and Randall (1990); Scott, Pankow, and Pratt (1992); and Scott et al. (1995).

Economic Loading and Overflow of Dredge Hoppers and Scows

Environmental considerations of overflow may be related to aesthetics, potential effects of water-column turbidity, potential effects of deposition of solids, or potential effects of sediment-associated contaminants. These actual or perceived environmental effects have often resulted in criticism of Corps dredging operations or restrictions on overflow. In some instances, the "no overflow" policies of some state regulatory agencies result in significant increases in project cost (Palermo and Randall 1990).

Economic load is defined as the load in a dredge hopper or scow that corresponds to the minimum unit dredging cost. Economic load is dependent on the material dredged, equipment used, distance to disposal site, and other site-specific factors. Economic load does not necessarily correspond to the maximum load or highest density load that can be obtained.

Operations involving overflow

Hopper dredging. The function of a hopper dredge is to dredge material hydraulically from the bottom of navigation channels. At the beginning of the dredging cycle, the hopper may be partially filled with residual water. Dredging is conducted with the vessel underway at a speed of 1 to 3 knots with the dragheads in contact with the bottom. Bottom sediments are entrained with the ambient water, lifted hydraulically by the dredge pumps, and discharged into the hoppers. Once the solids-water mixture (slurry) fills the hopper, the solid particles continue to settle in the hopper while the excess water passes overboard through the overflow system. When the desired load is attained, the drag arms are raised, and the dredge transports the material to the disposal site. Here, the hoppers are unloaded through bottom-opening doors or a split-hull mechanism. Upon completion of the unloading process, the doors are closed, and the dredge returns to the dredging area to repeat the operating cycle.

Clamshell and scow dredging. Scows or barges are normally used to transport material excavated with mechanical dredges. The scows usually are equipped for bottom dumping at the disposal site. The material is mechanically removed and placed in the scows, with little entrainment of water during the dredging cycle as compared with hydraulic dredging. Scows will be partially filled with residual water at the beginning of the filling cycle; therefore, the residual water is displaced as the scow is filled. If filling is continued past the point at which the scow is full, the overflow is spilled over the sides of the scow. The overflow consists of a mixture of residual water, entrained water, and solids.

Relatively little technical information is available on the loading and overflow of scows. Although several investigators have documented sediment resuspension due to clamshell operations, it is difficult to isolate the resuspension due to overflow and that due to the excavating action of the bucket.

Existing Corps guidance

Guidance in Engineer Manual 1110-2-5025 (U.S. Army Corps of Engineers (USACE) 1983) on economic loading and overflow of hopper dredges is:

> The use of (overflow) methods is controlled to varying degrees by environmental legislation and the water quality certification permits required by the various states in which dredging is being accomplished. The environmental effects of these methods must be assessed on a project-by-project basis. If the material being dredged is clean sand, the percentage of solids in the overflow will be small and economic loading may be achieved by pumping past overflow. When contaminated sediments are to be dredged and adverse environmental effects have been identified, pumping past overflow is not recommended. In such cases, other types of dredges may be more suitable for removing the contaminated sediments from the channel prism. If hopper dredges are not allowed to pump past overflow in sediments that have good settling properties, the cost of dredging increases. The settling properties of silt and clay sediments may be such that only a minimal load increase would be achieved by pumping past overflow. Economic loading (i.e., the pumping time required for maximum production of the hopper dredge) should be determined for each project. These determinations, along with environmental considerations, should be used to establish the operation procedures for the hopper dredge.

This guidance is basic in nature. However, there exists no detailed guidance on how to balance the potential economic benefits and potential environmental effects in reaching decisions related to overflow.

Economic load test for hopper dredges

Instructions for hopper-dredge operations are described by USACE (1953). Economic load tests are required at the beginning of dredging operations unless conditions in the area prevent the use of overflow procedures. These tests are used to determine the most economical operating cycle to use.

The economic load is the hopper load that is dredged and hauled in a single dredging cycle and yields the maximum rate of material removed from the project area at a minimum cost. For this test, the hopper load is measured periodically during loading using either the yardage meter or sounding and sampling techniques. The pumping, turning, and average or estimated disposal times are recorded and summed to obtain the total cycle time. The amount (cubic yards) of retained material per minute of total cycle time is computed from the load and total cycle time measurements. Next, the amount of retained material per increment of pumping is computed. The equivalence of these two values is the point of economic load. Therefore, the economic load is usually not the maximum load but depends upon a number of factors, one of which is the distance to the disposal site.

An economic load test was used in a special study to evaluate hopper-dredge overflow characteristics while dredging in the Mare Island Strait and Richmond Inner Harbor located in the San Francisco Bay area (U.S. Army Engineer District, San Francisco 1976). The purpose of the study was to determine dredge efficiency with and without overflow and to evaluate the economic load point that included the number of cubic yards and the pumping time to reach that point. Loading curves were generated for the two locations as shown in Figures 10 and 11. The Mare Island Strait curve shows that the loading curve maximum and the cost per cubic yard minimum occurred approximately 2 min after overflow began. For the Richmond Inner Harbor, overflow was required for 18 min to reach economic load. Different shoal configurations, sediments, and salinity were cited as reasons for the difference in time to reach the economic load. The minimum cost per cubic yard varied by a factor of 3 between these two sites.

Environmental effects of overflow

Concerns raised by resource agencies regarding overflow include potential adverse effects due to increased water-column turbidity/suspended solids concentrations, reductions in dissolved oxygen (DO) levels, and/or release of particle-associated contaminants. The effects of settled material on bottom-dwelling organisms have also been mentioned. However, environmental concerns with overflow are generally related to water-column effects. Aesthetic concerns about overflow have also been presented. The environmental effects of overflow are similar to those resulting from disposal of dredged material in open water or the resuspension of sediment during dredging operations.

Turbidity. The effects of turbidity/suspended solids have been studied for a variety of biological resources. In general, turbidity effects are characterized as short-term and localized. An exception is the potential for effects on sensitive resources such as oyster beds. Exposure conditions related to overflow operations would generally be less severe than for open-water dredged material disposal but may be greater than for resuspension due to dredging.

Contaminants. The potential for contaminant release in overflow has been evaluated only on a limited basis. During open-water disposal of dredged material, most contaminants normally present in the sediments remain strongly associated with particles. The finer particles in the range of particle sizes dredged would normally be associated with the overflow. Such fine particles have a greater affinity for adsorbed contaminants. In fine sediments DO

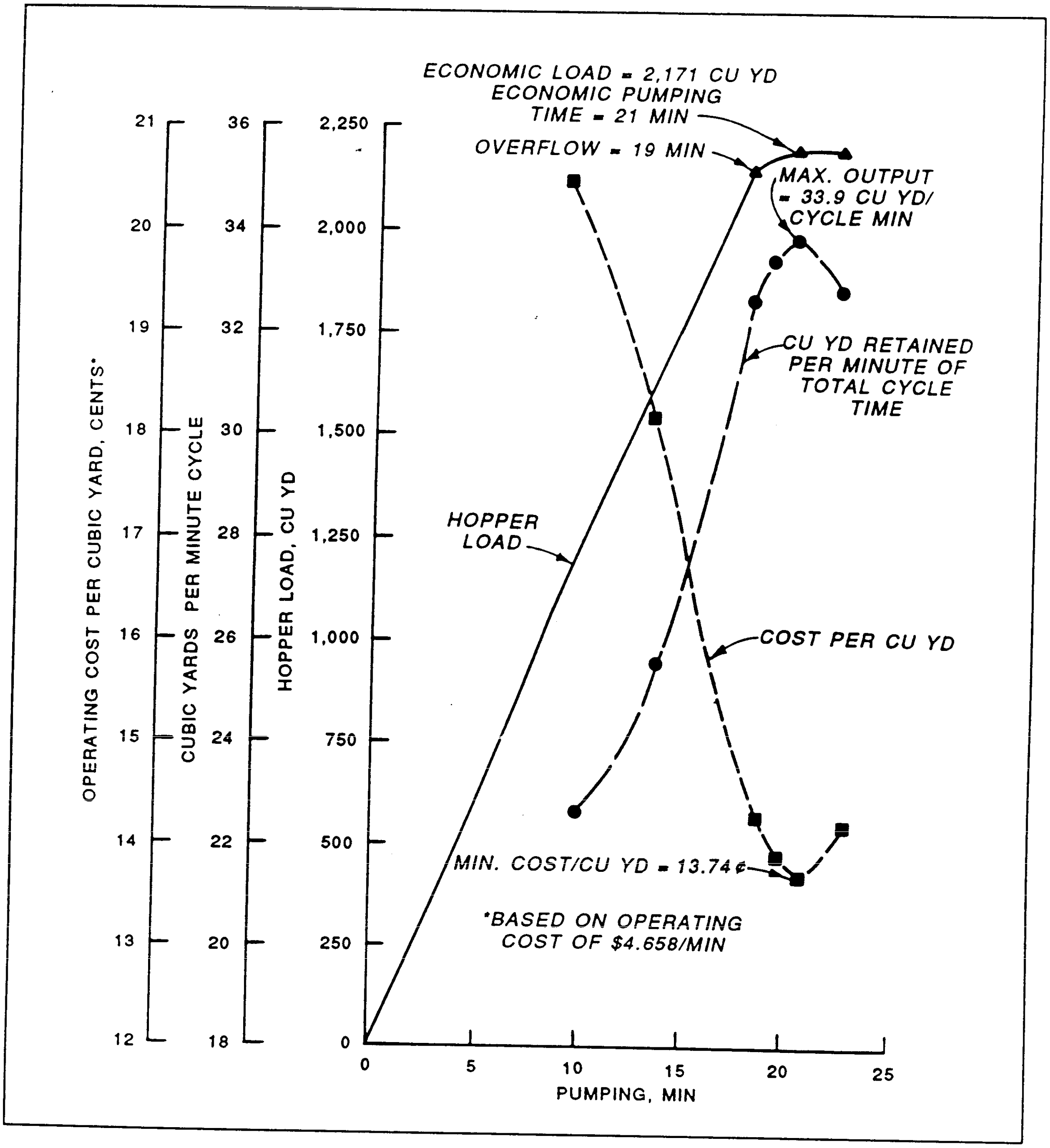

Figure 10. Economic load curve for Mare Island Strait (after USAED, San Francisco (1976))

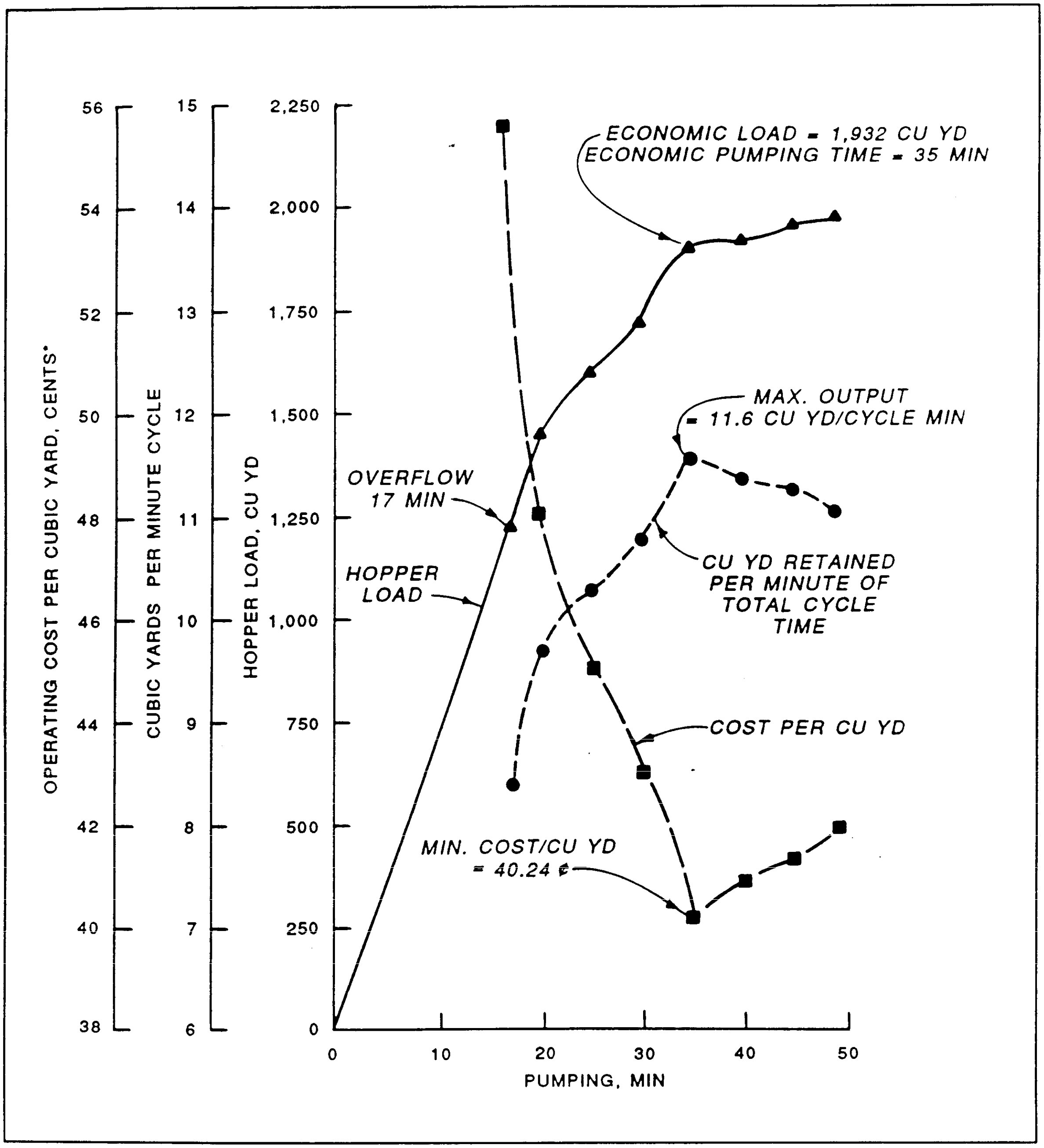

Figure 11. Economic load curve for Richmond Inner Harbor (after USAED, San Francisco (1976))

reduction may occur. However, in most cases, DO reduction is not significant, and it is a very site-specific issue.

Methods to Increase Hopper-Dredge Payloads

As an alternative to overflowing a hopper to increase bin load, the objective of an investigation by Scott, Pankow, and Pratt (1992) was to evaluate the effectiveness of selected devices and techniques for increasing the fine-grained sediment payload in dredge hoppers. Devices that attach to the end of the discharge pipe or are installed within the hopper bin were evaluated based on their effectiveness in separating the solids fraction of an inflowing slurry and the feasibility of prototype application.

Three types of devices were tested in a scale-model hopper constructed at WES. The first class of devices tested were flow diffusers that attach to the end of the discharge pipe. This device reduces the turbulence of flow into the hopper, creating an environment conducive to particle settling. The second class of devices tested, hydrocyclones and a solids separator, impart centrifugal forces to the inflowing slurry to separate the solids fraction. The third type of device tested was an inclined plate configuration in the hopper. The inclined plates create a density gradient within the slurry that increases the settling rate of solids from the suspension.

Test materials

The model-hopper tests were conducted with both silt and clay slurries. The clay was a commercial kaolinite with a mean particle size of about 2 microns. The silt material was a naturally occurring sediment that was passed through a 200-mesh sieve to remove the sands. The naturally occurring clay fraction of the silt material was essentially removed by suspending the material in water and draining off the suspended clays. Particle-size analysis was performed on the silt using standard pipette and electronic particle-sizing methods. The median particle size range was 12 to 17 microns, indicating a fine to medium silt. The characteristic settling velocity was determined to be 0.020 cm/sec at a bulk wet sediment density of both 1.045 and 1.090 gm/cu cm. These two densities were used in the tests.

Diffuser tests

The initial laboratory tests were designed to determine the influence of the method of slurry discharge into the model hopper on the retention rate of fine sediments. These tests investigated the use of diffusers connected to the slurry discharge pipe. A diffuser is a device designed to evenly distribute the feed slurry into the hopper, thus reducing the turbulence within the hopper and creating a quiescent flow environment conducive to particle settling. The tests were designed so that the hopper was allowed to overflow for a specific period of time while the total hopper load was monitored.

A variety of diffuser designs were tested with the two kaolinite clay mixtures for various inflow rates into the hopper. Kaolinite clay was used as the test medium because it represented the finest sediment size found in prototype dredge hoppers and, therefore, the most difficult to settle out of suspension. Radial, vertical, and horizontal designs of diffusers were tested.

The test results indicated very little or no economic load gain from the use of any of these devices for the two kaolinite clay mixtures tested. These diffusers offered no distinct advantage over conventional methods of placing slurry into hopper dredges; therefore, no further diffuser laboratory tests were conducted.

Hydrocyclone tests

A second class of devices for attachment to the discharge pipe was investigated. These devices were designed to concentrate the slurry solids before they are introduced into the hopper. They are commonly referred to as centrifugal separators or hydrocyclones. They operate on the principle of solid/liquid separation due to centrifugal forces imparted to the slurry. The slurry is introduced tangentially into the top portion of the conical device at a given flow rate. The conical shape of the device imparts a vortex motion to the slurry, creating significant centrifugal forces on the slurry that tend to concentrate the solid particles near the walls of the device, where they move downward and are eventually discharged at the bottom orifice as a thickened sludge. The clarified effluent is discharged as overflow through the top of the device.

Test results indicated that the hydrocyclone device was not successful in increasing the solids load in the hopper when used with a kaolinite clay suspension. Although literature suggests that hydrocyclones can efficiently separate particles within the 10- to 30-micron size range (fine to medium silts), the hardware requirements and subsequent required alterations to a working hopper dredge were not economically justifiable. Therefore, laboratory tests of the hydrocyclone centrifugal separator were not conducted with a silt slurry, and testing of the centrifugal separator was discontinued.

Inclined plate tests

Tests, developed by Scott (1990) and reported by Scott, Pankow, and Pratt (1992), investigated the effect of inclined baffle plates installed in the bin of a model hopper on the loading of fine-grained sediments.

Theory. In theory, the inclined baffle plates accelerate the separation of suspended solids from the liquid media by creating a density gradient within the slurry, which causes settling of the solids. The less dense clarified liquid is then transported along the downward-facing inclined plate to the surface of the hopper. As the clear water flows upward toward the surface, the higher density solids-laden water flows to the bottom of the hopper.

One of the earliest observations of the increased settling rate of suspensions between inclined plates was reported in 1920 when it was observed that blood in inclined test tubes settled out at a faster rate than in vertical tubes and that the settling rate increased with an increase in angle of inclination from the vertical axis. A good qualitative description of the enhanced settling of suspensions between inclined plates was given by Zahavi and Rubin (1975). They conducted tests with a clay suspension (particle density 2.71 gm/cu cm) between inclined plates. Dye was injected into the suspension between the plates, and the enhanced settling phenomenon was observed. Immediately after the well-mixed suspension was placed between the plates, a clear water layer appeared under the downward-facing plate. Dye injections showed that clarified liquid moved out of the suspension into this layer under the plate and flowed along the plate up to the surface.

Model tests. Tests were conducted with a laboratory model hopper bin using up to 24 inclined plates. The spacing between six plates was 10 cm and was 2.54 cm between 24 plates (Figure 12). Overflow tests were conducted at hopper fill rates of about 0.064 to 1.0 cm/sec. Vertical profile density samples taken during these tests indicated that at the low hopper fill rate (0.064 cm/sec), up to 15 percent of the feed solids were being retained in the hopper during overflow. At a higher, more practical range of fill rates (0.25 to 1.0 cm/sec), the density samples indicated that no feed solids were accumulated in the hopper.

Test results. Figure 13 illustrates the results of the silt slurry overflow tests. Tests were conducted at slurry densities of 1.045 and 1.090 gm/cu cm

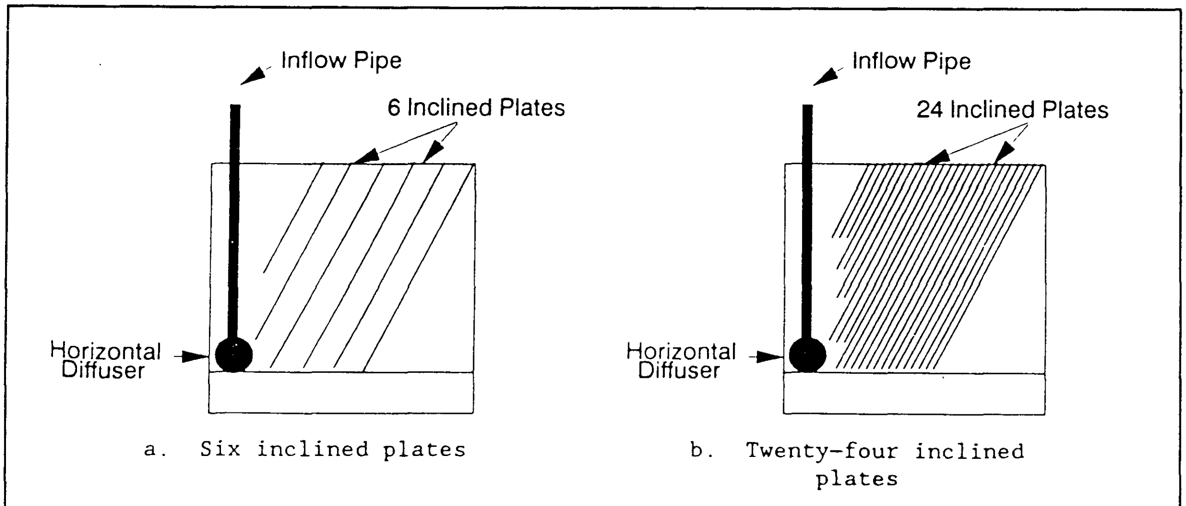

Figure 12. Side views of plate configurations in model hopper bin for increased payload inclined plate slurry tests

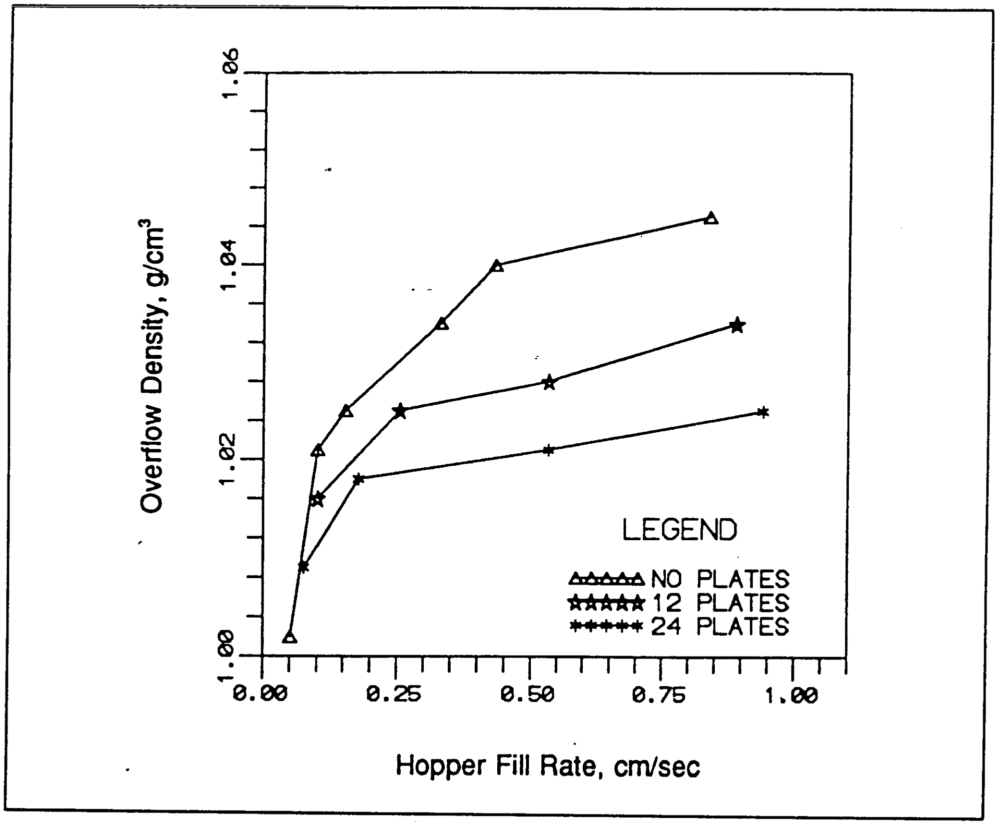

Figure 13. Overflow density increased payload inclined plate slurry tests, feed density = 1.045 gm/cu cm

to determine the effect of concentration on plate performance. Figure 13 shows the density of the overflow at equilibrium as a function of hopper fill rate for both the baseline conditions of no plates in the hopper and conditions of 12 and 24 plates in the hopper.

Figure 13 clearly shows that the plates are effective in lowering the overflow density, thus increasing the solids retained in the hopper. This figure indicates that the efficiency of the plates increases with hopper fill rates greater than 0.25 cm/sec, becoming constant at about 0.50 cm/sec. This efficiency is defined by the change in density that occurs between the curves representing conditions of no plates and 12 or 24 plates in the hopper.

It was found that, for a feed density of 1.045-gm/cu cm, the 24-plate arrangement with 2.54-cm plate spacings resulted in 50 percent more feed solids retained than for the case of no plates in the hopper. The 12-plate arrangement with 5.08-cm plate spacings resulted in about 25 percent more feed solids retained. This percentage increase was constant for hopper fill rates of about 0.50 to 1.0 cm/sec. With an increase in feed density to 1.09 gm/cu cm, the 24-plate arrangement resulted in about a 30-percent increase in feed solids retained in the hopper. This percentage increase was constant for hopper fill rates of about 0.50 to 0.80 cm/sec.

These results are based on all of the slurry passing between the full lengths of all plates in the model hopper bin. In prototype applications, a portion of the flow would not pass between plates because of space limitations in the hopper. This would result in a somewhat reduced solids-retention efficiency in the hopper.

Conclusions. The inclined plates in the model hopper occupied only a small portion of the available volume, but added substantial weight to the hopper. For a practical application, it would be necessary to fabricate the plates out of low-density plastics or composite materials such as graphite-epoxy that possess the material strength and abrasion resistance to survive in a dredge hopper environment.

By increasing the solids content of the slurry by a factor of two, the percent of feed solids retained in the hopper was reduced from 50 to 30 percent. Because of this decrease in plate efficiency with increasing concentration, the inclined plate concept with this configuration may be viable only for low-density slurries (< 1.1 gm/cu cm).

The inclined plate method demonstrated the potential for significantly increasing the payload of silt-sized material in dredge hoppers. Although the application of this technique to prototype dredge hoppers may not be practical unless a lightweight version is developed, it may hold promise for other specialty applications in which solids are to be separated from a discharge stream. In some cases, environmental regulations prohibit the discharge of solids from confined disposal sites. Weight-efficient inclined plate designs can be used to clarify a continuous discharge from these sites. Specialty barges can be designed and fabricated with inclined plate configurations for limited specialty dredging applications in which maximum solids loading is critical.

Technologies for Hopper-Dredge Production and Process Monitoring

Various methods exist for estimating hopper-dredge payloads, each with their own uncertainties. The load in the hopper can be estimated by measuring the depth of settled solids in the hopper and then manually sampling the solids to determine the load density. Since the hopper volume as a function of depth is known, the hopper load can be estimated by multiplying the measured density by the volume of material in the hopper. Not only is this method time-consuming and labor-intensive, but the accuracy is questionable because of the uncertainty of the sampling locations and procedures for determining density and the difficulty in determining the level of settled fine sediments in the hopper.

Direct measurement of the density of the dredged slurry in dredge hoppers has numerous advantages. A direct measurement system would eliminate the need for multiple sensors and the necessary hardware and software. Each additional sensor employed contributes some measurement error that ultimately contributes to the total load measurement uncertainty. Direct measurement of density in the hopper could result in reliable production data as well as a basis to describe how various types of dredged material will consolidate in the hopper. The only currently available technology capable of directly monitoring density profiles in dredge hoppers uses nuclear measurement principles. The major obstacles to using these devices in or around the dredge hopper are regulatory and safety concerns.

Objectives

The objectives of research by Scott et al. (1995) were to design, test, and implement hopper-dredge monitoring systems for accomplishing the following: (a) reliably calculate hopper-dredge production based on both average and direct methods of hopper density measurement; (b) acquire hopper-dredge process data for real-time dredge monitoring capability; (c) provide an automated system that produces production reports and graphic output with a minimum of user input, and (d) develop a method for determining the uncertainty of production calculations from data from the monitoring system.

To meet these objectives, two monitoring systems were developed: (a) a monitoring system based on the average measurement of hopper density determined from the bin measure approach for ascertaining hopper load, known as the automated load monitoring system (ALMS), and (b) a system for directly measuring slurry density in dredge hoppers based on the concept of electrical resistivity of sediments, known as the electrical resistivity method.

Automated load monitoring system

The ALMS method for determining average density in a dredge hopper is accomplished by measuring two dredge parameters: (a) the level of dredged material in the hopper, and (b) the draft of the dredge (Scott 1992b, 1994). The two instrumentation systems measure real-time hopper volume with two acoustic sensors and dredge displacement with two pressure transducers in the air bubbler lines. Hopper volume is determined by measuring the depth of the slurry in the hopper. With the dredge ullage table, which relates hopper depth to hopper volume, the depth of material in the hopper can be converted to volume. The draft of the hopper dredge is directly related to the weight of the dredge plus loaded water and sediment. The draft can be related to vessel displacement with a draft/displacement table typically available from the shipyard. The total weight of material in the hopper is equal to the weight of bin water in the hopper before the load is taken plus the slurry load added. This total weight divided by the volume that the material occupies in the hopper is the average density of the material in the hopper.

ALMS operation. A flowchart depicting the steps in an ALMS operation can be considered as having six distinct milestone points. At Point 1, the dredge has completed a dump, closed the doors, and is returning to the project site. During this time, the computer is checking two conditions every 2 sec. If the door is closed and the density is less than 1.05 gm/cu cm, the computer continues to loop through the checking process. When the slurry density is greater than 1.05 gm/cu cm, the computer initializes a load-start condition at Point 2, recording measurements of bin water volume and initial dredge displacement. From this time forward, the computer checks the condition of the doors (opened or closed) every 2 sec (between Points 2 and 3). When the dredge arrives at the disposal site and opens the doors (Point 3), the computer initializes a load-ending condition (Point 4), recording the final hopper volume and final dredge displacement. At Point 5, the production calculations are performed. At Point 6, a production report is generated, stored in a data file, and printed. When the doors close after the dump, the loop at Point 1 begins again. ALMS updates the computer screen every 2 sec with data output from each sensor.

Testing and evaluation. The ALMS was successfully tested during the week of August 1993 onboard the Corps' hopper dredge *Wheeler* at Matagorda Bay, TX, east of Corpus Christi (reported by Scott (1994)). Seven hopper loads were recorded during the testing and evaluation period. Figure 14 is a display of the hopper volume and dredge displacement for a typical load.

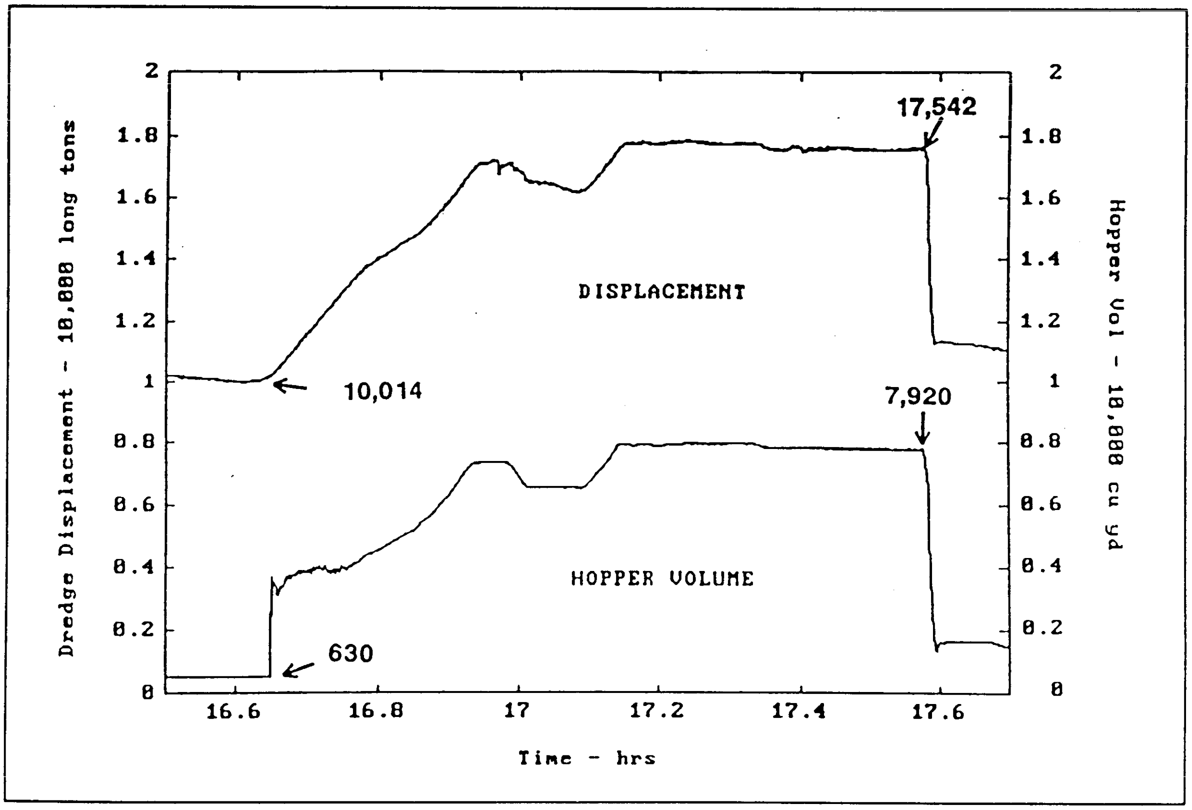

Figure 14. Hopper volume and dredge displacement during ALMS test to determine average density in hopper bin

The load starts when the density in the pipe begins to increase above 1.05 gm/cu cm and ends when the hopper-door relay is tripped. The accuracy of the system was determined by performing water tests with seawater of known density.

Summary. ALMS uses four instrumented systems to provide data on initial and final dredge-load conditions and produces a real-time production report as each load is completed, based on average density in the hopper bin. This system represents a significant advancement in hopper-load monitoring technology. It produces an accurate, repeatable measurement of bin water volume for each load, reducing the need for manual measurement or pumping out the hopper to a designated volume. The system produces immediate feedback to the dredge operator on dredge production, with screen updates to allow a visual indicator of real-time hopper volumes and dredge displacement. The computer stores all the raw sensor data for later analysis and verification, if needed. Data from the production report eliminate the need for time-consuming manual calculation of production. Accuracy of the instrumentation can be verified through the water-test process.

Electrical resistivity method

Electrical resistivity techniques are commonly used in geophysical explorations. Basically, geophysical electrical resistivity studies involve the measurement of potentials, currents, or electromagnetic fields that are introduced into the earth. Properties of subsurface materials can be determined by the variation in these measurements due to change in the electrical conductivity through the materials. The electrical resistivity of most soil mineral constituents is so high that most electrical current flow through a soil mass will be through the soil pore water. For this reason, the bulk resistivity of a soil sample will depend mainly on the amount and resistivity of the water contained in the sample, although clay exhibits some surface conduction effects and often displays a bulk resistivity different than other minerals.

Density measurements using the resistivity principle involve introducing a current source through electrodes into a medium and measuring the potential across electrodes within the vicinity of current flow. Resistivity is defined as a function of input current, measured potential, and electrode configuration. For the resistivity probe developed by Scott (1992a), an array consisting of evenly spaced electrodes placed in a line are used. Four of the electrodes are utilized at any one time. Current is introduced into the two outer electrodes of the four being used at that time, and the potential is measured between the two inner electrodes.

Laboratory resistivity studies. To evaluate the application of the resistivity principle for use with dredged materials, a laboratory-scale resistivity test cell was constructed. This probe consisted of 24 electrodes spaced 1 in. apart, imbedded in polycarbonate plastic. The electrodes consisted of stainless steel screw heads. Each electrode was wired to a connecting cable interfaced with a switch box that was used to select the current input and voltage measurement electrodes.

The purpose of the laboratory tests was to determine whether the vertical density profile of suspended and settled sediments could be accurately determined using electrical resistivity measurements. To support the laboratory resistivity probe tests, a calibration probe and related instrumentation were also developed.

Calibration tests with a variety of sediment types (sand, silt, and clay) in homogeneous and mixed sediment suspensions resulted in a series of empirically based calibration curves describing sediment density as a function of formation factor. The formation factor (Scott 1992a) is defined by the bulk resistivity measurement divided by the resistivity of the water in the slurry. The formation factor normalizes the resistivity-density relationship to any environmental water resistivities encountered (fresh or saline water). The laboratory probe was filled with various sediment mixtures, and density profiles were measured using the appropriate calibration curves.

Density profiles were obtained after several intervals of time to show the consolidation of the sediments as settling occurred. Just after mixing, the sediments remained suspended. With time, the fines remained in suspension and the coarse sand settled to the bottom. Analysis of data resulting from the laboratory study indicated that the resistivity method produced accurate repeatable density profiles and that a full-scale resistivity probe should be developed based on these findings.

Prototype resistivity probe. Based on design parameters determined from the laboratory studies, a prototype resistivity probe was designed and constructed. The probe was designed for installation in the hopper of the dredge *Wheeler* operated by the U.S. Army Engineer District, New Orleans. The probe was designed to profile the entire depth of the hopper, requiring a 40-ft probe length. Forty electrodes spaced at 1-ft intervals were required. The electrodes consisted of stainless steel hose clamps. The probe body was constructed of 10 individual 4-ft segments of 0.75-in.-diam plastic pipe. All electrodes were hard wired, with the wire bundle sealed inside the pipe segments. The individual electrode connections were attached to a switch box for manual operation of the probe. The probe was mounted on one side of a 42-ft-long epoxy-filled fiberglass mounting beam. The noncorrosive structural beam has strength properties of steel with less than half the weight of steel.

Prototype probe testing and results. The electrical resistivity probe was installed in the hopper of the dredge *Wheeler* during shipyard maintenance (Figure 15). The probe was mounted on steel mounting brackets attached to structural members in the hopper. The cable was run to accompanying instrumentation located in a remote area away from the hopper.

Field tests of the prototype probe were conducted when the dredge was operating at the mouth of the Mississippi River in the Head of Passes area.

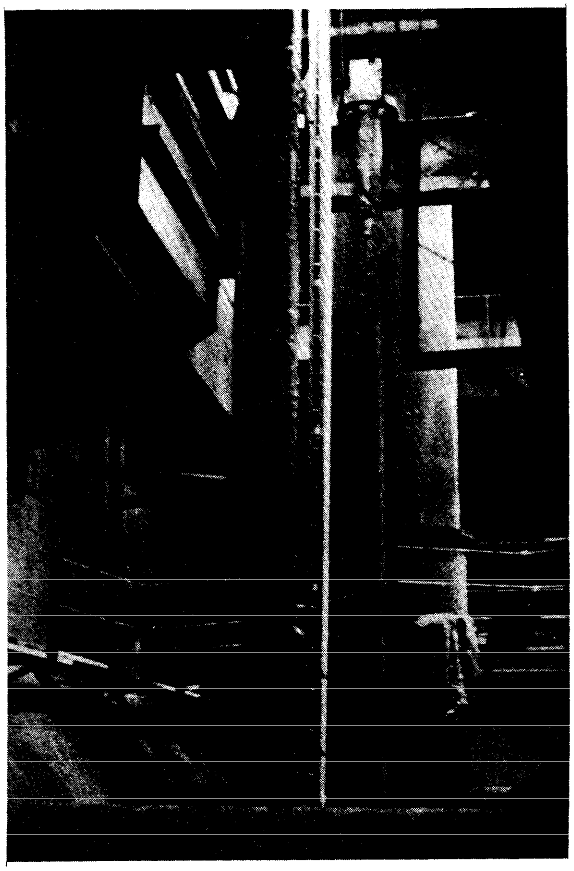

Figure 15. Electrical resistivity probe installed on hopper dredge *Wheeler*

Analysis of sediment samples taken at this location indicate a composition of approximately 59 percent coarse materials by weight (> 63 microns) and 41 percent of fine materials by weight (< 63 microns).

Density profiles in the *Wheeler* hopper measured with the electrical resistivity probe are depicted in Figure 16. Each curve on the graph represents a point in time during the dredging cycle, from the point of overflowing the weirs to arrival at the disposal site. The vertical axis represents the depth in the hopper, with 42 ft being the top of the overflow weirs. The lower end of the probe was attached at the bottom of the hopper approximately 8 ft above the hopper doors. The graph indicates that the material consolidated as a function of time in the hopper, even though a relatively high concentration of silt-size material was present. Average density in the hopper as measured by the electrical resistivity probe was within 5 percent of that measured by the nuclear density gauge on the production meter.

Summary. The use of the electrical resistivity method for monitoring the density profile in the hopper provides the dredge operator with a graphical record of dredged-material density characteristics in the hopper during all phases of the dredging cycle. During overflow operations, the density profile can be monitored in the hopper at any time with the system. This would inform the operator of the level of the material in the hopper, density of the overflow, and the rate of consolidation of solids in the hopper during overflow. For hopper dredges with adjustable weirs, the system could be used to inform the operator of the depth to which the weirs could be lowered, based on the stratification of density in the hopper, for increasing the solids load in the hopper (Scott 1992a, Scott et al. 1995).

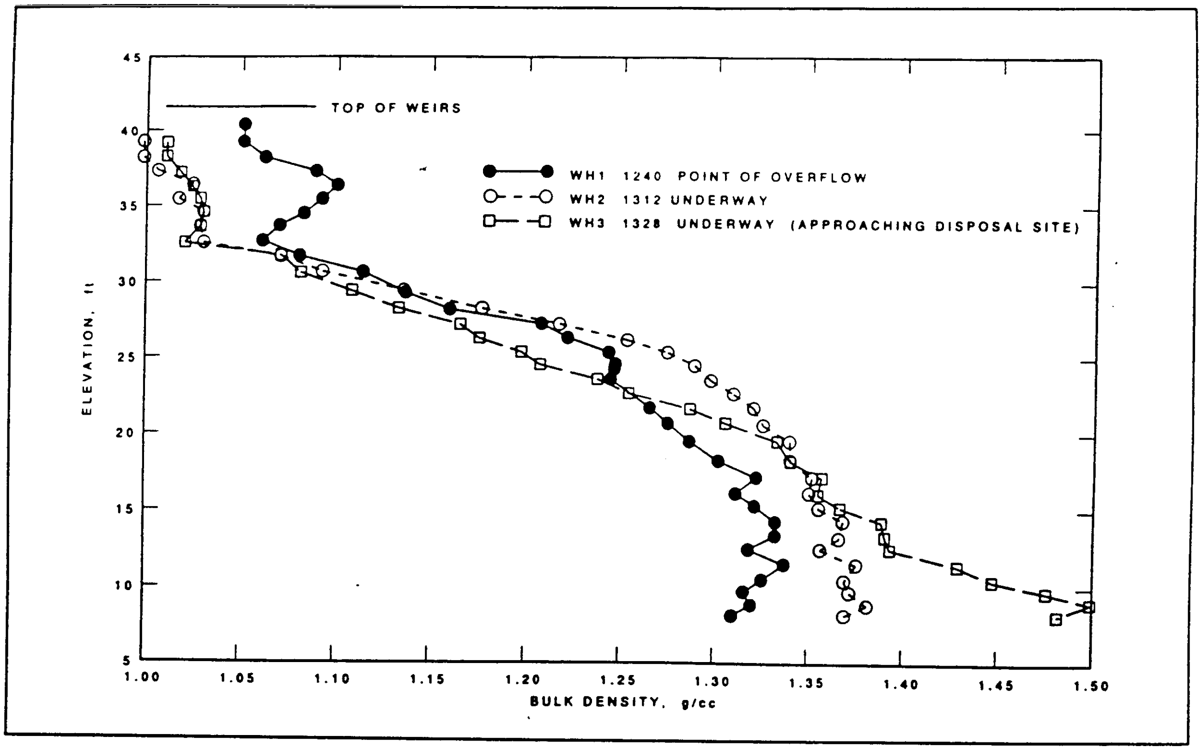

Figure 16. Electrical resistivity probe density profiles for a hopper load on the dredge *Wheeler*

5 Improved Draghead Design[1]

Dragheads used on Corps of Engineers hopper dredges were developed by empirical designs in the 1930s without benefit of modern technology. These dragheads have been modified throughout the years with a "whatever-works" approach. As navigation channels are being deepened and maintained throughout the United States, more demands are being placed on the entire dredge plant to increase its production in all types of bed material. Compacted fine sands require special techniques and equipment. Dragheads presently used on Corps dredges do not maintain an optimum production in varying bed material types at various depths. The objectives of research by Brogdon, Banks, and Ashley (1994) and Banks and Alexander (in preparation) were to develop more effective draghead designs for use in navigation channels consisting of compacted fine sands. Two different evaluations were conducted: (a) water jets with blades as a draghead enhancement device, and (b) a draghead fitted with uniform slots to enhance hydraulic efficiency to induce more material entrainment into the draghead.

Water Jets and Blades to Enhance Draghead Production

Laboratory tests to evaluate the effectiveness of water jets and blades to increase hopper dredge production were conducted at WES in a flume 60 ft long, 10 ft wide, and 4 ft deep, with one section of a prototype-size model of the California-style draghead used on the hopper dredge *Wheeler*.

Bed material

Bed material used for the flume tests was obtained from a dredged material disposal site on the Red River near Marksville, LA. The gradation of the

[1] Chapter 5 was extracted from Banks and Alexander (in preparation) and Brogdon, Banks, and Ashley (1994).

material matches very closely the general characteristics from a typical dredging area such as Aransas Pass, TX. The D_{50} size of the test material was 0.075 mm (fine sand).

Model draghead

The full-scale sectional model of a prototype draghead was used to alleviate similitude problems associated with scaling, especially those concerned with blade/bed material interactions and scaling of bed material particles. The sectional model of the draghead was 30 in. wide and 29 in. long, with one slot.

Test bed preparation

The bed material was placed in the flume to a depth of 1.0 ft. Preparation of the bed prior to testing involved several steps:

a. The material was covered with a thin layer of water, and a concrete vibrator was pulled through the sand bed to remove trapped air and to compact the material.

b. A concrete-smoothing device was used to smooth and increase compaction of the bed.

c. Final grade was achieved with a specially designed leveling grader.

Following final grading of the bed, cone penetrometer readings were taken at several locations in the bed test section to ensure compaction approximated prototype materials commonly found in Aransas Pass. All tests were conducted with the model draghead traveling at a speed of 1.0 mph, which corresponds to a slowly operating hopper dredge (Figure 17).

Test results

All tests were conducted at constant speed, and the results are presented by Brogdon, Banks, and Ashley (1994) in terms of volume of material removed from the test section during passage of the draghead. Test results show that water jets with no blades (knives) can significantly increase dredging production when the dredge is operating at slow speeds. The addition of knives placed in front of water jets operating at different pressures further increases the efficiency of the dredging process, as shown in Table 7.

It is anticipated that blades would tend to increase production at high travel speeds, since blades are sediment-displacement devices. Water jet erosion benefits would tend to increase as travel speed decreases, since the jetting forces would have a longer time to attack individual particles.

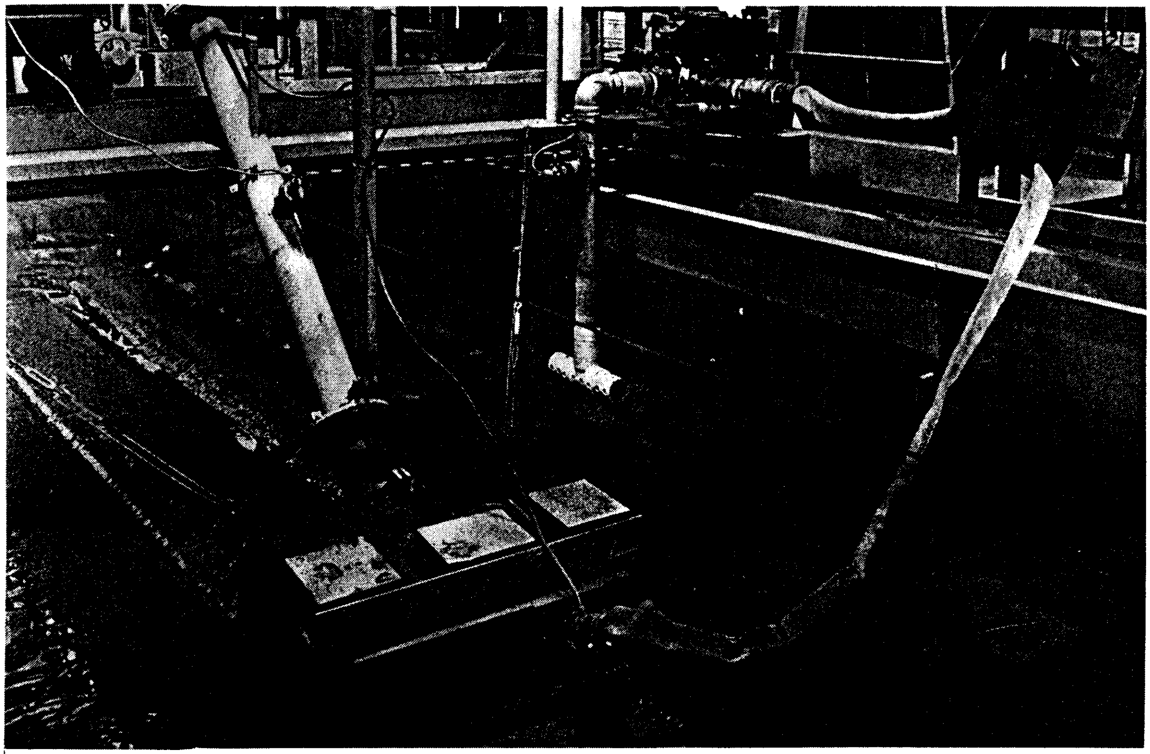

Figure 17. Test facility for evaluating effects of water jets and blades to enhance draghead production

Table 7
Model Tests of Water Jets and Blades to Enhance Draghead Production

Test No.	Water Jet Size, In., ID	Operating Pressure, psi	Volume Removed, cu ft	
			Without knife	With knife
B2A/B2B	No jet	0	1.0	1.6
B2C/B3C	0.75	40	1.8	2.3
B2D/B3D	0.75	70	3.4	2.4
B2E/B5A	1.00	20	1.4	2.1
B2F/B5C	1.00	40	1.6	2.5

A combination of tests were conducted with 0.75- and 1.0-in.-diam water jets. It was determined that the 1.0-in.-diam water jet at a pressure of 20 psi requires less than one-third the power required for the 0.75-in.-diam water jet operating at a pressure of 70 psi. Even though larger volumes are removed by the 70-psi pressure with the 0.75-in.-diam water jet than the 1.0-in.-diam water jet operating at 20 psi, the larger jet operating at the lower pressure is a more energy-efficient design. These two test conditions used approximately the same flow rates.

From a prototype viewpoint, replaceable jet nozzle blocks that can be machined to either 0.75-in. or 1.0-in. sizes would be the ideal configuration. Prototype pump configurations should be sized based on the number and sizes of jet used and be capable of providing a minimum of 20 psi at the jet outlet. This should provide adequate power for most compacted sediments. Considering that a prototype dredge cannot always reduce dredging speed in compacted sediments, blades should provide a readily installed compromise design for fast or slow dredging speeds.

Uniform Slots to Enhance Draghead Production

The objective of the research by Banks and Alexander (in preparation) was to determine the feasibility of using a uniform placement of inflow slots around the perimeter of a uniquely shaped draghead to enhance production capabilities. Experimental tests were conducted in the same laboratory facilities at WES where the water jets and blades had previously been evaluated. Side and bottom views of this uniform-slot model draghead are shown in Figures 18 and 19, respectively.

Test program

The evaluation of the effectiveness of the inflow slots was determined by comparison of the production provided by an unmodified scaled model of a California-style draghead, with the same style draghead enhanced by the addition of uniform slots (uniform-slot draghead) to provide better hydraulic entrance conditions and reduced energy head loss at the draghead. The draghead models were both 1-to-6 model-to-prototype size, and all tests were conducted with a clear-water pumping rate of 760 gpm. Comparison data for ascertaining which of the two model dragheads performed best consisted of determining the volume of bed material removed by the two different dragheads under identical test conditions in the laboratory facility. The volume of bed material removed by each of the dragheads tested was calculated from cross-section profiles surveyed after each test was completed.

Test results

Average results were obtained for 10 identical test runs each (average of 30 cross-section profiles) for the California-style draghead in the horizontal position (CALF), the California-style draghead in the 15-deg down position (CALD), the uniform-slot draghead in the horizontal position (USDF), and the uniform-slot draghead in the 15-deg down position (USDD).

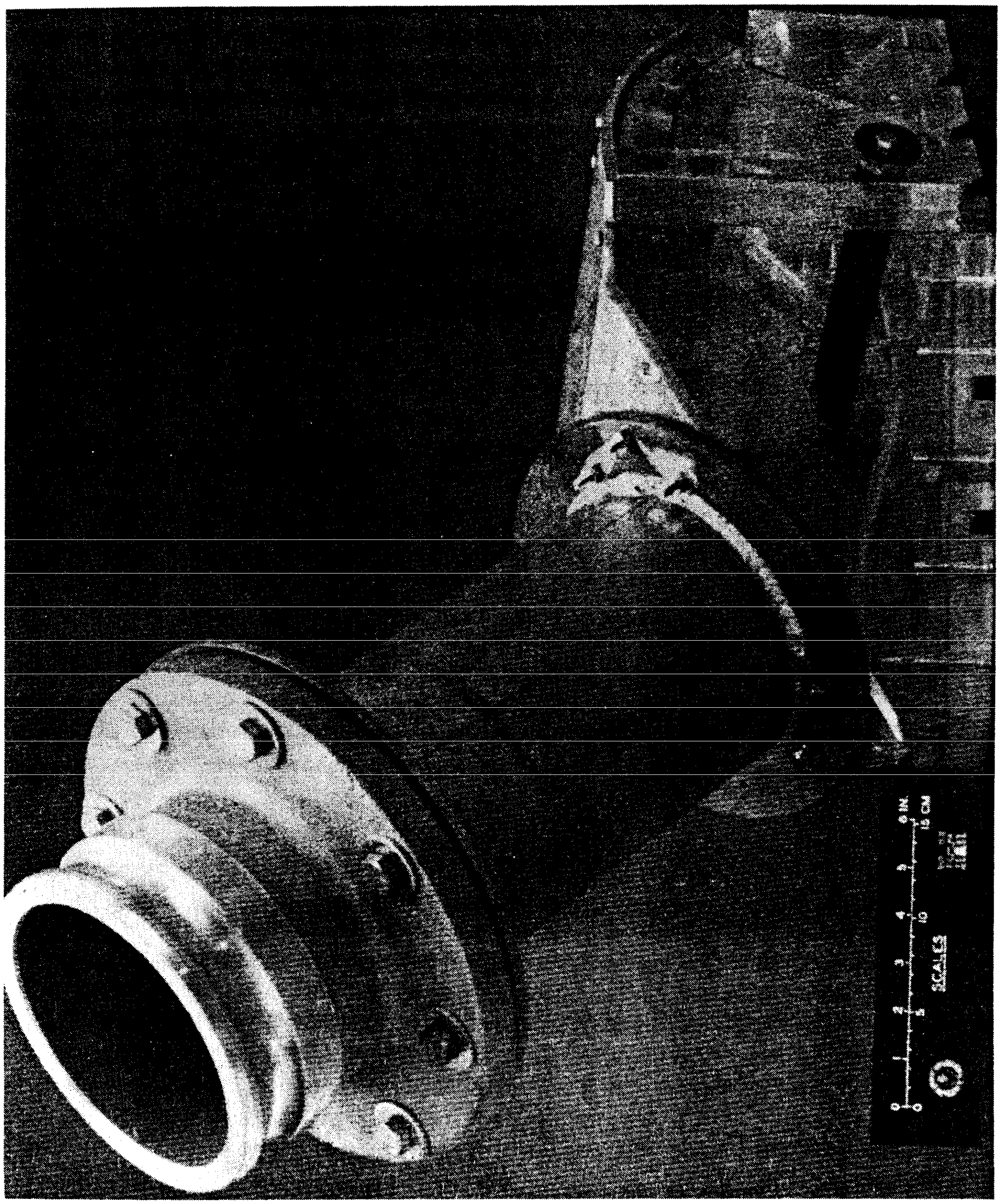

Figure 18. Side view of uniform-slot draghead model

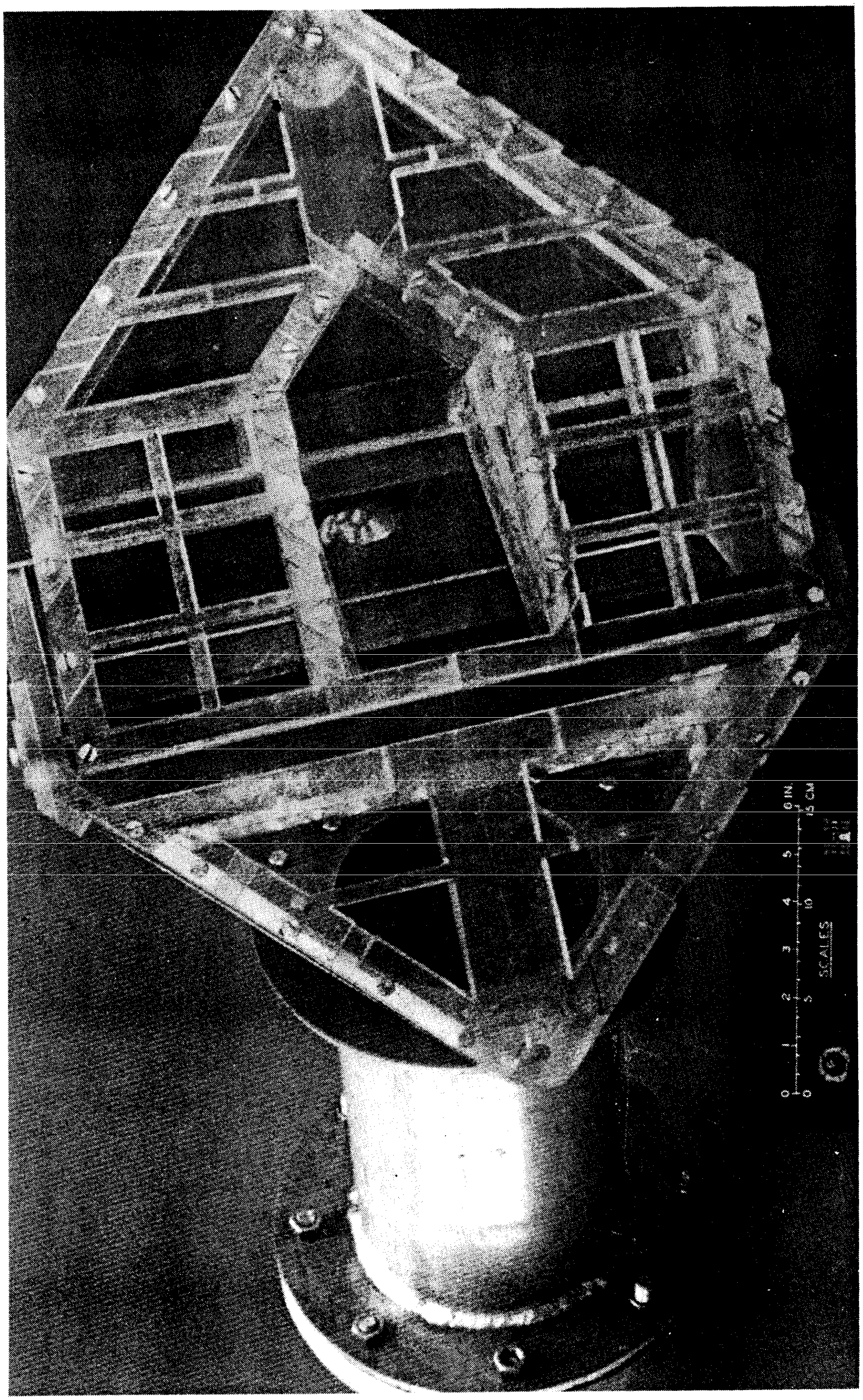

Figure 19. Bottom view of uniform-slot draghead model

California-style draghead. The CALF draghead tests removed an average 1.897 cu ft of bed material from the 10-ft test section. The average maximum depth of influence was 0.143 ft. The CALD draghead tests showed that an average of 2.923 cu ft of bed material was removed from the test section. The average maximum depth of influence was 0.214 ft.

Uniform-slot draghead. The USDF draghead tests removed an average of 2.144 cu ft of bed material from the test section and had an average maximum depth of influence of 0.136 ft. This draghead condition resulted in about 13 percent more bed material being removed when compared to the base CALF test results. The USDD draghead tests removed an average of 2.525 cu ft of bed material, about a 33-percent improvement over the base CALF. The maximum depth of influence was 0.163 ft.

6 Synopsis

The research described in this report pertained to the improvement of debris resistance of eductors (jet pumps) for sand bypassing and evaluation of the concept of water-injection dredging, the conceptual design of a single-point mooring DPO facility for Corps hopper dredges, improved technologies for hopper-dredge production and process monitoring, and design modifications to hopper-dredge dragheads to increase production.

Improved Eductors for Sand Bypassing

One goal of the research program was to design an eductor that would maintain good performance in various types of debris. Submersible pumps appeared to offer several positive features that made them potentially attractive as eductor alternatives in special locations. Fluidizers are buried perforated pipes through which water is pumped and released from orifices, causing the overlying sand to liquify and flow toward the eductors.

Eductors and submersible pumps

Eductors are hydraulic pumps with no moving parts. They operate by using a supply (motive) water pump to provide high pressure flow at the eductor nozzle. As the jet contracts the surrounding fluid, momentum is exchanged in the mixer as the jet slows while it accelerates the surrounding fluid, entraining additional fluid into the jet. As the surrounding fluid is entrained by the jet, it pulls in additional fluid from outside the eductor.

Submersible centrifugal pumps are typically single-stage vertical pumps with discharge diameters that range from 4 to 12 in. Submersible pumps differ from conventional dredges in that the submersible pump is placed directly in the material to be removed. Obviously, the smaller and lighter the submersible pump, the greater the number of deployment options. Submersible pumps (depending on the deployment method) can be easily maneuvered into areas of limited access. A primary advantage of submersible pumps over eductors is that they do not require a clean-water source.

Field tests of eductors and submersible pumps

The objective of these controlled field tests was to determine the comparative production rate of the DRP eductor, the IRI eductor, and two commercially available submersible pumps (H&H Pump Company, Model PF50x8, and Toyo, Inc., Model DP-150B) under conditions similar to those in a coastal environment. Tests were conducted in clean sand and in a series of different debris combinations similar to those expected on open-ocean coasts.

In clean sand, performance of the DRP eductor and the IRI eductor was about the same. Performance in debris was a function of the type of debris. The grate and fluidizers on the DRP eductor allowed better production in stone and garbage bags/swim fin debris than the IRI eductor; however, the DRP eductor grate was more prone to clogging with wood than the IRI eductor. The H&H pump as tested was not well-suited to the types of debris tested. It was very susceptible to both rocks and wood. The Toyo pump performed the best overall and was only bettered by the IRI eductor when pumping in wood debris.

Field tests comparing production of the DRP eductor and the IRI eductor also were conducted at the existing IRI eductor location at Indian River Inlet, DE, sand-bypassing plant. The DRP eductor performed slightly better than the IRI eductor by about 11 percent without considering other factors.

Fluidizers

Fluidization is a process in which fluid is injected into a granular medium (typically sand), causing the grains to lift and separate. The design objective for a fluidization system is primarily to create a trench of a given cross section and length. The detailed procedure for designing a fluidizer system has been given by Weisman, Lennon, and Clausner (in preparation), including a family of design curves for choosing the appropriate flow rate based on the relative depth of burial of the pipe with respect to pipe diameter and on the relative particle size with respect to trench dimensions.

Water-Injection Dredging

WID is a concept new to the United States where shoal sediment is fluidized, causing it to flow by density or riverine currents to deeper areas where it does not affect navigation. WID is based on a simple concept: vessel-mounted pumps inject water directly into the sediment voids through low-pressure jets mounted on a long horizontal pipe. This fluidizes the sediment, creating a gravity-driven density current that can flow down very mild slopes. The density current transports shoal material to deeper water where it can settle without impeding navigation or will be carried farther away by stronger natural currents.

The DRP's mission of investigating new dredging technologies led successfully to the first prototype field demonstration of WID in the United States. Application in sand greater than 0.2-mm diam will be very site-specific, requiring nearby deeper water and a smooth downslope gradient. The lack of pipelines and swing wires greatly increases mobility of a WID vessel and reduces disruption of normal navigation traffic to a minimum. Routine use of WID in areas where in-water disposal is not normally practiced will require additional considerations.

Dredging Equipment for Nearshore/Onshore Placement

The Corps desired the capability for DPO of hopper dredges in open water to be able to respond to national emergencies (such as hurricanes) where the ability to quickly place sand on the beach is needed. Significant amounts of material dredged by the Corps could also be used beneficially if easier and less expensive means were available to deliver the dredged material to a site where it could be used.

DPO is a method of removing dredged material from hopper dredges, where the dredge moors to an anchored floating structure, buoy, or multiple buoy berths. An underwater pipeline extends from the DPO buoy to shore. Hoses are connected from the DPO buoy to the hopper-dredge discharge manifold. The dredge mixes the dredged material with water to form a slurry and pumps the slurry from its discharge manifold through the hoses to the anchored floating DPO buoy and on through the underwater pipeline toward shore (Clausner 1992a).

Design criteria

Design loads and system analysis were based on the displacement and draft of the largest of the Corps hopper dredges, the *Wheeler*. The maximum design mooring load was determined to be 100 kips. The system was designed for operation in a water depth of 30 to 45 ft; however, operation is possible in water depths up to 75 ft with a slight reduction in capabilities.

The CALM system was selected because of the ability to transport the components in truck-size packages and reassemble quickly. Also, it proved to be the least costly of alternatives to fabricate. The system is anchored by four anchor chains that are arranged 90 deg apart.

DPO buoy system

The DPO buoy is a capsule-shaped buoy that is 28 ft long by 11 ft 6 in. wide by 7 ft 6 in. deep. Although not the conventional shape of a mooring buoy, the shape was chosen to facilitate towing the buoy and placement on flatbed trucks. The buoy can be disassembled into four components: buoy hull, fluid piping, fluid swivel, and mooring table. The buoy hull serves as the foundation for the fluid piping.

The CALM system can be transported by truck, rail, or barge to the assembly location. Components of the system can be consolidated and transported on standard flatbed tractor-trailer rigs. The entire system can be transported by as few as seven trucks. For ocean transport, the entire system also can be arranged on a standard 60- by 120-ft cargo barge.

Technology for Monitoring and Increasing Dredge Payloads for Fine-Grain Sediments

Dredge hoppers and scows are commonly filled past the point of overflow to increase the load. Some Corps Districts routinely allow overflow to increase the load, while others do not because of actual or perceived environmental and/or economic reasons.

Economic loading and overflow of dredge hoppers and scows

Economic load is defined as the load in a dredge hopper or scow that corresponds to the minimum unit dredging cost. Economic load is dependent on the material dredged, equipment used, distance to disposal site, and other site-specific factors. Economic load does not necessarily correspond to the maximum load or highest density load that can be obtained. The economic load is usually not the maximum load but depends upon a number of factors, one of which is the distance to the disposal site.

Methods to increase hopper-dredge payloads

As an alternative to overflowing a hopper to increase bin load, the objective of an investigation by Scott, Pankow, and Pratt (1992) was to evaluate the effectiveness of selected devices and techniques for increasing the fine-grained sediment payload in dredge hoppers.

Diffuser tests. A variety of diffuser designs were tested with the two kaolinite clay mixtures for various inflow rates into the hopper. Kaolinite clay was used as the test medium because it represented the finest sediment size found in prototype dredge hoppers and, therefore, the most difficult to settle out of suspension. Test results indicated very little or no economic load gain from the use of these devices for the two kaolinite clay mixtures tested.

Hydrocyclone tests. These devices were designed to concentrate the slurry solids before they are introduced into the hopper. Test results indicated that the hydrocyclone device was not successful in increasing the solids load in the hopper when used with a kaolinite clay suspension. Hardware requirements and subsequent required alterations to a working hopper dredge were not economically justifiable.

Inclined plate tests. Tests were reported by Scott, Pankow, and Pratt (1992) that investigated the effect of inclined baffle plates in a model hopper bin on the loading of fine-grained sediments. The inclined plates in the model hopper occupied only a small portion of the available volume, but added substantial weight to the hopper. For a practical application, it would be necessary to fabricate the plates out of low-density plastics or composite materials such as graphite-epoxy that possess the material strength and abrasion resistance to survive in a dredge-hopper environment.

Technologies for Hopper-Dredge Production and Process Monitoring

Objectives of the research by Scott et al. (1995) were to design, test, and implement hopper dredge monitoring systems to reliably calculate hopper dredge production based on both the average and direct methods of hopper density measurements. To meet these objectives, two monitoring systems were developed: (a) a monitoring system based on the average measurement of hopper density determined from the bin measure approach, and (b) a system for directly measuring slurry density in dredge hoppers based on the concept of electrical resistivity of sediments.

Automated load monitoring system

The ALMS method for determining average density in a dredge hopper is accomplished by measuring two dredge parameters: (a) the level of dredged material in the hopper, and (b) the draft of the dredge (Scott 1992b, 1994). The two instrumentation systems measure real-time hopper volume with two acoustic sensors and dredge displacement with two pressure transducers in the air bubbler lines. With the dredge ullage table, which relates hopper depth to hopper volume, the depth of material in the hopper can be converted to volume. The draft can be related to vessel displacement with a draft/displacement table typically available from the shipyard. The total weight of material in the hopper is equal to the weight of bin water in the hopper before the load is taken plus the slurry load added. This total weight divided by the volume that the material occupies in the hopper is the average density of the material in the hopper.

Electrical resistivity method

Density measurements using the resistivity principle involve introducing a current source through electrodes into a medium and measuring the potential across electrodes within the vicinity of current flow. Resistivity is defined as a function of input current, measured potential, and electrode configuration. For the resistivity probe developed by Scott (1992a), an array consisting of evenly spaced electrodes placed in a line is used. Four of the electrodes are utilized at any one time. Current is introduced into the two outer electrodes of the four being used at that time, and the potential is measured between the two inner electrodes. The electrical resistivity probe was installed and successfully demonstrated for field use onboard the hopper dredge *Wheeler*.

Improved Draghead Design

Dragheads presently used on hopper dredges do not maintain an optimum production in varying bed material types at various depths. The objectives of research by Brogdon, Banks, and Ashley (1994) were to develop more effective draghead designs for use in navigation channels consisting of compacted fine sands. Two different evaluations were conducted: (a) water jets with blades as a draghead enhancement device, and (b) a draghead fitted with uniform slots to enhance hydraulic efficiency to induce more material entrainment into the draghead.

Water jets and blades design

Laboratory tests to evaluate the effectiveness of water jets and blades to increase hopper-dredge production were conducted at WES in a flume 60 ft long, 10 ft wide, and 4 ft deep, with one section of a prototype-size model of the California-style draghead used on the hopper dredge *Wheeler*. The full-scale sectional model of a prototype draghead was used to alleviate similitude problems associated with scaling, especially those concerned with blade/bed material interactions and scaling of bed material particles. The sectional model of the draghead was 30 in. wide and 29 in. long, with one slot.

Test bed preparation. Gradation of the bed material tested closely matched the general characteristics of a typical dredging area. The D_{50} size of the test material was 0.075 mm (fine sand). The bed material was placed in the flume to a depth of 1.0 ft. Preparation of the bed prior to testing involved several steps, including compaction to desired density. Following final grading of the bed, cone penetrometer readings were taken at several locations in the bed test section to ensure compaction approximated prototype materials commonly found in Aransas Pass, TX.

Test results. All tests were conducted at constant speed (1 mph), and the results are presented by Brogdon et al. (1994) in terms of volume of material removed from the test section during passage of the draghead. Test results show that water jets with no blades (knives) can significantly increase dredging production when the dredge is operating at slow speeds. The addition of knives placed in front of water jets operating at different pressures further increases the efficiency of the dredging process.

Uniform-slots design

The objective of research by Banks and Alexander (in preparation) was to determine the feasibility of using a uniform placement of inflow slots around the perimeter of a California-style draghead to enhance dredge production.

Test program. Effectiveness of the inflow slots was evaluated by comparison of the production provided by an unmodified 1-to-6 model-to-prototype scaled model of a California-style draghead with the same style draghead enhanced by the addition of uniform slots (Uniform-Slot draghead) to provide better hydraulic entrance conditions and reduced energy head loss at the draghead. Comparison data for ascertaining which of the two model dragheads performed best consisted of determining the volume of bed material removed by the two different dragheads under identical test conditions in the laboratory facility.

Test results. Average results were obtained from 10 identical test runs each (average of 30 cross-section profiles) for the California-style draghead in the horizontal position (CALF), the California-style draghead in the 15-deg down position (CALD), the Uniform-Slot draghead in the horizontal position (USDF), and the Uniform-Slot draghead in the 15-deg down position (USDD).

The CALF draghead tests removed an average 1.897 cu ft of bed material from the 10-ft test section. The CALD draghead tests showed that an average of 2.923 cu ft of bed material was removed from the test section. The USDF draghead tests removed an average of 2.144 cu ft of bed material from the test section, while the USDD draghead tests removed an average of 2.525 cu ft of bed material.

The Uniform-Slot draghead in the horizontal position removed about 13 percent more bed material than the unmodified California-style draghead in the horizontal position. The Uniform-Slot draghead in the 15-deg down position removed about 33 percent more bed material than the unmodified California-style draghead in the horizontal position.

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Investigations conducted under the Dredging Research Program (DRP) Technical Area 3, "Dredge Plant Equipment and Systems Processes," resulted in new technologies and enhanced existing dredging systems to achieve economic load during dredging operations. Improvement included more effective eductors and a single-point mooring system for direct pumpout of hopper dredges onto beaches. Technology for dredge production and process monitoring was improved, and designs for hopper-dredge dragheads were modified to increase production. The following equipment, systems, or processes were improved: (a) eductors with more efficient sand-bypassing features and water-injection dredging to fluidize shoals and permit transport by density of natural currents; (b) dredging equipment for nearshore/onshore placement, including a direct pumpout capability for hopper dredges; (c) technology for monitoring and increasing dredge payloads for fine-grain sediments, including an automated load monitoring system and an electrical resistivity method; and (d) draghead design enhancements for more efficient production, including water jets and blades to loosen compacted sediments.

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