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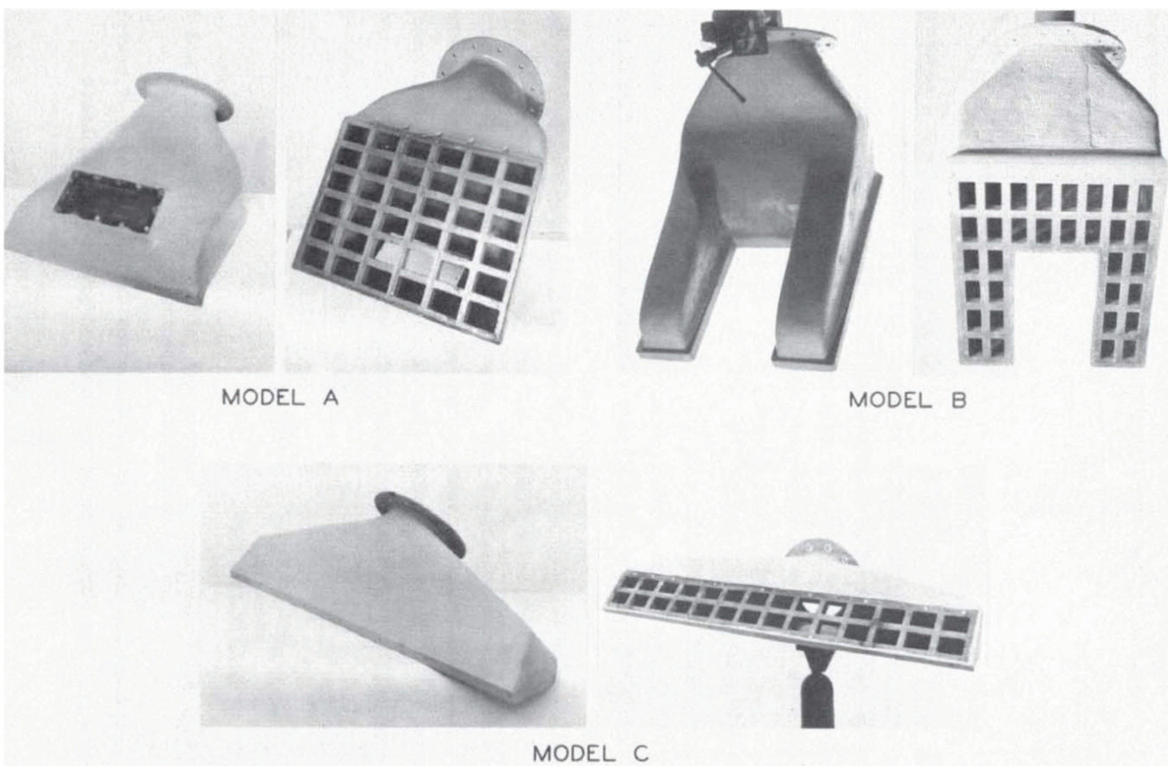
Dredging Operations and Environmental Research (DOER) Program

Literature Review of Dredging Physical Models

Brian C. McFall, Duncan B. Bryant, and Timothy L. Welp

June 2018



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Abstract

This U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, special report presents a review of dredging physical model studies with the goal of understanding the most current state of dredging physical modeling, understanding conditions of similitude used in past studies, and determining whether the flow field around a dredging operation has been quantified. Historical physical modeling efforts have focused on the improvement of performance and efficiency. All dredging physical models in the last 20 years have been cutterhead dredges, although approximately one-third of the dredging performed by the U.S. Army Corps of Engineers is done by hopper dredges with dragheads. Identified research gaps include simplified draghead and cutterhead shapes, improper sediment scaling, and the lack of flow-field quantification around dredging operations. Quantifying the flow field around dredging operations is the most pressing research gap due to entrainment concerns from regulatory agencies.

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Contents

Figures

Preface

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC, under the USACE Dredging Operations and Environmental Research (DOER) Program. The HQUSACE DOER Program Manager was Dr. Todd S. Bridges, U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL). Mr. Jeffrey A. McKee was the HQUSACE Navigation Business Line Manager overseeing the DOER Program. Mr. W. Jeff Lillycrop, ERDC Coastal and Hydraulics Laboratory (CHL), was the ERDC Technical Director for Civil Works and Navigation Research, Development, and Technology Transfer portfolio.

The work was performed by the ERDC CHL Coastal Engineering Branch (HN-C) and the Coastal Processes Branch (HF-C) of the Navigation Division (HN) and the Flood and Coastal Storm Protection Division (HF), respectively. At the time of publication of this report, Mr. Gregory W. Dreaper was Acting Chief, CEERD-HN-C; Ms. Ashley E. Frey was Chief, CEERD-HF-C; Mr. Charles E. Wiggins was Acting Chief, CEERD-HN; and Dr. Cary A. Talbot was Chief, CEERD-HF. The ERDC CHL Acting Deputy Director was Dr. Jackie S. Pettway, and Mr. Jeffrey R. Eckstein was the Acting Director.

The Commander of ERDC was COL Bryan S. Green, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
miles/hour	0.44704	meters/second
pound (force)	4.44822	Newtons
ton	8896.44	Newtons

1 Introduction

1.1 Background

Although dredging has occurred for centuries, few dredge technology physical models are documented in literature. A thorough literature search was conducted using several searchable databases including Web of Science, Google Scholar, and the U.S. Army Engineer Research and Development Center Library. Many more dredging physical model studies have likely been confidentially conducted and not published in literature due to the proprietary nature of the design and technology in the dredging industry.

1.2 Objective

The goals of this literature review are to understand the most current state of dredging physical modeling, to note conditions of similitude used in past studies, and to determine whether the flow field around a dredge has been quantified. Additionally, research gaps and future research needs are considered and identified.

1.3 Approach

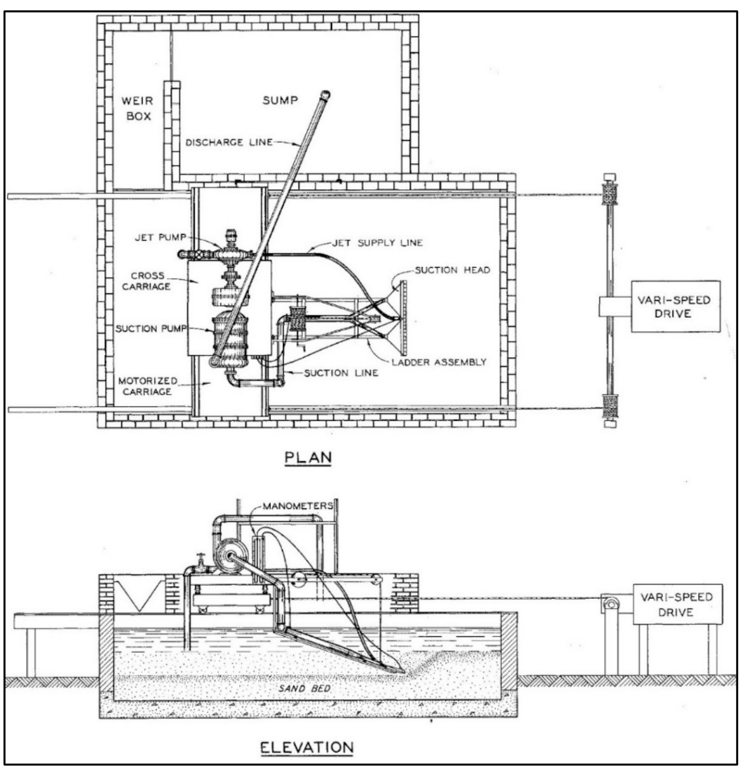
This report documents the limited number of published dredging physical models, including plain suction, draghead, and cutterhead dredge models. The flow field around dredging operations has been a relevant research topic during the last few decades. Regulatory agencies have concerns about entrainment risk of fish and other endangered species near dredging operations, particularly hopper draghead dredging operations. Without understanding the local flow field, estimating the risk associated with entrainment is difficult.

2 Historical Physical Models

2.1 Plain suction physical model

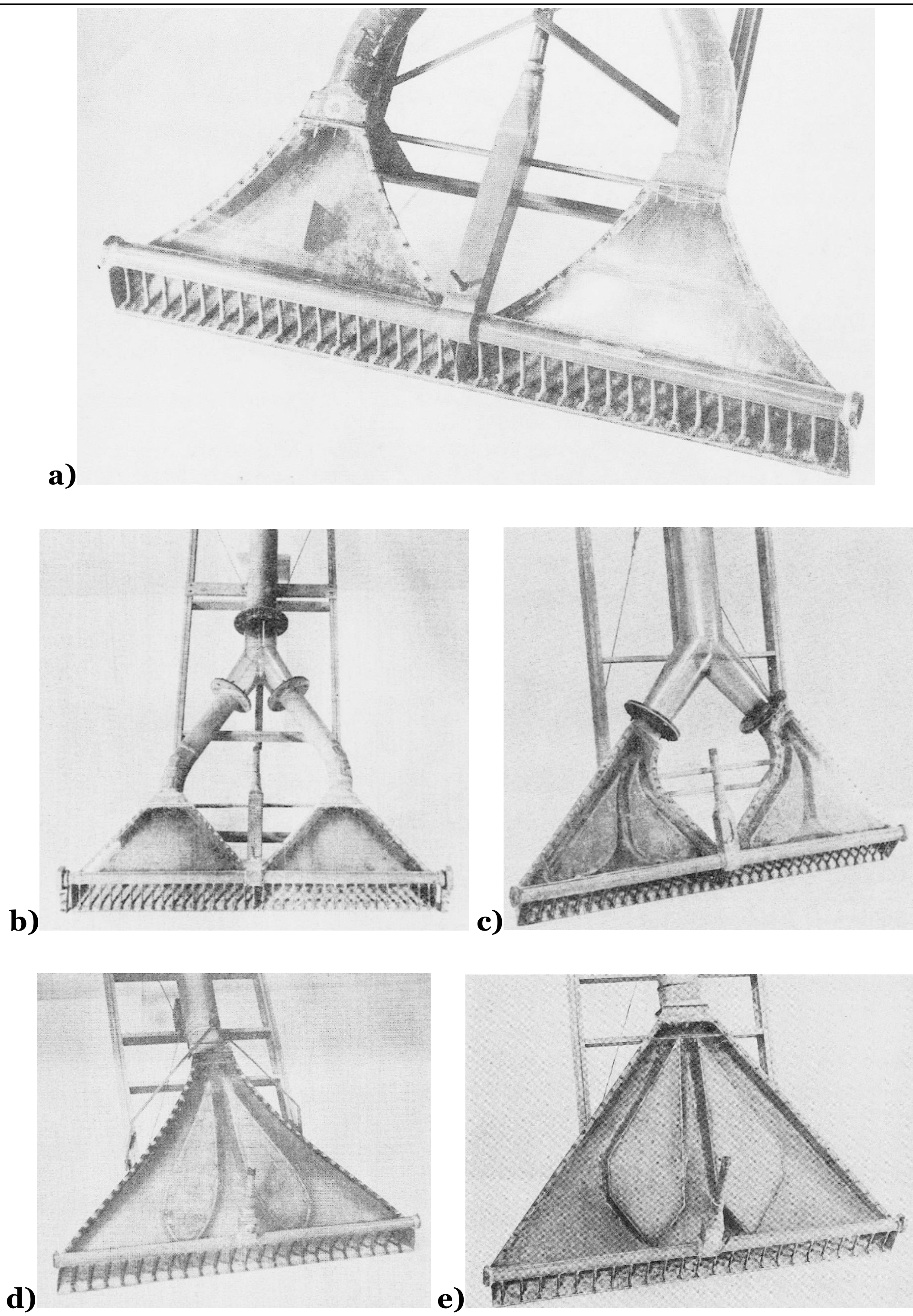
The U.S. Army Corps of Engineers (USACE) conducted a 1:10 scale physical model at the Waterways Experiment Station (WES) of dustpan-type suction heads for the dredge *Jadwin* from 1942 to 1944 (USACE 1947). The purpose of the study was to investigate the performance of a newly designed suction head for the dredge *Jadwin* compared to the existing double-dustpan head. The width of the model dredge heads was 3.2 feet (ft) and the length from the water entrance to the trunnion on the dredge ladder was 6 ft. Tests were conducted in a 16 ft long, 10 ft wide, and 4 ft deep flume. A suction pump with 3.8 inch (in.) suction line and jet pump with 1.5 in. jet line traveled on a double carriage mount on top of the flume. Although the sediment grain size was not provided, it was noted that a sand bed with sufficient depth to allow a maximum bank of 1.5 ft (model) was built in the flume. The suction pump discharged into a sump to trap the dredged material. The sump also had a series of baffles to still the water before allowing it to flow over a weir into the flume. The experimental setup for the study is shown in Figure 1.

Figure 1. Experimental setup for testing dustpan suction heads (USACE 1947).



The suction heads tested were the flared-wall double-dustpan (existing suction head), straight-line double-dustpan, flared-wall single dustpan, and straight-line single dustpan. The suction heads tested are shown in Figure 2. The tests did not show any particular suction head design to be outstanding in performance, but the flared-wall single dustpan and the straight-line double-dustpan heads were expected to perform with equal efficiency compared to the existing flared-wall double-dustpan. Less efficient performance was expected from the straight-line single dustpan. Results from the model may be scaled to prototype using generalized Froude similitude when the suction head was pumping water. However, the sediment grain size for the bed material was not scaled; thus, similarity was not established for tests where the suction head was tested on sand bed. The latter tests may not be scaled quantitatively, but the qualitative comparative results of the efficiencies and performance of the different suction heads may be useful.

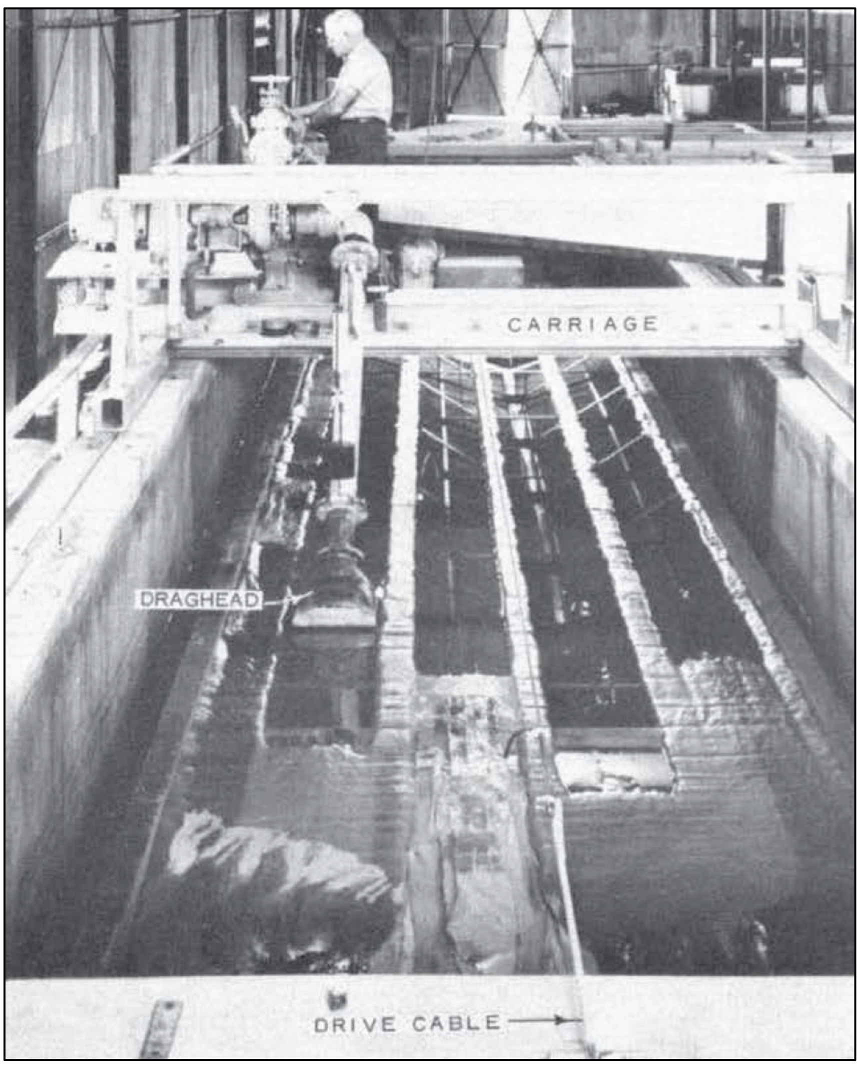
Figure 2. Suction heads tested: a) flared-wall double-dustpan, b) straight-line double dustpan, c) modified straight-line double dustpan, d) flared-wall single dustpan, and straight-line single dustpan (USACE 1947).



2.2 Draghead physical models

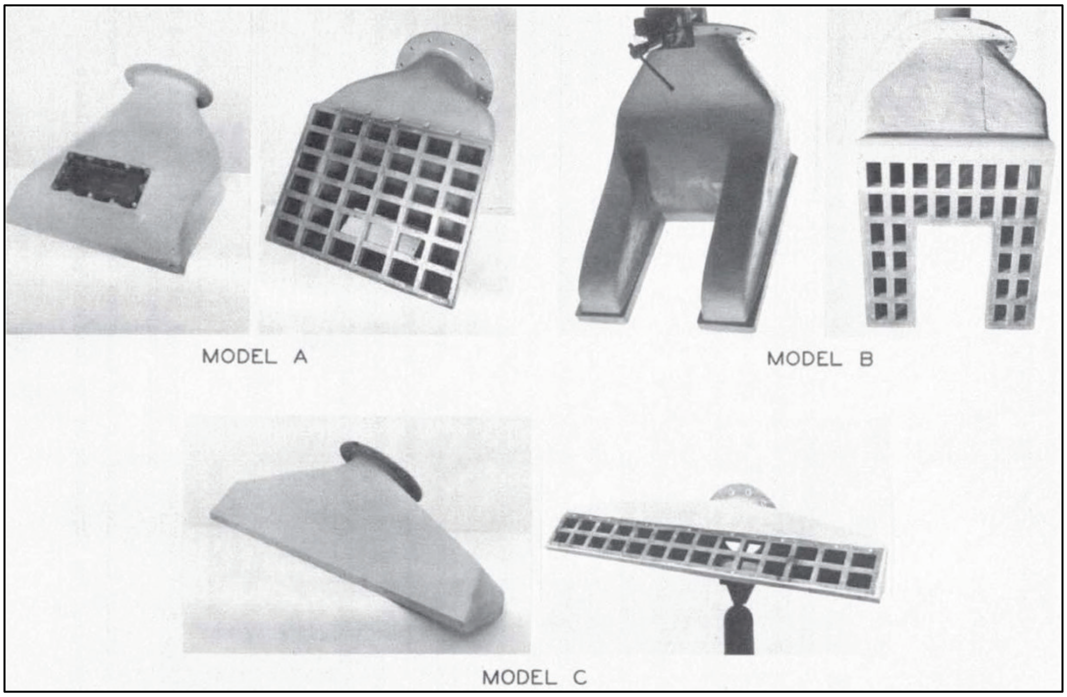
From 1959 to 1963, a draghead physical model study was conducted at the WES (Franco 1967). This hydraulic model was conducted to determine the factors affecting the efficiency of dragheads and to develop parameters for use in the design and operation of dragheads in sand. The study was conducted in a 60 ft × 10 ft flume with 1:6 scale model draghead and suction line. A 600 gallons per minute (gpm) centrifugal pump with a 5 in. suction line and 4 in. discharge line was installed on a carriage mounted to the top of the flume. The drag arm consisted of a 5 in. pipe connected to the suction end of the pump with a 90° swivel elbow to allow the drag arm to be raised or lowered by rotating at the elbow. The flume and carriage system used in the study is shown in Figure 3.

Figure 3. Experimental setup for testing different dragheads (Franco 1967).



Three basic draghead designs were tested: square draghead based on the Ambrose type, U-shaped draghead based on the California type, and rectangular-shaped draghead with a large width-to-length ratio. The dragheads were built of polyester resin and fiberglass are shown in Figure 4.

Figure 4. Polyester resin and fiber glass model dragheads: Model A. square, Ambrose type; Model B. U-shaped, Calilfornia type; Model C. rectangular shaped (Franco 1967).



Although the draghead and suction line were scaled 1:6, the facility size limitation prevented proper scaling of the water depth, suction line length, pump elevation above the water, and bed sediment grain size. The median grain size, d_{50}, of the tested bed sediment was 0.23 millimeter (mm), which would correspond to a prototype grain size of 1.38 mm. The larger prototype grain size would require higher velocities in the suction pipe to erode the bed. This significant change in the grain size would also impact the system head, flow rate, and turbidity.

Although direct, quantitative results were not determined from the study, some practical, qualitative results were derived. The U-shaped, California-type draghead was the most efficient of the dragheads tested when dredging “hard” compact sand. The rectangular, wide-type draghead would provide a higher dredging rate if the necessary suction, or differential pressure, could be provided.

Sato et al. (1978) studied the effects of different shaped dragheads on the suction performance. This was studied by measuring the bed pressure distribution under circular, square, rectangular, and U-shaped, California-type dragheads. The flow rate, clearance between the draghead and the bed, and draghead transient speed were varied in the study. When the draghead was stationary, the circular, square, and rectangular dragheads produced pressure contours close to the shape of the draghead, but the pressure contours from the California type draghead impacted regions much farther from the draghead.

When the dragheads were moving, the experiments showed that the pressure contours at the bed were "inverse U-shaped," meaning the pressure contours began at the leading edge of the draghead and continued behind the draghead. Varying the suction flow rate and clearance impacted the pressure values but did not significantly impact the width of the region affected by the draghead. Based on the bed pressure measurements, this study concluded that the California and square dragheads had superior performance.

Woolley and Powell (1989) studied the hydraulic performance of California dragheads using 1:8 and 1:2.2 scaled physical models at the Scripps Institute of Oceanography. The 1:8 scale model was used to determine instrumentation and data collection procedures. The model was based on the California dragheads used by the USACE *Hains*-class hopper dredges. Sediment median grain size was 0.185 mm, and the draghead was connected to a 60 gpm pump mounted on mobile cart above a glass flume. Using Froude similarity and the sediment fall speed, the prototype median grain size would be 0.4 mm. This prototype scale was larger than average in the Pacific Northwest, making the results qualitative. The density of the slurry inside the draghead appeared to be reasonably uniform, and the track left by the draghead in the sand bed matched the field results reported by Hartman and Slotta (1976). Results from the 1:8 scaled model indicated that the draghead performance could be successfully modeled qualitatively.

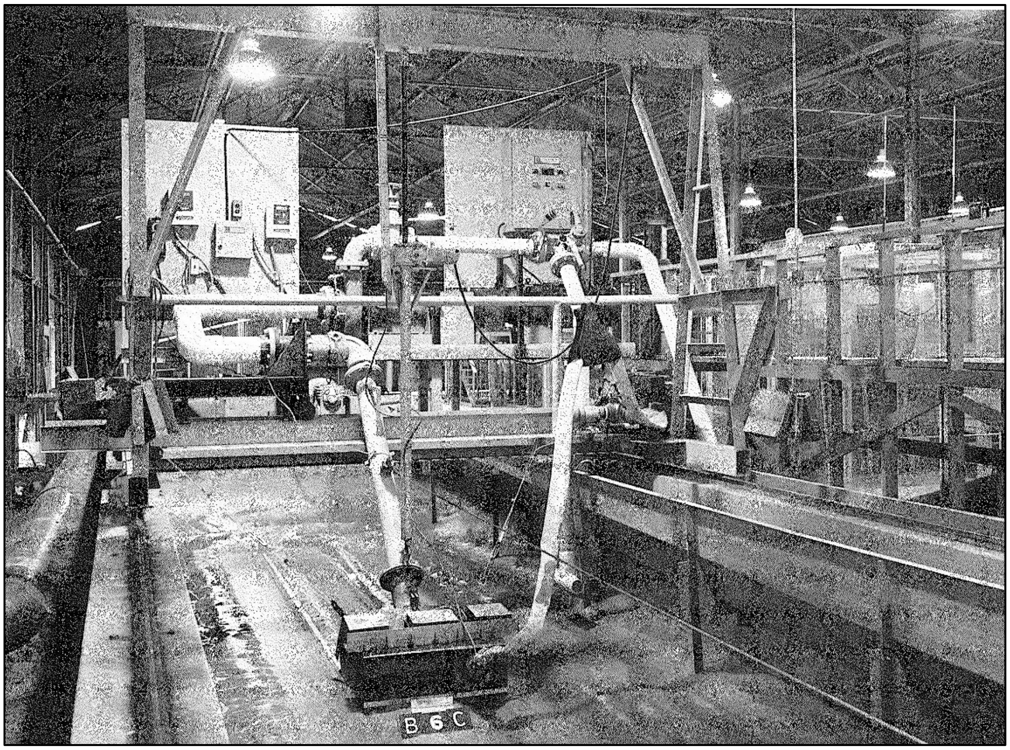
The 1:2.2 scaled model of one visor section, or "toe," of the "split toe" California draghead of the dredge *Yaquina* was conducted to optimize the draghead slot geometry. Only one visor was used to maximize the model size. Using only one visor allowed for qualitative results of the flow across the draghead slots but is not applicable to quantify the flow field around the draghead. The model was conducted in a 5 meter (m)-wide, 12.2 m long, and variable depth basin with maximum depth of 3.05 m. An 800 gpm pump was mounted on a motorized carriage above the basin that was operated with a typical transient speed of 61 cubic meters per second, corresponding to a prototype speed of 2.6 knots. A nuclear density meter was mounted to the suction side of the pump, and a flow meter was installed on the pump's discharge line. The sand bed in the basin had a sediment median grain size of 0.180 mm. Results from this model study indicated the reverse five narrow slot, 45° vice 135° grouser angle, configuration to be the superior design with a 21% advantage in overall production. These results were validated at prototype scale with the dredge *Yaquina* at Barratts Range on the Umpqua.

Woolley (1987) noted the 1:2.2 scaled model was used again in 1986 with fine-grained sand. The dredging efficiency was reduced in fine-grained sand compared to the previously tested medium sand. The reverse slot draghead was tested at prototype scale in coarse sand at Airport Bar in the Columbia River adjacent to Portland, OR, and no significant improvement was noted. Thus, the dragheads were determined not to be the controlling factor when digging coarse sand (d_{50} > 0.6 mm).

Another draghead physical model was conducted at the WES from 1987 to 1989 (Brogdon et al. 1994). The objective of this study was to test various water jets and knives attached to the draghead for dredging compacted fine sands. The dragheads tested four types and sizes of nozzles and water jets, two angles of attack, two heights above the bed, and four pressures at the nozzle head. Bimetal knives or blades with 2 in. and 4 in. depth of penetration were tested with approach angles of 30° and 45° (Banks 1988).

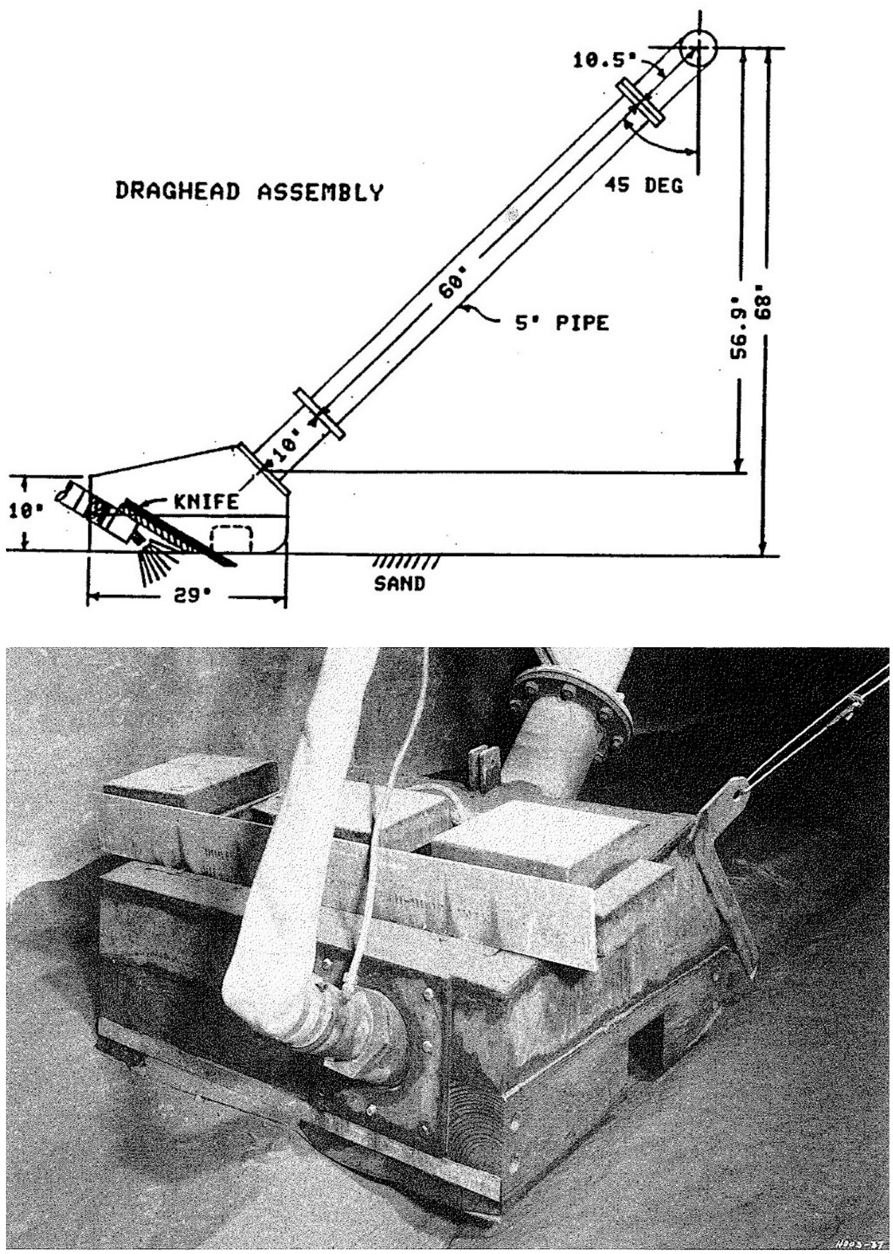
The experiment was conducted in 60 ft long, 10 ft wide, and 4 ft deep flume. A carriage spanned the width of the flume, and it traversed the along angle iron rails mounted to the flume walls at a speed of 1 mile per hour. The pumps, dragarm, draghead, and discharge line were mounted to the carriage. The dredge pump was a 900 gpm centrifugal pump with a 20 horsepower eddy current variable speed drive motor and 5 in. suction line. The drag arm was connected to the pump with a 90° swivel elbow to raise and lower the draghead. A high-head 2.5 in. fire pump was used to supply water to the water jets. The experimental setup is shown in Figure 5.

Figure 5. Experimental setup for testing waterjet and knives for increased draghead efficiency (Brogdon et al. 1994).



The fine sand bed material was obtained from the Red River dredged material disposal site near Marksville, LA. The d_{50} of the sediment was 0.0750 mm. The draghead tested was a full-scale sectional model reproduced of the midsection of the California-type draghead from the hopper dredge *Wheeler*. The full-scale sectional model approach was chosen to avoid similitude issues associated with the draghead/bed interaction. The draghead was 30 in. wide and 29 in. long with one slot opening 3.5 in. wide. The sectional model draghead can be seen in Figure 6.

Figure 6. a) Schematic of the draghead assembly and b) sectional model draghead (Brogdon et al. 1994).



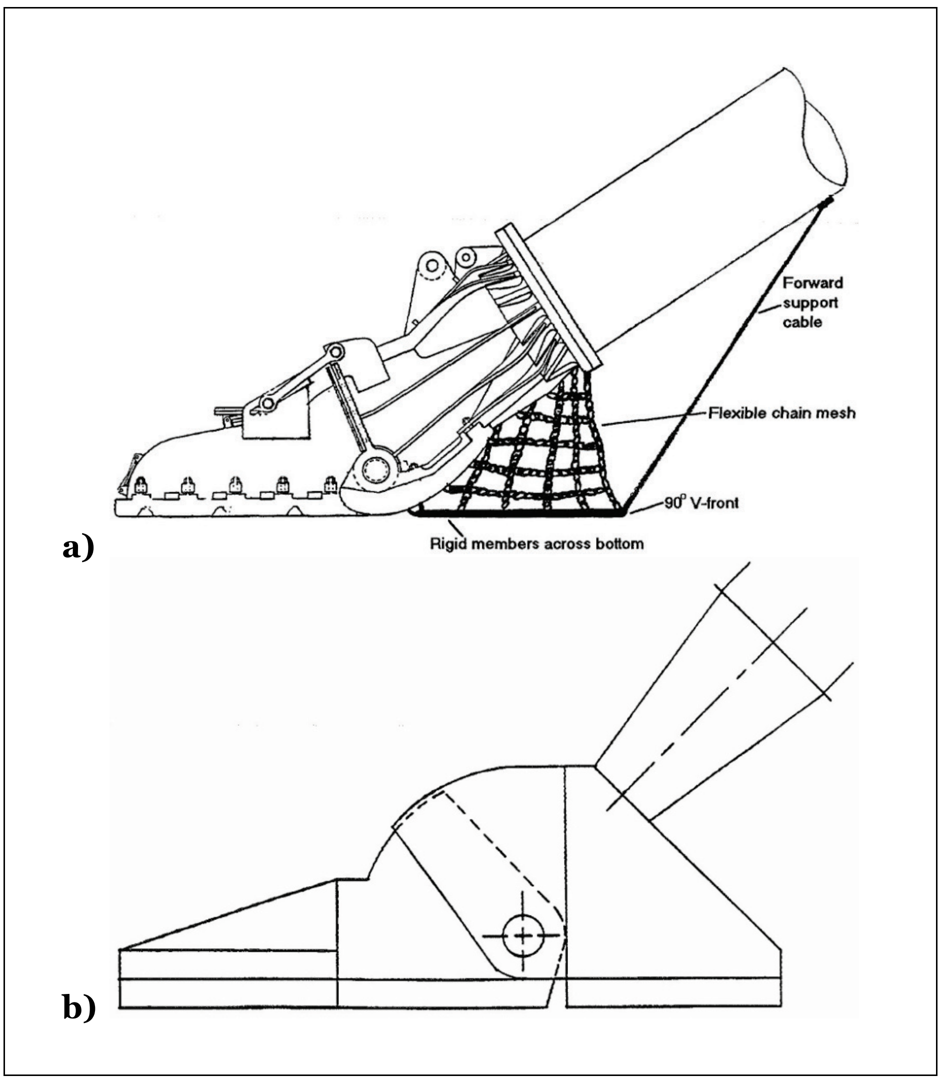
a)

b)

The study concluded that the volume of material removed from the bed increased with increasing water jet pressure. It also noted that production increased 23%–34% with the application of a single blade placed in the line of the flow through a single side slot of the model draghead.

Banks and Alexander (1994) used the same USACE facility to conduct scaled model tests in the development of a sea turtle deflection apparatus by comparing results of a chain deflector and a rigid V-shaped deflector. The deflectors are shown in Figure 7. The draghead, deflectors, and model turtles were constructed with a 1:6 model scale. Turtles were modeled with neutrally buoyant foam discs. The rigid deflector was 100% effective at deflecting the model turtles when the lead edge angle of the deflector was maintained and the draghead maintained contact with the bottom. The rigid deflector pushed a small ripple of sand in front of the draghead, but production values were comparable to standard California draghead model tests without the deflectors. The rigid deflector was subsequently tested in a field study.

Figure 7. a) Chain deflector on standard California draghead and b) rigid V-shaped turtle deflector (Banks and Alexander 1994).



Larson et al. (1994) used a 1:4 scale draghead model at the Scripps Institute of Oceanography to develop a device to prevent the entrainment of Dungeness crabs. A variety of design alternatives were evaluated to determine which produced the greatest reduction in entrainment and smallest impact on the draghead production. Entrainment was determined using plastic particles to represent crabs. Tests were also conducted with live crabs by dropping live crabs in the test tank in front of the draghead during test runs to determine if crab behavior would affect the performance of the device. The final design included side skirts and a modified sand wave generator. This design produced a 95% reduction in entrainment with a 5%–6% reduction in production. Similar results were observed with the California draghead.

Powell (1994) used the same 1:4 scale draghead and facility as Woolley (1987) and Larson et al. (1994) to map the peripheral velocity field around a California draghead to estimate juvenile salmonid entrainment. Suction to the draghead was provided with a 3 in. centrifugal pump with a maximum flow rate of 440 gpm. The draghead was 1:4 scale model of the size draghead used on the dredge *Yaquina*. The flow visualization was recorded with an underwater camera. Flow velocities were measured with acoustic Doppler velocimeters (ADV). Tests were conducted with and without flow in the channel and with and without towing. The flow velocity in the channel and tow velocity was 0.77 feet per second (ft/s), corresponding to a dredge speed of 1.82 knots.

One of the goals of the study was to establish the location of flow fields around the draghead, which exceed 0.25 ft/s, the estimated escape speed of juvenile salmonids. The draghead was positioned upside down with the suction grate facing upward, and fluid velocity measurements were taken at 387 points. In another set of experiments, the draghead was correctly oriented and the suction grate was positioned 10 in. above the bed with the toe of the draghead tilted downward 15° from horizontal. Live trout fry or neutrally buoyant particles were released near the draghead. Flow-field diagrams were hand sketched from the experiments. When the draghead was stationary, the entrainment critical velocity was observed on the sides and even above the draghead. When the draghead was moving, the critical entrainment velocity stretched longitudinally and contracted laterally. Additionally, it was observed that when the draghead was moving, the few fry or particles entrained were primarily from underneath the draghead. To minimize the entrainment risk during dredging operations, it was recommended to increase draghead tow velocity and add small horizontal plates to the draghead, particularly on the front.

2.3 Cutterhead physical models

Slotta (1968) conducted flow visualization experiments around a stationary and rotating cutterhead. The physical model consisted of a 1:15 scale plastic model (6.5 in. diameter) representing an 8.1 ft diameter cutter weighing approximately 14 tons. The flow was visualized using hydrogen bubbles created by electrolysis. The experiments were conducted in a 6 ft long, 2 ft wide, and 15 in. deep clear, plexiglass flume. A 50 gpm pump was used for suction and recirculating the streamflow.

Dimensional analysis was performed, and this study attempted to satisfy similitude criteria for the Reynolds scaling, the Froude scaling, kinematic (velocity) scaling, and the specific speed scaling of the rotating cutterhead. Reynolds similitude is given as

$$\left[\frac{U_{suction} D_{cutter}}{\nu}\right]_{model} = \left[\frac{U_{suction} D_{cutter}}{\nu}\right]_{prototype} \quad (1)$$

where $U_{suction}$ is the suction velocity, D_{cutter} is the cutterhead diameter, and υ is the kinematic viscosity of the water. Froude similitude is given by

$$\left[\frac{(U_{suction})^2}{g D_{cutter}}\right]_{model} = \left[\frac{(U_{suction})^2}{g D_{cutter}}\right]_{prototype} \quad (2)$$

where g is the gravitational constant. Kinematic similitude is given by

$$\left[\frac{\omega_{cutter} D_{cutter}}{U_{suction}}\right]_{model} = \left[\frac{\omega_{cutter} D_{cutter}}{U_{suction}}\right]_{prototype} \quad (3)$$

where ω_{cutter} is the rotational speed of the cutter. Similitude of the specific speed of the rotating cutterhead is given by

$$\left[\frac{\omega_{cutter}\sqrt{Q_{suction}}}{(H_{velocity})^{3/4}}\right]_{model} = \left[\frac{\omega_{cutter}\sqrt{Q_{suction}}}{(H_{velocity})^{3/4}}\right]_{prototype} \quad (4)$$

where $Q_{suction}$ is the discharge and $H_{velocity}$ is the velocity head which is given by

$$H_{velocity} = \frac{(U_{suction})^2}{2g} \tag{5}$$

It is impossible to concurrently have Reynolds and Froude similitude. It was determined that Reynolds similitude would be important, but no quantitative measurements were available to substantiate the use of one similitude over another.

Joanknecht (1976) conducted a cutterhead physical model in an attempt to define the appropriate similitude relationships. The two model cutterheads were tested with scales of 1:3 and 1:4. The experiments were conducted in a 30 m long and 2.5 m wide flume. A sand pump with 100 mm diameter suction and discharge pipeline was mounted on a carriage on top of the flume. An auxiliary carriage was used to mount the cutter installation, which could raise and lower the cutter arm. The sand bed was created with a mean grain size of 0.2 mm.

This study determined the dominant parameter for kinematic similarity between the model and prototype is the Froude number based on the grain size which is given as

$$\left[\frac{v_t}{\sqrt{gd}}\right]_{model} = \left[\frac{v_t}{\sqrt{gd}}\right]_{prototype} \tag{6}$$

where v_t is the terminal velocity of a grain in water and d is the nominal diameter of the grain. The variation of the Froude number differs from previous studies that used the inlet velocity and diameter. This Froude criteria based on the grain size would be satisfied if the same grain size is used in the model as in the prototype. Although if the grain size changes, the grain density is required to change to alter the terminal velocity to maintain this similitude. It should be noted that no parameter of the cutterhead or velocity field generated by the cutterhead is accounted for in this relationship. This similitude was allegedly substantiated in this paper by using the results from the two different cutterheads, but since the same sand grain size was used for both tests, this criteria was automatically satisfied.

Mol (1977a, 1977b, 1977c) conducted flow experiments around the cutter and modeled cutting sand in the flume facility using Froude similitude. The cutterhead diameter was 0.6 m, and the ladder angle was 30°. The sand bed was constructed of 0.12 mm sand. Once the cutterhead reached a critical threshold, an outward flow tended to be created. Spillage from the cutter occurred when enough sediment was in the cutterhead rotation.

Miltenburg (1983) used a cutterhead physical model to study the flow and mixture process inside the cutterhead. The cutterhead diameters ranged from 0.32 to 0.4 m, and Froude similitude was applied for the velocity flow field near the cutter. The sand bed consisted of fine-grained sand with a sediment diameter of 0.18 mm. The study analyzed the cutter speed, suction velocity, and swing speed. An increase in production was noted with a decrease in cutter speed and increase in suction flow rate.

Brahme (1983) and Brahme and Herbich (1986) measured the flow field around a suction pipe in various orientations and the influence of the velocity field on sand pick-up behavior. The experiments were conducted in a steel tank 8 ft long, 4 ft wide, and 4 ft deep. Three different pipe diameters kept at three different heights above the bottom were tested. Velocity measurements were taken using a hot-film anemometer, micropropeller flow meter, and color dyes. The following conclusions were made:

1. In general, velocity increased with an increase in the flow rate passing through the suction pipe.
2. Velocity was fairly high very close to the pipe intake but dropped rapidly with distance from the pipe.
3. The regions of high velocity moved upwards with increasing distance between the pipe intake and the bottom of the tank.
4. Very little change was observed in the velocity field for the same suction discharge with differing pipe diameters.

Using dimensionless plots, it was determined that the velocity field around a suction pipe could be given by

$$\frac{Q}{r^2V} = Dimensionless\,Velocity\,Field \tag{7}$$

where Q is the flow rate in the pipe, r is the radial distance from the center of the pipe intake, and V is the velocity at any point in the field. The dimensionless plots were tested in the range h/H from 0.1 to 0.225 and d/H from 0.03 to 0.055, where h is the distance of pipe intake above the bottom, H is the depth of the water in the tank, and d is the pipe diameter. It was found that the velocity field was dependent on flow rate in the pipe but was independent of the velocity at the intake, pipe diameter, and angle of the pipe.

Two stationary basket-type cutterhead models with scales 1:12.25 and 1:2.45 were attached to the pipe and tested to validate the dependency on the flow rate regardless of the obstruction caused by the presence of the cutter on the intake. The velocity field measurements matched the unobstructed pipe intake when the flow rate remained constant.

To investigate sediment suspension around a cutterhead, the cutter was rotated at speeds from 75 to 195 rpm, suction flow rate was 56 gpm for the 2 in. pipe to 50 gpm for the 1.11 in. pipe, the swing velocity ranged from 0.04 to 0.3 ft/*s*, and three different sediments were used. The sediment consisted of microbeads, fine sand, and medium sand with specific gravities of 2.45, 2.66, and 2.64, respectively, and median grain size diameters of 0.093, 0.21, and 0.39 mm, respectively. Samples of suspended sediment were collected near the bottom in front of the cutter for different cutter rotation speeds, suction flow rates, and swing velocities. In general, sediment suspension increased with cutter speed, decreased with increased suction flow rate, and increased with increased swing velocity.

Suspended sediment samples taken farther from the cutterhead were also analyzed. In the vertical direction, there was a significant decrease in the suspended sediment one suction-pipe diameter above the cutter head. In the horizontal direction, the suspended sediment was found to be slightly higher behind the cutter than in front, and at a distance of 10–15 pipe diameters away from the cutter, the suspended sediment dropped to approximately 10% of that near the cutter.

Herbich and Devries (1986) used a 1:8 scale physical model of a basket-type cutterhead to study the effect of various operating parameters on suspended sediment. The sediment consisted of fine sand with median grain sizes of 0.1 and 0.2 mm. The cutterhead diameter was 72 in., and the suction pipe diameter was 16 in. Suspended sediment samples were taken with five syringes placed radially approximately 18 in. vertically from the cutterhead.

The operating parameters tested were the thickness of cut relative to the cutter diameter, cutter speed (rpm), and the ladder angle. The suspended sediment was minimized when the cut was equal to the cutter diameter. Cuts shallower and deeper than the cutter diameter increased the suspended sediment. An increase in suspended sediment was noted with increased cutter speed. An increase in the ladder angle from 22° to 29° increased the suspended sediment along the leading edge of the cutter but decreased in the trailing area of the cutting region. Similar to results of Brahme and Herbich (1986), the amount of suspended sediment above the cutterhead was very small.

Burger (2003) used model cutterheads with diameters from 0.3 to 0.4 m with a cutting angle of 45° to investigate the path of single particles moving in and around the cutterhead. The parameters varied in the study were the particle size, particle density, suction flow rate, and cutter speed. The analysis of the particle size produced no conclusive correlation, but decreasing the particle density decreased the particle residence time. Increasing the suction pipe flow rate decreased the particle residence time. The importance of particle inertia was noted as the threshold ratio for a particle to be thrown out of the suction range. It is defined by the relationship between the tangential cutting force and the drag force created from suction. It was also observed that the particles were more likely to be thrown out of the suction range when the cutterhead was swinging in the overcutting direction.

Glover (2002) and Glover and Randall (2004) analyzed similitude criteria previously applied for the design of a laboratory facility for dredging physical models at Texas A&M University. The analysis found the velocity field could be scaled by the model flow rate by

$$\left[\frac{Q}{\left(D_{cutter}\right)^{2} v_{t}}\right]_{model} = \left[\frac{Q}{\left(D_{cutter}\right)^{2} v_{t}}\right]_{prototype} \tag{8}$$

This dimensionless parameter is a variation of the dimensionless parameter derived by Brahme and Herbich (1986), but unlike Equation (7), this relationship takes into consideration the geometric scaling of the velocity field magnitude relative to the settling velocity of the sediment. This is important for the velocity field created by the suction inlet to be scaled such that the similarity of the sediment pickup behavior is achieved.

Glover (2002) noted a model bed material composed of fine sand (d_{50}=0.1 mm) allows prototype bed material from fine to coarse sand to be modeled without excessive model flow and pipe velocity capabilities of conventional centrifugal pumps. The flume constructed for dredging physical models at Texas A&M University is 150 ft long, 12 ft wide, and a maximum water depth of 10 ft. The flume also has a sediment pit that is 25 ft long and 5 ft deep. A dredge carriage, described by Randall et al. (2005), rides on top of the flume walls and carries a centrifugal pump with a 4 in. suction line and 3 in. discharge. The model dredge consists of the carriage, ladder, and cradle. The cradle moves the ladder side-to-side to simulate the swinging cutterhead. A flat blade cutter is used with 13.5 in. diameter to the outside tips of the blades. A magnetic flow meter is used to measure the flow of slurry, and a nuclear density gauge measures the slurry density. Henriksen et al. (2007) provided testing procedures for conducting research on suspended sediments on cutterhead dredging in the facility.

Henriksen (2009) used this facility to study the suspended sediment around cutterhead dredging operations. Sand with a median grain size of 0.26 mm was used in the experiments. The cutter speed (rpm), suction flow rate, and thickness of cut were varied in this study. In general, the suspended sediment measurements increased with increased cutter speed. Increased suction flow rate resulted in increased production and decreased suspended sediment, but the suspended sediment measurements actually increased at the highest flow rate tested at specific spatial locations around the cutter. The thickness of cut results follow previous trends with cuts shallower and deeper than the cutter diameter increased the suspended sediment, and the suspended sediment was minimized for full cuts compared to partial cuts. The suspended sediment caused by undercutting was three to six times greater than the suspended sediment caused by overcutting. A strong vertical diffusion gradient of suspended sediment was observed, and this gradient was attributed to the large amount of turbulence and dissipation created from the cutterhead.

3 Research Gaps and Future Research

The dredging physical models conducted over the last 70 years have been studied and analyzed. These models include plain suction, draghead, and cutterhead dredging techniques. All of the dredging physical models from the last 20 years have been related to cutterhead dredges. Approximately 60 million cubic yards of material are dredged annually by hopper dredges with dragheads in the United States. Advances made in cutterhead physical modeling and dimensional analysis can be applied to draghead physical models.

The research gaps in dredging physical modeling can be broken into three categories:

1. Shape
2. Sediment Scaling
3. Flow-Field Measurements around Dredging Operations.

Identified research gaps associated with each of these categories are addressed in the subsequent sections.

3.1 Shape

The majority of the dredging physical model studies identified have used idealized, simplified draghead and cutterhead shapes. The use of idealized components is common with all types of physical models, but no studies were located that tested the IHC-style draghead or shaped cutterhead styles with various “teeth” configurations, both of which are commonly used by private dredging companies. This research gap is likely due to the proprietary nature of dredging technology used by private dredging companies, although a generic IHC style draghead could be tested without compromising trade secrets.

The exception to the simplified dragheads in scaled physical models is the California draghead, which is used by U.S. Army Corps of Engineers and construction plans are available to the public. Several studies used precisely scaled California dragheads to improve draghead efficiency or reduce entrainment risks. There will be a continued research need to physically model modifications to dragheads and cutterheads to improve efficiency or reduce entrainment risk.

3.2 Sediment scaling

Correct scaling of bed sediment has not been accomplished in past dredging physical models. To avoid scaling concerns, Brogdon et al. (1994) used a section of a full-scale draghead to test the sand bed behavior at a 1:1 scale. The bed material size, porosity, shear strength, and cohesive properties have an influence on the efficiency and entrainment rates of sediment. These properties will also directly affect the flow field around the draghead. Future studies would benefit by using multiple sizes and types of sediments.

3.3 Flow-field measurements around dredging operations

Regulatory agencies have concerns about entrainment risk of fish and other endangered species near dredging operations, particularly dragheads. Without understanding the local flow field, estimating the risk associated with entrainment is difficult. The seven identified studies on dragheads have focused on sediment entrainment rates and efficiency. These draghead physical models studies were performed at scales of 1:8 to 1:1. Quantitative flow-field measurements have been limited to simple pipe inlets and static cutterheads. Powell (1994) took flow-field measurements around a draghead, but the results are shown with hand sketched diagrams and are not detailed enough for computational model validation. Computational modeling validation is dependent on accurate velocity or pressure measurements taken around a draghead during dredging operations. While data collected in the field would have the greatest value, current measurement technology such as ADV or acoustic Doppler current profilers are neither detailed enough nor robust enough to survive the forcing during active dredging.

3.4 Future research

Additional studies are recommended to address the identified research gaps of shape, sediment scaling, and flow-field quantification. To reduce the research gap affiliated with the shape, additional physical models with an IHC style draghead and cutterheads with various “teeth” configurations should be conducted. More dredging studies are recommended with multiple sediment grain sizes and density to prevent sediment scaling issues commonly found in past studies. Quantifying the flow field around dredging operations, particularly dragheads, is the most pressing research gap because of the current regulatory agency concerns of entrainment risks for endangered fish and species. A future study should quantify the flow field around California and IHC style dragheads during operations to address these concerns. Results from this study may lead to subsequent studies of mitigation measures to reduce entrainment risk based on the quantified flow field.

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14. ABSTRACT
This U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, special report presents a review of dredging physical model studies with the goal of understanding the most current state of dredging physical modeling, understanding conditions of similitude used in past studies, and determining whether the flow field around a dredging operation has been quantified. Historical physical modeling efforts have focused on the improvement of performance and efficiency. All dredging physical models in the last 20 years have been cutterhead dredges, although approximately one-third of the dredging performed by the U.S. Army Corps of Engineers is done by hopper dredges with dragheads. Identified research gaps include simplified draghead and cutterhead shapes, improper sediment scaling, and the lack of flow-field quantification around dredging operations. Quantifying the flow field around dredging operations is the most pressing research gap due to entrainment concerns from regulatory agencies.

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