LABORATORY MEASUREMENTS OF THE SUCTION INLET FLOW FIELD OF A MODEL CUTTER SUCTION DREDGE

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ABSTRACT

This paper describes the three-dimensional velocity flow field measurements in the vicinity of the inlet mouth of a cutterhead suction dredge. Using acoustic Doppler velocimeters (ADVs), an accurate visualization of the velocity flow field was used to determine a region of inflow around the cutterhead. This experimental study evaluates the correlation between the velocity flow field and other dredge parameters such as suction intake diameter without the cutterhead and with a stationary cutterhead. Prior studies of the flow field around the cutterhead provided a means to predict the velocity at the cutterhead suction inlet. The flow field studies provide an extension into three dimensions as well as a verification of the previous results. The highest velocities were found to occur nearest the cutterhead, specifically in the lower hemisphere of cutterhead where the suction intake is located. The magnitude of these values greatly decreased with increasing distance from the cutterhead. In addition, the flow rate is directly correlated to the velocity around the cutterhead. The cutterhead did not cause any noticeable decrease in velocity at higher flow rates of 0.0189 - 0.02217 m³/s (300 - 360 GPM). However, at a flow rate of 200 GPM (0.01262 m³/s) the velocity did decrease by approximately 25% when the cutterhead was attached.

Keywords: Dredging, experimental measurements, flow field, region of inflow, inlet flow effects.

INTRODUCTION

The flow field in the vicinity of the inlet mouth of a cutterhead suction dredge is very complex. The complexity is caused by the interaction between the suction flow, rotating cutterhead blades, and swinging of the ladder. Studies have been conducted in the past that measured the magnitudes of the velocities in two dimensions in a limited number of scenarios, mostly with a stationary cutterhead or no cutterhead at all. An investigation of greater breadth is needed to better understand the nature of the flow field. Using acoustic Doppler velocimeters (ADVs), a more accurate visualization of the velocity field is used to determine the region of inflow around the cutterhead. Similitude is used to determine any relationships between dredge parameters such as suction intake diameter and suction flow rate.

PREVIOUS FLOW FIELD STUDIES

Laboratory Measurements of Flow into a Cutter Suction Inlet

A laboratory study of the flow into the suction inlet of a model cutter suction dredge in the Haynes Laboratory dredge/tow tank facility at Texas A&M University was conducted in the summer 2011. The results of this study are contained in Dismuke (2012) and are described further in this paper. Modern acoustic Doppler velocimeters and a computer controlled dredge carriage were used to collect the data and evaluate the effects of flow rate, cutter speed, and swing speed on the suction inlet flow field. Water was used with no sediment.

Brahme and Herbich (1986) published their research on flow around a cutterhead and inlet, and investigated how inlet flow affected turbidity. The goal was to determine ways to reduce turbidity in the vicinity of the cutterhead and suction intake. The high velocities were found to occur nearest the cutterhead, specifically in the lower hemisphere of the cutterhead where the suction intake is located. The magnitude of these values greatly decreased with increasing distance from the cutterhead. In addition, the flow rate is directly correlated to the velocity around the cutterhead. The cutterhead did not cause any noticeable decrease in velocity at higher flow rates of 0.0189 - 0.02217 m³/s (300 - 360 GPM). However, at a flow rate of 200 GPM (0.01262 m³/s) the velocity did decrease by approximately 25% when the cutterhead was attached.

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avoid resuspension of potential pollutants in the sediment (Brahme and Herbich 1986). In contrast to work previously done by Slotta (1968), Brahme and Herbich (1986) wanted to measure the flow field both qualitatively and quantitatively. This was important since the velocity field around the cutterhead determines the amount of suspended sediment that is picked up by suction inlet. A new parameter measuring the radial distance between the suction inlet and suspended sediment, \( R_1 \), was studied by Brahme (1983). This new parameter was useful in determining the area of inflow to the cutterhead suction.

Brahme and Herbich (1986) made the following general observations:
1. Velocity increased as the flow rate through the suction pipe increased.
2. Velocity was highest near the suction pipe inlet but decreased rapidly away from the inlet.
3. The region of highest velocity was always near the suction pipe inlet.
4. A change in pipe diameter did not affect the velocity field.

A dimensionless parameter, \( Q/r^2 V \), where \( Q \) is the suction flow rate, \( r \) is the radial distance to the center of the suction inlet, and \( V \) is the velocity at any point, was developed to estimate the velocity field if the volumetric flow rate and radial distance from the suction inlet are known. The velocity field at the intake can be determined by plotting this dimensionless parameter for different values of \( x/h \) and \( r/H \), where \( x \) is the distance from the bottom, \( r \) is the radial distance, \( h \) is the distance from the suction pipe inlet to the sediment, and \( H \) is the water depth. This is important since it was found that the velocity field did not depend on the intake velocity or intake diameter if the volumetric flow rate remained constant. Thus, the inlet velocity field only depends on the flow rate through the suction pipe.

**Dredge Carriage Design and Modeling**

Glover (2002) conducted research on dredge carriage design and laboratory modeling of hydraulic dredges. Three sets of scaling laws were examined. One scaling parameter was based on sediment pick-up behavior, the second was based on similarity with respect to the Froude number, and the third was based on similarity with respect to cavitation during the cutting process. Since solid-fluid interaction is so complex in nature, it has been difficult to develop model-prototype similitude. Glover (2002) related quantities such as suction flow rate, swing speed, cutterhead RPM, bank height, and depth of cut to sediment production. Two different scaling relationships for the flow through the suction were used:

\[
(\frac{Q_{suction}}{\text{model}}) = (\frac{Q_{suction}}{\text{prototype}}) \left(\frac{D_{cutter}}{D_{cutter}}\right)_{\text{model}}^2 \left(\frac{V_{setting}}{V_{setting}}\right)_{\text{model}}
\]

(1)

\[
(\frac{Q_{suction}}{\text{model}}) = (\frac{Q_{suction}}{\text{prototype}}) \left(\frac{D_{cutter}}{D_{cutter}}\right)_{\text{model}}^2
\]

(2)

All three scaling laws (hydraulic, kinematic, and dynamic) cannot be achieved with one set of modeling parameters. Glover (2002) found theoretically that kinematic similarity exists for the velocity fields created by the suction inlet, cutterhead rotation, and swing speed. Further, there is a strong suggestion that for an accurate hydraulic model to exist, the model suction inlet must be scaled such that the sediment pick-up behavior is similar to that of the prototype. Thus, the ratio of the velocity field geometry to the cutterhead diameter must be the same for both the model and prototype, and the ratio of the velocity field magnitude to particle settling velocity must also be the same for both the model and prototype dredges.

**Computational Model of Flow Around a Freely Rotating Cutterhead**

Dekker et al. (2003) used numerical and experimental models to examine the complex flow inside a freely rotating cutterhead in order to better understand how the sediment and water mixture in an actual dredging environment behaves inside the cutterhead. A simplified model, considering only water, was used so the multiphase nature of the flow was not considered. An experiment and computational fluid dynamics (CFD) model were setup to investigate and compare the velocity and pressure fields inside and along the blades of the cutterhead. Two model parameters
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important for the characterization of the different flows used in these experiments were the flow number ($\theta$) and Reynolds number ($Re$).

\[ \theta = \frac{Q}{\Omega R^3} \quad \text{Re} = \frac{\Omega R^2}{v} \]  

(3)

A potential flow model was used because of its relative simplicity. In comparison with other flow models based on Reynolds-averaged Navier Stokes equations with empirical closure for turbulent stresses, the computation times are modest (Pope, 2000). Since the Reynolds number is large in almost all cases regarding dredging, the flow entering the cutterhead can be assumed to be irrotational with no large boundary layer separation (Dekker et al., 2003). The experimental study was performed at the Delft University of Technology. An aluminum cutterhead with an outer radius of 0.35 m was used; this is very similar to the cutterhead used at the Haynes Coastal Engineering Laboratory. The cutterhead blades are attached to a cutterhead ring and inside that ring the blades are also attached to a conical plate as seen in Figure 1 (Dekker et al., 2003).

Figure 1. Geometry of cutterhead used in experiments and the locations of measurement (Dekker et al., 2003).

In all of the tests, the flow was turbulent ($N_t = 2.6 \times 10^5 \text{ to } 14.8 \times 10^5$). The flow field was measured at 12 points inside of the cutterhead using acoustic Doppler velocimeters as shown in the geometry of cutterhead above (Figure 1). The ADVs were stationary and recorded the three velocity components at 25 Hz. The results showed a comparison between their measured and computed velocity vectors inside of the cutterhead. In both cases, the radial and circumferential velocities were nondimensionalized, the circumferential velocity by $\Omega R$ and the axial velocity by $Q/\text{A}_{pipe}$. The velocities were nondimensionalized so that the two models could be compared on both and a quantitative and qualitative level. The axial velocities were generally small, except for the points lying in front of the suction inlet. The CFD analysis showed the same behavior, however the magnitudes were approximately 50% of the experimentally collected velocities. As the flow is increased, it was shown that the suction flow has a direct impact on the velocities as indicated by the velocity vectors directed in the opposite direction of the rotation.

**EXPERIMENTAL SETUP AND DESIGN**

**Tow/Dredge Tank**

The Haynes Coastal Engineering Laboratory has a three-dimensional shallow water wave basin and a two-dimensional tow/dredge tank. A dredge carriage was designed, built, and installed in 2006 to facilitate experiments and testing of various dredging techniques. The tow-dredge tank is 45.7 m (149.90 ft) long, 3.05 m (10.01 ft) deep, and 3.70 m (12.10 ft) wide. In addition, a sediment pit is located near the west end of the tank that is 7.6 m (24.93 ft) long and 1.7 m (5.58 ft) deep. There are six observation windows, three located on the north side of the tank in the center and three in the sediment pit. Both the shallow water wave basin and tow/dredge tank are capable of having...
35,000 GPM (2.208 m³/s) of water current pumped through the tanks using four axial flow pumps. In the tow/dredge tank, the water enters the tank through a diffuser located at the west end of the tank.

**Dredge Carriage**

The B. G. Hindes dredge carriage was conceptually designed by Glover (2002), and Glover and Randall (2004) describe the finalized design. The dredge carriage was delivered to the Haynes Coastal Engineering Laboratory in April 2005. Construction and installation were completed by Oilfield Electric Marine Inc. (OEM) and Digital Automation Control Systems (DACS) in 2007. The dredge carriage consists of the ladder cradle, upper and lower ladder, articulating arm, and cutter head. Movement of the carriage is restricted to the east and west directions along two guide rails. Measuring devices that are included on the carriage are: a flow meter, a nuclear density gauge, a horizontal location laser, pressure, torque, and six force sensors. The flow meter and density gauge are used to accurately predict the production during dredging tests (Glover 2002). The dredge carriage is a 1:6 scale of a 0.609 m (2 ft) prototype cutter suction head dredge which means that the suction inlet is 0.102 m (0.33 ft) and discharge outlet is 0.076 m (0.25 ft).

**Experimental Setup**

The experiment and data collection took place in the sediment pit located in the tow/dredge tank. Since the ladder can only be raised a maximum of 0.91 m (3 ft) above the tow/dredge tank floor it was necessary to use the sediment pit so that the ladder would have a wider range of vertical motion, making it possible to collect more data points without any unintended boundary interference.

The cutterhead was initially placed at a 30° cutting angle. Cutting angles vary between 20° and 30° in most dredging scenarios. Three acoustic Doppler velocimeters (ADVs) were positioned 0.61 m (2 ft) away. The ADVs are high-resolution acoustic Doppler velocimeters that measure water velocity in three dimensions with an accuracy of 1% of the measured velocity (Nortek, 2009). Velocity measurements were taken at a sampling rate of 25 Hz and a sampling volume of 0.25 cm³ (0.015 in³). The setup is shown in Figure 2 and 3. The ADVs were positioned either vertically or horizontally. In this case, the ADVs were mounted facing horizontally inward towards the cutterhead. The ADVs were spaced three suction inlet diameters (3D) apart in the vertical direction.

**Figure 2. Side view of experimental setup.**
Data Collection Grid Design

Two collection grids were designed, and the diameter (D) of the suction inlet was used as the basis for the spacing between each data collection points. This is a customary length scale used in the design and analysis of various dredging parameters. In order to form a preliminary region of inflow, the equation for the conservation of mass was used. Based on the cross sectional area of the cutterhead intake, 0.008107 m² (0.0873 ft²), and a flow rate of 0.025 m³/s (400 GPM) the preliminary boundary had a diameter of 1.016 m (3.33 ft). This was determined under the conservative assumption that the velocity near the boundary of the region of inflow was 1% of the intake velocity. A grid of measurement points around the cutterhead was chosen based on the theoretical region of inflow. The grid design differed depending on whether or not the cutter was attached. When the cutterhead is attached, a 1x8x5 grid was used for the two planes nearest to the cutter and a 2x14x5 grid was used for the plane farthest away from the cutter. By increasing the fineness of the grid, a more detailed view of the region of inflow was available. For both designs, data were collected with the cutterhead attached and detached and at different flow rates. The flow rates that were tested were 0.0126, 0.0189, and 0.0227 m³/s (200, 300, and 360 GPM). For each flow rate, data were collected at all points in the measurement grid. The cutterhead was then attached and measurements were taken with the cutterhead being stationary.

Data Conversion

Once data was collected it was converted into a suitable format using commercial data conversion software. The output data formed individual velocity time series at each point of measurement. The velocity at each point was measured for 60 seconds at 25 Hz that corresponded to a total of 1500 individual points. The data were then filtered to remove spike noise caused by Doppler signal aliasing in turbulent flows as well as other factors (Voulgaris and Trowbridge, 1998). A number of different despiking algorithms have been developed to remove spike noise from ADV data. Goring and Nikora (2002) proposed an efficient three-dimensional phase space method that did not require any empirical coefficients. Wahl (2003) modified Goring and Nikora’s method by using true 3D phase space rather than a projection in 2D space and found that the algorithm identified more spikes. Goring and Nikora’s (2002) method for spike removal was chosen for use on the data collected. Mori, Suzuki, and Kakuno (2007) evaluated the use of the three-dimensional phase space method on ADV data in bubbly flows and developed a MATLAB software package that automates the despiking process. Figure 4 shows a comparison between the original data and despiked data at one measurement point. The results discussed after this point have all been despiked.
Figure 4. Comparison of original and despiked data using the method developed by Mori, Suzuki, and Kakuno (2007). (a) $u$-component of velocity, (b) $v$-component of velocity, and (c) $w$-component of velocity.

Finally, the global axis was transformed so that it was parallel to the cutterhead axis. As described earlier, the cutterhead was positioned at a $30^\circ$ angle with respect to the x-axis of the ADV’s coordinate system. Each velocity vector must be transformed from the coordinate system of the ADVs (x, y, and z) to the coordinate system of the cutterhead (x’, y’, and z’). This was accomplished with a simple coordinate transformation. Figure 5 shows the two coordinate systems transposed onto one another and the old velocity vectors alongside the transformed velocity vectors.

Figure 5. Velocity vector transformed from ADV axis to cutterhead axis.
RESULTS AND DISCUSSION

Flow Rate Effects

The primary goal is to determine the region of inflow that the suction from a cutterhead suction dredge pump has on the area surrounding it. The velocity into the suction inlet generally increases with increasing flow rate. This is true at the intake where the velocity is determined with the continuity equation (Equation 4). However, it is less obvious at points away from the suction inlet where more complex flow occurs or when there is cutterhead rotation.

\[ Q = VA \] (4)

The data show the relationship between the flow rate and the extent of the velocity field. It is expected that the velocity decreases as distance from the intake increases as well as decrease with decreasing flow rate. The different scenarios are grouped together by whether the cutterhead is attached or not. So, for each cutter rotational velocity it is simple to compare the difference in velocities between scenarios with the flow rate at 200 GPM (0.0126 m³/s), 300 GPM (0.0189 m³/s), and 360 GPM (0.0222 m³/s) rotating at 0 RPM as well as with no cutterhead attached. Error bars extend one sample standard deviation above and below the calculated maximum velocity.

Figure 6 and Figure 7 show that the maximum velocities decrease with decreasing flow rate. For each flow rate, the maximum velocity at a distance of 60 cm (1.97 ft) from the suction inlet is approximately 50% of the maximum velocity in the plane of the suction inlet (x = 0 cm). This behavior is present in both the scenario with no cutterhead attached and with a stationary cutterhead. Maximum velocities measured nearest the cutterhead with the stationary cutterhead were similar to those when no cutterhead was attached. In fact, the velocities are slightly greater at the lowest flow rate, 200 GPM (0.0126 m³/s), without the cutterhead attached, possibly due to the lack of obstruction. Herbich and Brahme (1986) also found that the presence of a stationary cutterhead did not affect the region of inflow of the velocity field. However, it is possible that maximum velocities are reduced without affecting overall extent of sediment pick-up.

![Figure 6. Maximum velocity at various x-planes for the no cutterhead attached scenario.](image-url)
In the two scenarios shown in Figures 8 and 9, the highest velocities caused by the suction occur very near the cutterhead. Since the decrease in velocity was so great, at least 50%, it is likely that the effects of the cutterhead rotation and suction decrease significantly at a distance greater than or equal to 30 cm (0.98 ft) in front of the cutterhead. It is difficult to determine from the data collected whether this is true at all points around the cutterhead or only directly in front of the suction intake.

Examining the planes that are perpendicular to the floor of the dredge tank and parallel to the south wall, the y-planes, adds a second dimension to the analysis of how the flow rate affects the maximum velocity. With and without the cutterhead attached the correlation between flow rate and maximum velocity was strong. Whether the cutterhead was attached or not, the maximum velocities peaked just to the right and left of the cutterhead. Figure 8 shows that the highest velocities with no cutterhead attached occurred to the right of the suction inlet. Since the suction inlet is symmetrical it is surprising that the measurements do not reflect this symmetry, that is, that the velocities on either side of the cutterhead should be approximately equal. In Figure 9 the maximum velocities peak approximately 44 cm (1.44 ft) to the left of the center of the suction intake and 44 cm (1.44 ft) to the right of the center of the suction intake. The cutterhead was 25.4 cm (0.83 ft) in diameter which means that the maximum velocities occurred 31 cm (1.02 ft) to the left and right of the cutterhead.

The analysis of the maximum velocities in each of the different z-planes was less helpful that the other two planes of measurement. For both scenarios there were much higher velocities at the upper and lowermost planes of measurement. This can be explained simply in the scenarios when the cutterhead is present. Since the cutterhead is 25 cm (0.82 ft) in diameter, measurements could not be taken directly in front of the suction inlet, so the nearest measurements were located approximately 30 cm (0.98 ft) away. The suction inlet is kidney bean shaped so velocities should be higher in the lower half of the cutterhead as well as below cutterhead.

**Figure 7. Maximum velocity at various x-planes for the cutterhead attached, 0 RPM scenario.**
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Cutterhead Effects

In many situations some type of agitation is required to loosen the sediment and allow for the suction to draw the sediment into the suction pipe inlet. Depending on the type of material being dredged, the dredge operator chooses the most efficient rotational speed of the cutterhead. The rotational speed must be great enough so that the sediment is taken inside the cutterhead and into the suction inlet. Below a certain cutterhead rotational speed the sediment particles will simply roll off of the cutterhead blades and very little of the sediment is removed.

The different scenarios with the cutterhead attached are grouped together by their flow rate. So, for each flow rate it is simple to compare the difference in velocities between scenarios with and without the cutterhead attached. At all three flow rates the same overall behavior was observed. Figure 10 shows that the highest velocities for the 0.0189
m³/s (300 GPM) scenarios occurred in the plane nearest the cutterhead; approximately twice that measured in the other two planes. This is the same behavior that was observed when analyzing the effects of flow rate on the velocities.

![Figure 10. Maximum velocity at various x-planes for the different 0.0189 m³/s (300 GPM) scenarios.](image)

Plots of the maximum velocity versus the various y-planes were useful in determining where the suction velocity was greatest with respect to the cutterhead. When no cutterhead was attached it was expected that the velocity would be greatest directly in front of the suction inlet and either decrease or stay approximately the same as the distance increased to the left or right of the inlet. It is unknown exactly how the addition of the cutterhead affects the behavior of the velocity field around the cutterhead. Examining the maximum velocity helps determine this behavior. There are many similarities between previous Figures 8 and 9 in the flow rate section and Figure 11 presented in this section.

In Figure 11, it is observed that the highest velocities occur to the right of the cutterhead due to the geometry of the cutterhead blades and the counterclockwise rotation. Ideally, the cutterhead blades would not affect the velocity field and velocities would be equal at all points around the cutterhead. However, the blades (when not rotating) partially block the flow from entering from the left side and therefore decrease the velocity. In this case, the velocities are greatest at approximately 44 cm (1.44 ft).
Region of Inflow

Three important aspects of cutter suction dredging process are:
1. The velocity field
2. The extent that sediment is picked up after suspension
3. Turbidity generation
The first two aspects are the subjects of this investigation since turbidity generation has been studied in depth in previous experiments. Up until this point the velocity field irrespective of sediment has been examined. The insights gained from the behavior of the velocity field play an important role on how much sediment is picked up. Since a cutterhead works by cutting the sediment and placing much of the sediment into suspension around the cutterhead, the velocities needed to take the sediment into the intake are relatively small when compared to the maximum velocity at the intake (Herbich and Brahme, 1986).

In order to pick up the suspended sediment, the vertical component, \( w \), of the velocity field created by the suction, rotating cutterhead, and swing speed needs to be greater than that of the vertical component of the particle settling velocity, \( w_s \), of the sediment. There are many methods for calculating the particle settling velocity, mostly empirical. One of the more commonly used equations in dredging was formulated by Schller (1992):

\[
v_t = 134.14(d_{50} - 0.039)^{0.72}
\]

where \( v_t \) is the settling velocity, \( d_{50} \) is the median grain diameter in mm. This equation is suitable for use with various sand particle sizes but becomes less accurate as the grain size increases. Usually dredged material consists of a variety of different sediments including silts, clays, and sands. For this analysis the only material that was used in the calculation of particle settling velocities was sand. The prototype settling velocity was then determined using equation (5).

The prototype \( d_{50} \) was then scaled down for use with the model dredge. Glover and Randall (2002) developed a variation of the scale laws determined by Slotta (1968) and Burger (1998) that took into account Herbich and Brahme’s (1986) dimensionless velocity field parameter.

\[
\begin{align*}
\frac{\omega_c D_c}{U_{suction}}_{\text{prototype}} &= \frac{\omega_c D_c}{U_{suction}}_{\text{model}} \\
\frac{N_c D_c}{V_{settling}}_{\text{prototype}} &= \frac{N_c D_c}{V_{settling}}_{\text{model}}
\end{align*}
\]

Using equation (7) along with known values of the prototype and model intake diameter, prototype and model cutterhead rotation speed, and prototype settling velocity the model settling velocity was calculated. Knowing the model particle settling velocities provided a range of velocities that could be compared to those gathered during experimentation. The process for determining the region of inflow is as follows: velocity values were plotted at each point for all scenarios, for each view (front, top, and side) a circle or ellipse was found that enclosed all velocities equal to or less than the maximum at each particle size, the regions were then combined into a three dimensional model that allowed for better visualization of the region of inflow. Finally, based on the skeleton provided by the region of inflow from each view, an ellipsoid was formed that corresponded to the three dimensional region of inflow. In each case the direction of the velocity was verified using quiver plots of the measured data. This ensured that the sediment was being drawn towards the cutterhead rather than being thrown out. The error was \( \sim 10-20 \) cm (0.33-0.66 ft) due to the spacing of the measurements. When determining the regions of inflow for fine sand, the velocities on either side of the cutterhead were much greater than those of the particle settling velocities, even at the boundary of measurement. This means that the region of inflow should actually extend further than shown in the results. However, velocities were not measured at distances greater than six suction inlet diameters from the cutterhead. Figure 13 shows the basic shape of the region of inflow. The three characteristic lengths are the major axis diameter, the minor axis diameter, and the outward radius.
Figure 13. Basic geometry of the region of inflow.

Figure 14 shows the volume of each region of inflow for each scenario based on three different grain sizes (fine, medium, and coarse). As the grain size increases, a greater flow rate is needed to pull the sediment into the intake. This is why not all scenarios are shown for coarse grain sizes. A number of observations can be made about the size of the region of inflow at each grain size. Fine sand was used first to determine the region of inflow. This is the smallest grain size used, so the regions of inflow are larger than those for the other grain sizes. In each scenario the region of inflow extended outside of the range of measurement. So the results shown are only a lower bound for the region of inflow. Measurements should be taken at points further away from the cutterhead to more accurately determine the outer boundary of the region of inflow.

Increasing the sediment to a medium grain size of 0.25-0.5 mm (0.0098-0.0197 in) did not decrease the number of scenarios that were able to pull sediment into the intake. There is a general increase in the size of the region of inflow with increasing flow rate. Herbich and Brahme (1986) found that velocity field scaling is solely dependent on the volumetric flow rate rather than the velocity at the suction intake, and these results also show that the flow rate has a significant impact on the region of inflow.

The outward radius extends ~50% less than the major and minor axes since the cutterhead rotation does not contribute as significantly to the velocity field directly in front of the cutter. In almost all cases for medium sand the major and minor axes were within 0.152 m (0.5 ft) of each other. There is very little change in the outward radius across all scenarios. A limit exists to the outward radius in both cases that is comparatively small compared to the area of inflow above, below, and to either side of the cutterhead. When the cutterhead was not attached to the suction intake the limit was ~0.61 m (2.0 ft) and with the cutterhead the limit was ~0.91-0.99 m (3.0-3.25 ft). That is an approximate 150% increase in the outward radius with the cutterhead attached. This is due to the stationary cutting blades directing more of the suction velocity to the area directly in front of the suction intake. Once the grain size was increased to coarse sand with median grain diameter of 0.5-1.0 mm (0.0197-0.0394 in) the number of scenarios that had a region of inflow significantly decreased. Only half of the scenarios were able to potentially pick up any coarse sand.
Dimensional Analysis

The model dredge was designed as a 1:6 scale to a full size dredge operating with a 61 cm (24 in.) suction diameter, 183 cm (72 in.) cutterhead diameter rotating at 40 RPM, a pump capable of pumping 1.89 m³/s (30,000 GPM) of slurry at a specific gravity of 1.3, a swing velocity of 50.8 cm/s (1.67 ft/s), and operating with sediment ranging from fine to coarse sand (Glover, 2002). In the design of the model dredge Glover used hydraulic scaling based on the sediment pick-up behavior, kinematic scaling based on the Froude number, and dynamic scaling based on the cutting forces. Since the model has been scaled in each of the three ways, it should pick up a geometrically similar volume of material to the full size dredge.

The region of inflow for the prototype dredge is of interest to dredging companies. In order to scale the geometry of the region of inflow the velocity field geometry and velocity field magnitudes must be scaled. This requires that the ratio of the velocity field geometry to the suction diameter for the prototype must equal to that of the model and that the ratio of the velocity field magnitudes to the settling velocity for the prototype must be equal to that of the model (Glover 2002).

\[
\begin{align*}
\frac{D_{ROI, prototype}}{D_{suction, prototype}} &= \frac{D_{ROI, model}}{D_{suction, model}} \\
\frac{U}{V_{settling, prototype}} &= \frac{U}{V_{settling, model}}
\end{align*}
\]

In the above equations \(D_{ROI}\) is the diameter of the region of inflow, \(D_{suction}\) is the diameter of the suction intake, \(U\) is the velocity at a point, and \(V_{settling}\) is the settling velocity of particle. Using equation (8) the geometry of the region of inflow can be directly calculated.

\[
D_{ROI, prototype} = \left( \frac{D_{suction, prototype}}{D_{suction, model}} \right) \cdot D_{ROI, model}
\]

So, with a 1:6 scale between model and prototype the region of inflow for the prototype dredge will be six times greater in the horizontal, vertical, and outward directions. Figure 15 shows the volume of the prototype region of inflow for various particle sizes.
Comparison to Herbich and Brahme (1986)

Herbich and Brahme (1986) conducted research around the complex flow surrounding a cutterhead during operation. Progress was made in the investigation of velocity flow fields, sediment resuspension around the cutterhead, and factors influencing turbidity near the cutterhead and how to reduce it. Hydraulic model studies helped to show that the dimensionless velocity field parameter, $Q/r^2V$, was valid and could be used to predict velocities around the cutterhead fairly accurately. Additionally, their measurement of velocities around a three dimensional cutterhead served as a basis for this paper. So, it is appropriate to draw comparisons between the results they obtained and those derived from the data collected in this study.

The 1986 experiments took place in a steel tank measuring 2.4 m (8 ft) long, 1.2 m (4 ft) wide, and 1.2 m (4 ft) deep. Two cutterheads were used with scales of 1:12.25 and 1:2.45. One difference in their setup was the orientation of the suction intake. It was positioned at 90° to the horizontal, whereas the ladder arm detailed in Experimental Setup section was at 30° below the horizontal. Herbich and Brahme (1986) also ran tests at 60° to the horizontal and determined that the angle of the suction intake did not have any significant effect on the flow field or velocities. Another difference in their experimental setup is the measurement technique used to record velocities at various points around the cutterhead. In 1986, acoustic Doppler velocimetry was not available so velocities were measured using a combination of a micropropellor turbulence and velocity flow meter, a hot-film anemometer, and color dyes. ADVs are considered to be more accurate than these methods and were used in this experiment.

In their investigation, velocity fields were determined for three different pipe diameters at three different heights above the bottom of the tank in contrast to varying the flow rate and cutterhead rotation speed. A description of the exact pipe diameters and heights was not included in their paper so replicating their results exactly is not possible. The dimensionless number, $Q/r^2V$, was used in conjunction with the velocity data to create a plot for different values of $x/h$ and $r/H$ where $r$ is the radial distance from the center of the pipe suction inlet, $x$ is the vertical distance from the tank bottom, $h$ is the distance from the tank bottom to the center of the suction inlet, and $H$ is depth of water in the tank. The velocity field parameter, $Q/r^2V$, was averaged over all the conditions in the experiment so that the results could be consolidated onto one plot. Once again this creates a problem when trying to compare data, however, orders of magnitude can be observed and used for comparison. Figure 16 shows the contours of $Q/r^2V$ from Herbich and Brahme’s (1986) results.
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Figure 16. Results from Herbich and Brahme (1986). The dimensionless velocity field parameter plotted for various values of $r/H$ and $x/h$.

Figures 17 and 18 show $Q/r^2V$ plotted for various values of $x/h$ and $r/H$ for the data collected for this paper. Each plot shows the average of $Q/r^2V$ for the three different flow rates at a different cutterhead rotation speed as well as with no cutterhead attached. The suction inlet and cutterhead are located at $r/H=0$ and $x/h=1$.

Figure 17. The average of $Q/r^2V$ for three different flow rates (200, 300, and 360 GPM) with no cutterhead attached plotted for various values of $r/H$ and $x/h$. 
Figure 18. The average of $Q/r^2V$ for three different flow rates (200, 300, and 360 GPM) with cutterhead rotation speed of 0 RPM plotted for various values of $r/H$ and $x/h$.

Herbich and Brahme (1986) results show that higher values of $Q/r^2V$ are observed near the suction intake. The dominant factor being that the velocity field parameter is inversely proportional to the radial distance from intake. Similarly, there is a clear increase in the velocity field parameter near the cutterhead in the three previous plots. The magnitudes are larger than those shown in the Herbich and Brahme (1986) study, at times almost 200% greater, but this is to be expected since the flow rate is much greater. The values shown in Figure 17 and 18 are very similar despite the addition of the cutterhead. This furtherthe idea that the velocity field is only dependent on the volumetric flow rate through the suction pipe. By using equation (11) the velocity fields used in the three previous plots can be scaled to the approximate flow rate and suction diameter used in Herbich and Brahme (1986) study.

$$\frac{Q}{D^2V}_{\text{prototype}} = \frac{Q}{D^2V}_{\text{model}} \quad (11)$$

This is similar to the scaling law that Glover (2002) used based on the dimensionless parameter developed by Herbich and Brahme (1986). Glover replaced the field velocity with the settling velocity of the sediment and the radial distance from the suction with suction intake diameter. Here, only the radial distance is replaced. Replacing the radial distance with the suction diameter ensures that there is geometric scaling of the flow field. Figure 19 and Figure 20 show the values of the dimensionless velocity field parameter in Figure 17 and Figure 18 scaled down to 0.0035 m$^3$/s (55 GPM) and a suction diameter of 0.0279 m (1.1 in). The values are smaller and very similar to those in Figure 16. The discrepancy between the values is likely caused by the use of averaged values for $Q/r^2V$. 
CONCLUSIONS

By using the results presented in this paper, dredge operators, dredging engineers, and researchers will have a better understanding of the behavior of the flow field around a cutterhead as well as the region of inflow. The suction flow rate, cutterhead rotation speed, and swing speed each caused increases in the magnitude of the velocity around the suction inlet.

Analysis of the suction flow rate helped visualize how the flow affected the region of inflow around the cutterhead. It was found that the maximum velocities are directly proportional to the flow rate. These maximum velocities caused by the suction occur very near the cutterhead. At a distance of 60 cm (1.97 ft), or 5.9 suction inlet diameters,
in front of the cutterhead tip, the maximum velocities were approximately half that of those in the nearest plane to the cutterhead. At lower flow rates the addition of a stationary cutterhead did not affect the velocities. This behavior was also observed by Herbich and Brahme (1986). As the distance increased from the cutterhead tip to the plane of measurement there was a decrease in correlation between the flow rate and maximum velocity.

The most important aspect of this investigation pertained to the determination of the region of inflow around the cutterhead. It was found that the region of inflow was nearly symmetrical around the cutterhead, but the shape could more accurately be described as an ellipsoid. The volumes of the regions of inflow ranged from 0.85 m³ (30 ft³) to 1.84 m³ (65 ft³) for the model dredge and from 63.70 m³ (6,500 ft³) to 363.6 m³ (13,900 ft³) for the prototype dredge. The region of inflow when picking up fine sand was the largest. There was a 20% reduction in the major and minor axes of the region and 33% reduction in the outward radius when the grain size was increased to medium sand. Finally, as the grain size was increased further to a coarse sand the volumes of the regions of inflow decreased by approximately 50%.

Herbich and Brahme (1986) showed that the velocity field is only dependent on the volumetric flow rate through the suction pipe. Scaling the suction pipe diameter and flow rate down to those used by Herbich and Brahme (1986) yielded similar values of Q/r²V.

The flow around a cutterhead is complex and more detailed analysis is needed in the future. The addition of each different operating parameter, suction flow, cutterhead rotation, and swing speed, increases this complexity. A greater extent of measurements needs to be taken in order to determine the true region of inflow for all flow rates, cutterhead rotation speeds, and swing speeds. The theoretical region of inflow used to determine the extent of the measurements for this paper was too small and should be increased. Similarly, a higher resolution of data points should be collected. This would help determine more accurate dimensions for the region of inflow as well as make it simpler to use visualization software that require many points of measurement.

The addition of sediment into each scenario would better simulate real world dredging conditions and possibly validate any velocity measurements. Expanding the methods of velocity gathering could help achieve this. Using PIV (particle image velocimetry) and high-speed cameras might provide a more accurate model of the region of inflow.

REFERENCES


Glover, G.J. (2002). “Laboratory modeling of hydraulic dredges and design of dredge carriage for laboratory facility.” Master’s Thesis, Ocean Engineering Program, Zachry Department of Civil Engineering, Texas A&M University, College Station, TX.


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CITATION