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LABORATORY MEASUREMENT OF CUTTER SUCTION DREDGED SEDIMENT VOLUME

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ABSTRACT

The laboratory dredge carriage and dredge/tow tank located in the Haynes Coastal Engineering Laboratory at Texas A&M University is used to measure the dredged sediment volume after cutter suction dredging. The 101.6 mm (4 inch) suction by 76.2 mm (3 inch) discharge centrifugal dredge pump is used to pump the sand/water slurry. The ladder supports the suction pipe and cutter drive shaft. A 16 cubic meter (21 cubic yard) hopper barge is used to contain the sediments dredged. A laser measurement system is used to measure the before and after bathymetry of the sediment in the dredging area. During the summer of 2007 and 2008 the laboratory dredge carriage was used to dredge sand (d_{50} = 0.27 mm) in the sediment pit that is 7.6 m (25 ft) long, 3.7 m (12 ft) wide and 1.5 m (5 ft) deep. The hopper is instrumented with pressure gauges to measure the draft of the hopper. The development of the method for evaluating the dredged sediment volume is described for placing the dredge slurry into the hopper and for placing the slurry into an isolated location in the tank that is similar to a confined placement area. The results demonstrate the ability to measure sediment volume using an instrumented hopper barge, nuclear density gauge and flow meter, and laser profiling system.

INTRODUCTION

Over the years, many attempts to measure the volume of sediment dredged have taken place. Armstrong and Grant (1977) designed a float that can be used to measure the sediment in a hopper to determine the pay load of a trailer suction dredge. This measurement device is mechanical and gives a continuous record of the dredged sediments in the hopper, for the relative density for which it is set. Fortino (1966) describes pneumatic and electrical methods to measure the flow of the dredged materials from the pump. This method can be used as a method to measure the sediments in the hopper. Rokosch, Van Vechgel and Van der Veen (1986) investigated the measurement of the optimum load for mixed loads. Mixed load is a combination of settled and suspended materials. Displacement and pressure based measurements were used and it was found that total load and suspended material in a mixed load can be separately determined. A different approach was used by Meyer et al (1986) to measure the sediments in the hopper and they stated that dredge displacement is insufficient to measure optimum load for fine sediments as it fails to determine distribution of load from fore to aft of the hopper. Henriksen and Randall (2007) concluded that the

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data collected from the Dredge/Tow Carriage at the Haynes Coastal Engineering Lab will be beneficial for understand the resuspension of sediment created during cutter head dredging operations. Measuring production of model dredge was one of the possibilities for future studies using the Dredge / Tow Carriage.

The objective of this paper is to describe the measurement of the amount of dredged material that is excavated by the model cutter suction dredge and the amount of material not captured by the dredge system using a confined placement area in the dredge/tow tank, a model hopper and a Laser profiler. The design and instrumentation of a model hopper barge for the measurement of the volume of sediments dredged is described.

MEASUREMENT PROCEDURES

The quantification of the amount of material removed by dredging is difficult to measure. The resuspension of sediment is the material that is found in the water column as a result of the cutter excavating the bottom sediment, and residual is the amount of sediment that is not captured by the suction at the dredge pump inlet during dredging. In these experiments, the amount of bottom sediment that is removed by dredging is quantified using a containment location in the tank and a hopper barge. A laser system is used to measure the volume of sediment removed from the sediment pit. The water in the dredge/tow flume is stationary, but water flow is available at a maximum rate of 35,000 GPM for future studies.

The Haynes Coastal Engineering Laboratory has a facility wherein a model cutter suction dredge is used to simulate the dredging operation using a real time cutter suction dredge. The model cutter suction dredge as shown in Figure 1 is supported by a carriage that runs on the rails of a 45.72 m (150 ft) long, 3.657 (12 ft) wide, and 3.353 m (11 ft) deep dredge/tow flume. Testing different drag heads, suction heads, cutter heads and hopper disposal can be efficiently conducted in the flume. It also has an additional 7.62 m (25 ft) long by 1.524 m (5 ft) deep sediment pit. The 0.3 m (12 in) cutter is mounted on an articulating ladder that is attached to a vertical ladder that transverses the sediment pit. The articulating ladder allows for a ladder angle of 0 to 50 degrees with the horizontal. A model hopper is available to receive the sediment/water slurry from the dredge equipment. The model hopper is attached to the carriage by means of a square bar, such that the hopper floats in the dredge/tow tank. The draft for the hopper is calculated using calibrated pressure transducers, and these measurements are used to determine the weight of the slurry in the hopper.

Figure 1. Carriage on the tow tank in the Haynes Coastal Engineering Laboratory at Texas A&M University.

LASER PROFILE SYSTEM

In order to quantify the amount of sediment removed from the sediment pit during dredging or the amount placed in a confined disposal unit after dredging a laser profiling system is used. The laser is mounted on an aluminum frame and is programmed to translate and record data over a rectangular region of 5.0 m x 2.5 m (16.25 ft x 8.2 ft). The laser is optically safe and can be used in the laboratory without additional safety precautions. The laser can measure a distance of 200 to 1000 mm with a resolution of 0.02- 0.5 mm resolution and an error of +/-2 mm. Photographs of the laser as well as the laser on the mounting system are shown in Figure 2.

Figure 2. Profile laser (left) and the laser mounting system (right).

The laser system is used to measure the material in the confined disposal area in the tank and the volume of dredged material removed from the sediment pit. An initial profile of the smooth sediment profile in the sediment pit is measured before dredging begins as shown in Figure 3.

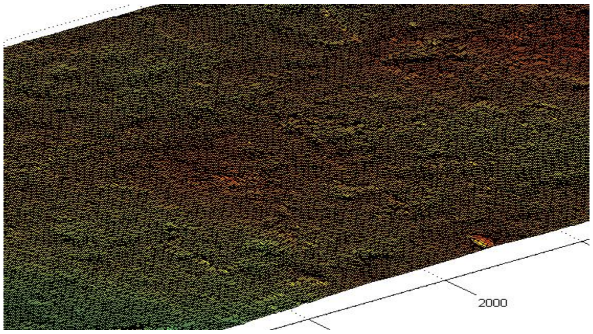

Figure 3. Initial profile of the sediment pit prior to dredging.

The cutter suction dredge performed six cuts along the sediment pit. Each cut was one meter away from the next. Cutter speed was 80 rpm while the flow rate was 568 liters/min (150 GPM). The sediment was pumped from the sediment pit to a confined disposal area (Figure 4) so that the amount of sediment removed could be quantified.

Figure 4. Picture of the confined placement area (CPA) dredging area in the tank.

Once dredging was finished the water is drained and the laser system is used to quantify how much sediment is in the confined disposal area. A laser profile is also taken of the sediment pit after the dredging occurred. The repeatability of the experiment is investigated by conducting the experiment twice.

Dredged Volume Measurements Using Confined Placement Area in Dredge/Tow Tank

Pictures of the sediment output from dredging to the confined placement area (CPA) after dredging as well as the sediment pit after dredging is illustrated in Figure 5. The discharge pipe shown in Figure 5 is mounted as shown to prevent the sediment from traveling out of the sediment pit.

Figure 5. Sediment discharge into the confined placement facility (CPF) (left) and sediment pit and model dredge carriage after dredging (right).

The laser profile system produced very accurate plots of the sediment dredged and discharged. In order to plot the laser pictures, a program was written in Matlab. This program enters the file created by the laser and removes any strange singularities by smoothing the profile. It then plots the profile and performs an integration to determine how much sediment has either been deposited or removed. An image of the sediment placed in the confined disposal area is shown in Figure 6.

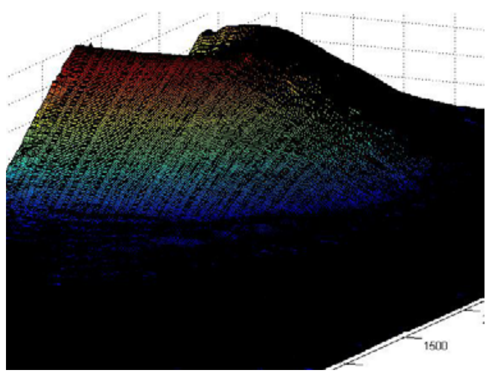

Figure 6. Laser profile of sediment output in confined placement area.

The laser profile system also produced images of the cuts made by the model dredge carriage, and Figure 7 shows a zoomed-in picture of two of the cuts. The Matlab program is also structured to produce transects of the profile. A transect of the sediment pit is illustrated in Figure 8 that displays five dredging cuts.

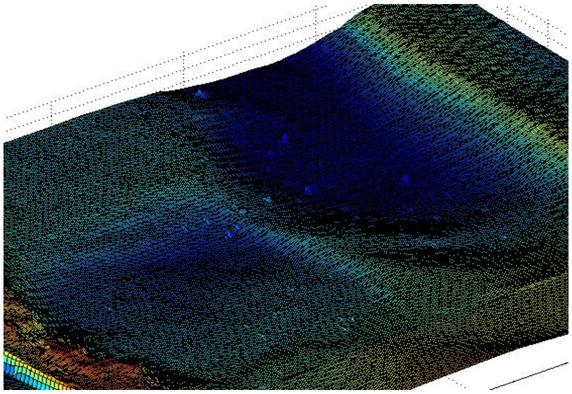

Figure 7. Two dredging cuts are shown using the laser profile system.

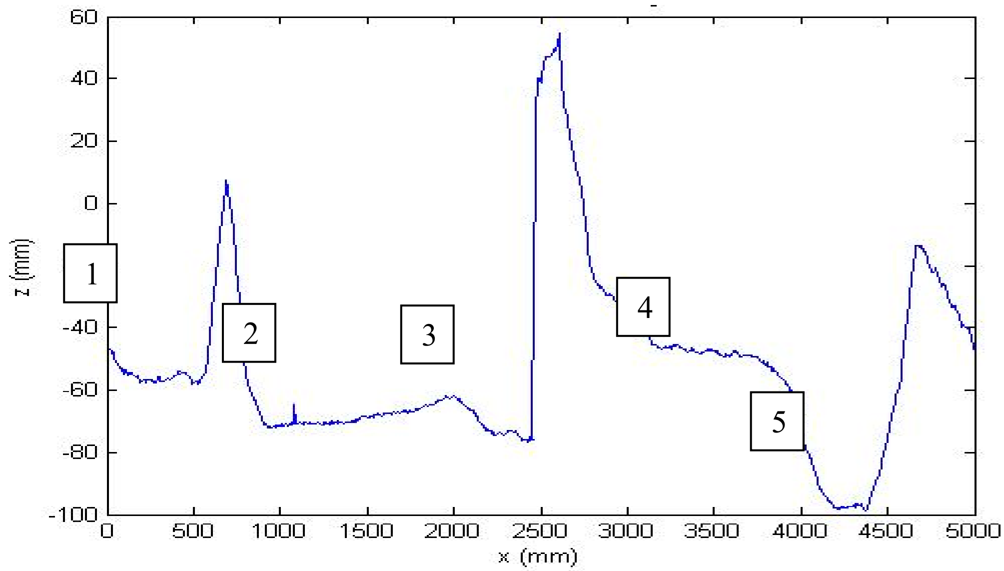

Figure 8. Transect of the laser data showing five dredge cuts.

Table 1 shows the results of the dredging test conducted in the Haynes Coastal Engineering Laboratory. It is important to note that this result may have been slightly affected by the settling of the laser measurement system when it was placed in the sediment pit, and modifications to the testing procedure were required as described next.

Table 1. Resuspended dredged material loss estimation of the dredging test.

Test [30.5 cm (12 in) cut, 568 LPM (150 GPM), 6 Cuts)
0.761cubic meters removed from pit
0.686 cubic meters deposited in CPA
9.10% difference

LASER PROFILER IN CONSTANT HEIGHT SUPPORT FRAME

Due to the settlement problem of initial laser profiler measurements, the laser profiler was mounted on a constant height aluminum frame (Figure 9) to measure the sediments removed during the dredging process. The laser can translate in the longitudinal (x) and lateral (y) horizontal directions, as it takes the depth readings. The laser can measure a distance (depth, z) of 200 to 1000 mm with a resolution of 0.02- 0.5 mm resolution and an error of +/-2 mm. The laser in this case is programmed to take depth readings at every 5 mm and 20 mm x and y increments respectively and the maximum reach of the laser is an area of 5000 mm X 2500 mm. The laser is used for quantifying the sediments dredged using the model cutter suction dredge by measuring the difference in the before and after dredging bathymetry of the sediment pit, thus the volume of sediments removed.

Figure 9. The laser set on a frame ready to take measurements.

HOPPER DESCRIPTION AND INSTRUMENTATION

A model hopper barge is constructed with a 0.238 cm (3/32inch) thick steel plate. The outer dimensions of the hopper are 609.6 x 335.3 x 172.7 cm (240 x 132 x 68 inches) while the internal volume is 15.9 cubic meters (20.8 cubic yards). The hopper rests on four jacks (Figure 10) inside the dredge/tow tank when the tank is not filled with water.

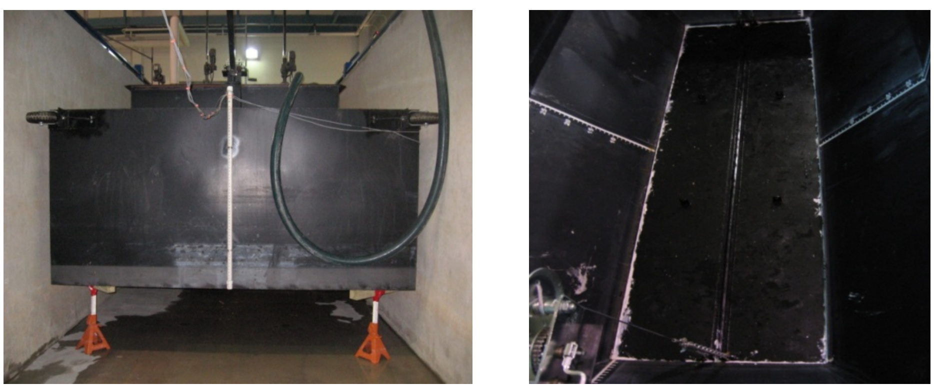

Figure 10. Hopper resting on the jacks in the tow tank, also seen is the PVC pipe that cases a pressure sensor (left) and hopper doors closed and caulked before the dredging operation and a scale is shown that is used to measure the volume in the hopper (right).

The hopper has two winches mounted on the top of the barge with cable and chain attached to the doors at the bow and stern those are used for the opening and closing of the hopper doors. Rubber tires (Figure 10) are attached on all four sides of the hopper that act as fenders to prevent the hopper from hitting the walls of the tank. When the hopper floats on water, the doors do not open completely due to the buoyancy force of the water acting on the doors and lead blocks are attached to the doors to overcome this problem.

Pressure sensors are housed in water tight PVC pipes and are attached on all four sides of the hopper. The pressure sensors are used to measure the amount of slurry collected in the hopper during dredging. A data acquisition system (DAS) captures pressure variation every second and converts it into an electrical signal. Measuring tapes attached to the PVC pipes also help in knowing the draft of the hopper when empty and full. The draft of the empty hopper is

17.8 cm (7 in), and thus the weight of the hopper is calculated to be 2910 kg (6416 lb). A linear scale is drawn in the internal volume so as to give a fair idea of the height of the slurry in the hopper. This helps in calculating the volume of sand in the hopper. Before the dredge/tow tank is filled with water, the hopper doors are completely closed and caulked. The hopper is attached to the carriage by a 3.05 m (10 ft) long rod and moves in the same direction as the carriage maintaining a constant gap between the carriage and the hopper. Once the dredging operation starts, the slurry is pumped into the hopper. A provision for overflow is provided to drain the excessive water. After dredging is completed, the carriage and the hopper are moved to the extreme end of the tow tank away from the pit where the hopper doors are opened to release the sediment from the hopper. Throughout the dredging operation, the pressure sensors are continuously recorded and analyzed to get the weight of the sediments in the hopper.

Two Way Valve

A valve, on the carriage, that was used to pump the dredged sediments was replaced by the two way valve (Figure 11). Hoses are attached to the two-way valve, and one hose is directed back to the tow tank (valve 1) while the other is directed to the hopper (valve 2). The pump is primed with the valve 2 closed and valve 2 open. When the dredging operation begins valve 2 is opened and valve 2 is shut simultaneously. This is done when the density of the dredged sediments increases as the cutter starts to cut into the sediments.

Figure 11. The two way valve on the carriage.

PRESSURE SENSOR CALIBRATION

The four sensors are attached using clamps at the center of all four sides of the hopper, Figure 12 shows one of the pressure sensor tubes attach to the hopper barge and pressure sensor extend from the bottom of the tube. The tubes were sealed which permitted the use of non submersible pressure sensors. As the hopper is filled during the dredging operation, the water pressure on the sensors increases or decreases as the weight on the floating hopper increases or decreases respectively. Data from each pressure sensor is identified; and the readings are continuously recorded, using the data acquisition system (DAS) every second as the hopper is filled. This data are compared to the calibrated data to determine the draft of the hopper and the weight of the slurry in the hopper.

Prior to testing, each of these pressure sensors is calibrated at different depths of water. The PVC pipes were held together and lowered when the probes just touched the water surface, and the data for the depth zero inches is recorded for a period of 30 s. Similar readings were recorded at depths of 5.1 cm, 10.2 cm and so on up to 96.5 cm (2 in, 4 in and so on up to 38 in). The pressure sensor records one signal every second thus approximately 30 readings for each depth were obtained. The calibration curves show the sensors are linear, and an example calibration curve is illustrated in Figure 13.

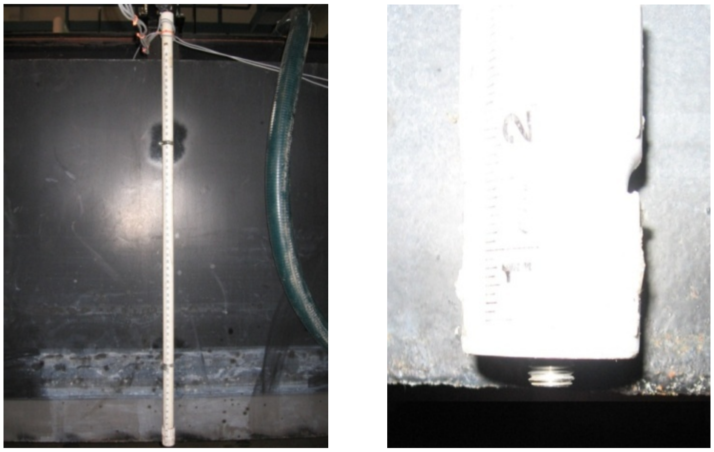

Figure 12. Example pressure sensor PVC tube (left) and pressure sensor at bottom of tube (right).

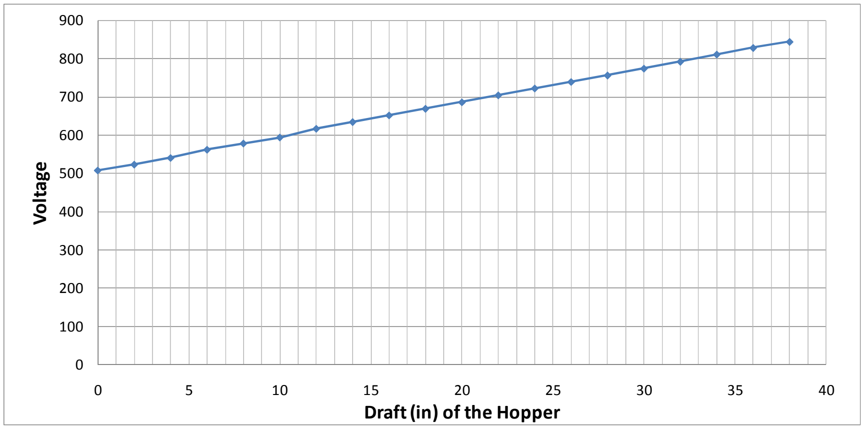

Figure 13. Pressure calibration curve for sensor 1 (Multiply inches by 2.52 to obtain centimeters).

MEASUREMENT OF DREDGED VOLUME IN MODEL HOPPER BARGE

The sand removed during dredging is determined using draft measurements outside the hopper barge and a height measurement inside the hopper to determine the volume of sand and water inside the hopper. The calibrated pressure gauges provide measurements corresponding to the variations in the load. The average hopper draft (h) is calculated by averaging the values from the four pressure gauges. The amount of sand and water inside the hopper is determined from the internal height (I_m) measured vertically inside hopper as illustrated in Figure 14.

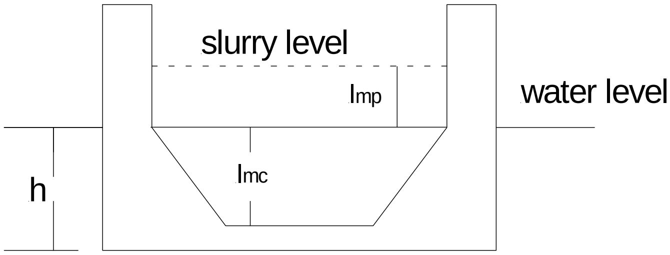

Figure 14. Schematic of model hopper.

The total weight of the hopper (W_t) is

$$W_t = W_e + W_i \tag{1}$$

where W_e is the weight calculated from the pressure gauge reading when the hopper is empty and W_i is the weight of the slurry in the hopper. The total weight of the hopper is also the displaced volume of the hopper multiplied by the specific weight of the water in the dredge/tow tank

$$W_t = \gamma_w V_d \tag{2}$$

where V_d is the displaced volume of the hopper and γ_w is the specific weight of water. The draft of the hopper (h) and the weight per unit draft (m_l) of the hopper displacement are defined by

$$\frac{h}{m_l} = \gamma_w V_d \tag{3}$$

The relationship between the draft (h) and the hopper total weight is illustrated in Figure 15 and m_l is the slope of the line.

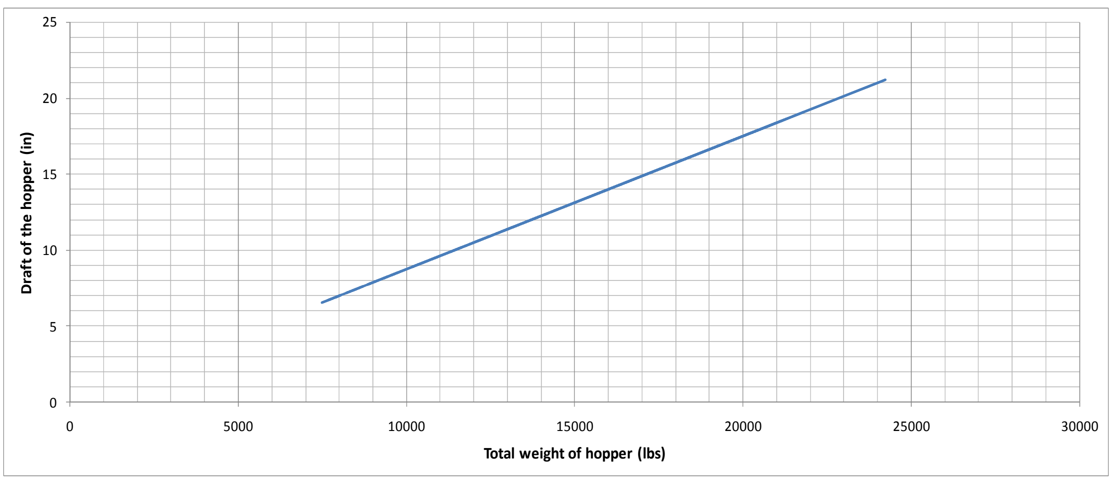

Figure 15. Graph showing the increase in weight of the hopper as draft (h) changes.

The total weight of the hopper and dredged slurry is

$$W_t = W_e + W_i = \frac{h}{m_l} \tag{4}$$

The volume of the slurry inside the hopper is the sum of the volume of sand (V_s) and water (V_w), and it is determined by the height of the slurry in the hopper. Based on the geometry of the hopper, the volume of the hopper can be divided into two parts, a cuboid (V_c) and a frustum of a pyramid (V_p). I_{mp} is the height of the frustum of a pyramid while I_{mc} is the height of the slurry in the cuboid.

$$V_s + V_w = V_c + V_p = I_{mp} m_p + I_{mc} m_c \tag{5}$$

The volume V_p and V_c are plotted against the respective heights, I_{mp} and I_{mc} and the slopes m_p and m_c are determined.

Figure 16. Graph showing the change in volume of the hopper as I_m changes.

The volume of sand (V_s) in the hopper is determined using

$$V_s = \frac{\frac{h}{\gamma_w m_1} - \frac{W_e}{\gamma_w} - m_p I_{mp} - m_c I_{mc}}{SG - 1} \tag{6}$$

where SG is the specific gravity of the sand. An example calculation of the sand volume using one of the pressure sensors (sensor #1) is tabulated in Table 2. Similarly the volume of sand for sensor #4 was found to be 0.126 m^3 (0.165 yd^3). There were four pressure sensors mounted on the hopper barge with # 1 and #2 at the bow and stern respectively and #2 and #3 centered port and starboard. Pressure sensor #3 malfunctioned during the tests so only the sensors #1 and #4 (bow and stern) were used, and the average of the two volumes results in average volume of 0.196 m^3 (0.256 yd^3).

Table 2. Example calculation of dredged sand volume for pressure sensor #1.

W_t (lb)	**h(in)**	**m_1(ft/lb)**	**I_{mc}(in)**	**I_{mp}(in)**	**V_p(ft^3)**	**V_c(ft^3)**	**m_c(ft^3/ft)**	**m_p(ft^3/ft)**	**V_s(yd^3)**
21510.1	18.8	7.29E-05	29	(44-29) = 15	60.47	140	23.24	112	0.347
W_t (kg)	**h(m)**	**m_1(m/kg)**	**I_{mc}(m)**	**I_{mp}(m)**	**V_p(m^3)**	**V_c(m^3)**	**m_c(m^3/m)**	**m_p(m^3/m)**	**V_s(m^3)**
9756.83	0.478	4.89E-5	0.737	0.381	1.712	3.96	2.159	10.41	0.265

Production Calculating Using Flow meter and Density Gauge

The flow meter on the carriage is also used to determine the volume of sediments pumped into the hopper. The flow meter records the flow in GPM of the sediments while the density gauge measures the specific gravity of the slurry every second as it is pumped into the hopper. The production (cubic meters/hr or cubic yards/hr) is calculated using

$$P = C_v Q \tag{7}$$

where C_v is the concentration by volume and Q is the flowrate. The concentration by volume is

$$C_v = \frac{SG_s - 1}{SG_{solids} - 1} \tag{8}$$

where SG_s is the measured slurry specific gravity being pumped by the model dredge and SG_{solids} is the specific gravity of the insitu sand. This is used to calculate the instantaneous production of sand and the instantaneous production is integrated over time to give the total production of insitu sand. An example of this calculation is illustrated in Figure 17 where the flowrate (red line) and specific gravity (blue line) are used in equations 7 and 8 to calculate the instantaneous production for the slurry (green line) and sand (purple line). The instantaneous production shown in the graph was integrated to get total production of sand using a specific gravity of 1.65 that resulted in a total insitu production of 0.196 m^3 (0.256 yd^3).

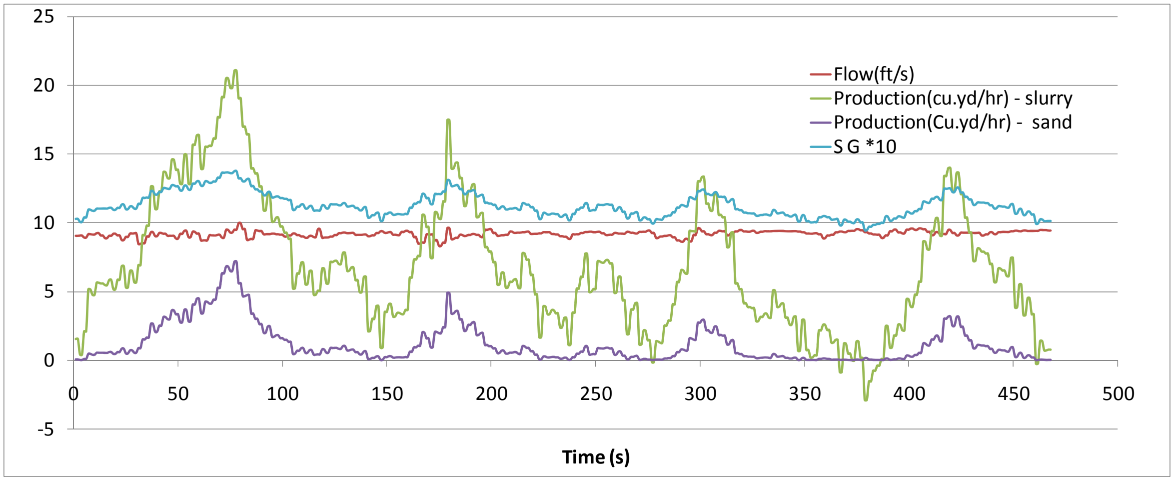

Figure 17. Example production plots while discharging slurry into hopper barge during dredging with model cutter suction dredge.

Table 3. Production of sand during testing for different values of insitu specific gravity.

Values of SG_s	2.1	2.0	1.9	1.85	1.8	1.7	1.6
Volume of sand removed.	0.150	0.165	0.183	0.194	0.206	0.236	0.275

CONCLUSIONS AND RECOMMENDATIONS

The measurement of the resuspended dredged material lost or not picked up by dredge suction is the major interest of the study. To improve the measurements, it is recommended that a 10.2 cm (4 in) or 20.4 cm (8 inch) depth of cut be used. The articulating ladder of the dredge carriage tends to bulldoze the sediment pit when a 30.5 cm (12 in) cut is used. Steeper ladder angles and shallower cuts are recommended to eliminate this problem. The laser system measured the amount of dredged material in the confined placement area. The laser mounting system was simply repeatedly placed on blocks in the confined placement area (CPA). However, this was not as simple in the sediment pit. Once the sand has been cut, it becomes more fluidized and cannot withstand the weight of the laser mounting system. A constant height laser profiler system that is hung from the top of the dredge/tow tank is recommended. It is recommended that an acoustic sediment profiler be investigated for profiling the sediment pit to eliminate the need to drain the water from the tank that is required to use the laser profiler system.

The results of the laser profile measurements in indicated that 9.1 % of the material dredged by the laboratory cutter suction dredge was not picked up by the dredge and settled back into the sediment pit location. No current was present in the experiments. Settlement problems with the laser measurement system created uncertainty in measuring the sediment volume remove, and consequently a new support frame was design to have the laser head remain a constant height above the sediment pit.

The values of the volume of sand dredged measured from the hopper instrumentation are in close agreement with the values from the density gauge. However, the in situ SG of the dredged material would give a closer insight on the actual amount of volume dredged. The reading of height up to which the slurry is filled in the hopper oscillates due to the sloshing action in the hopper. It is recommended that more accurate methods of measuring of the internal height such as a water level or acoustic gauge.

The process of switching the two way valves, starting to record the data from the pressure gauges, and the initiating the carriage to dredge is a simultaneous process and involves different individuals. Automating these activities from a single point is recommended.

The laser profiler can be run on the sediment pit to measure the volume sediments removed from the pit. The hopper can be used to collect the dredged sediment. Placing the dredged volume on dredge/tow tank floor and running the laser on the sediments would also help in measuring the amount of sediments dredged. Measuring the insitu sediment specific gravity in sediment pit before dredging is needed.

ACKNOWLEDGEMENTS

The authors acknowledge the partial support for the research reported in this paper through Dr. Joe Gailani of the US Army Engineer Research and Development Center.

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