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AIMS & SCOPE OF THE JOURNAL

The *Journal of Dredging* is published by the Western Dredging Association (WEDA) to provide dissemination of technical and project information on dredging engineering topics. The peer-reviewed papers in this practice-oriented journal will present engineering solutions to dredging and placement problems, which are not normally available from traditional journals. Topics of interest include, but are not limited to, dredging techniques, hydrographic surveys, dredge automation, dredge safety, instrumentation, design aspects of dredging projects, dredged material placement, environmental and beneficial uses, contaminated sediments, litigation, economic aspects and case studies.

CUTTER SUCTION DREDGE SIMULATOR

R. E. Randall[1], P. S. deJong[2], and J. C. Henriksen[3]

ABSTRACT

The cutter suction dredge is the most commonly used dredging equipment for dredging navigable waterways. Production engineers usually estimate the production of dredges, and the dredge operator (leverman) operates the dredge. In order to improve the performance and education of the production engineer and the leverman, cutter suction dredge simulators are available for training of these dredging personnel and others involved with operation of a dredging company. Seven dredge simulator short courses have been conduct since 1999 and the experiences gained from these courses indicate the courses are valuable training tools. The simulators consist of dredging controls and instrumentation interfaced with a personal computer. Software has been developed that accurately simulates the dredge movement, the cutting of the sediments, and the hydraulic transport of dredged sediment. Results of the dredging simulation exercise are recorded and used to critique the operator in order to demonstrate dredging fundamentals such as effects of cavitation, critical velocity, winch power, pump power, effect of different sediments, pipeline and pump configuration, and maneuvering of the dredge.

Keywords: Dredge simulator, dredge training, cutter suction dredge, hydraulic dredge training experience.

INTRODUCTION

The hydraulic cutter suction dredge (Figure 1) size is commonly defined by the diameter of the discharge line and range in size from 0.15 to 1.22 m (6 to 48 in). A common size for a cutter suction dredge is 0.61 m (24 in). Small cutter suction dredges are considered to range from 0.15 to 0.30 m (6 to 12 in). The cutter suction dredge consists of a large barge shape vessel that normally doesn't have propulsion equipment and is mobilized to the job site by other vessels.

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Spud Carriage

Figure 1. Cutter Suction Dredge Texas (Courtesy of Great Lakes Dredge & Dock).

There are several large self-propelled cutter suction dredges that pick up the spuds and have their own propulsion to move to the next location such as the J.F.J. De Nul shown in Figure 2. Cutter suction dredges have centrifugal pumps on board that are used to pump slurry (mixture of solids and water) to a placement location. The dredge has a ladder that supports the cutter, cutter drive unit, and the suction line leading to the suction side of the dredge pump. At the end of the suction line and cutter drive shaft is the cutterhead that is used to loosen and cut sediment that must be removed from the bottom of the waterway. The cutter may have special teeth for excavating the bottom. The excavated material is mixed with the surrounding water and drawn up the suction pipeline due to the low pressure created by the pump. The dredged material may consist of clay, silts, sands and gravel, and the slurry may be as much as 20% sediments by volume and the other 80% is the ambient fluid. In some cases, an additional submerged pump (ladder pump) is located on the ladder when dredging depth is deep (greater than 9.1 m or 30 ft) in order improve production due to cavitation limitations.

Figure 2. J.F.J. De Nul Self-Propelled Cutter Suction Dredge (Courtesy of Jan De Nul).

On the discharge side of the main dredge pump, a long pipeline is used to transport the slurry to the placement location that is typically a confined disposal site. The length of the pipeline may be as long as several miles. The power available and head developed by the pump or pumps must be enough to overcome the hydraulic losses occurring in the total pump and pipeline system. Additionally, the velocity in the pipeline on the suction and discharge side must be above the critical velocity required to suspend the sediments in the carrier fluid. This critical velocity depends primarily on sediment grain size, sediment specific gravity, and pipeline diameter. Additional pumps (called booster pumps) are sometimes needed to transport the dredged material through very long pipelines.

The dredged material lay on the bottom of the waterway, and therefore, the dredge must move along the waterway (channel) to excavate the sediments. The dredge typically uses spuds, winches and anchors to move ahead in the waterway. Spuds are large vertical cylinders that are located at the stern of the dredge. Cutter suction dredges use two spuds arranged at a specified separation distance at the stern or with one at the stern and one in a moveable carriage arrangement. Advancing the dredge is accomplished by alternately raising and lowering the two spuds at the appropriate positions, and consequently the dredge walks up the channel or is advanced using the spud carriage.

Winches and wires on the port and starboard side of the dredge are used to swing the dredge back and forth across the channel bottom to bring the cutter in contact with the sediment that is to be removed. The swinging of the dredge is about the one spud that is in the sediment. The two spud walking dredge arrangement has a maximum production efficiency of approximately 50%, which means the dredge is removing sediment only half of the time. Dredges with the spud carriage arrangement are more efficient and usually can be removing sediment 75% of the time. The winches must have enough power to move the cutter across the channel, and the wires must be strong enough to prevent breaking and costly downtime for the dredge. The winch wires are normally attached to anchors placed in the channel, and these anchors must be moved as the dredge moves up the channel.

The operation of a cutter suction dredge just described is complicated and requires skilled dredge operators. These skilled operators (levermen) are essential for a successful and profitable dredging operation. In many cases, these skills are attained through on the job training and over many years under the tutelage of an experienced operator. The operator is assisted by crew who must move anchors, operate engines and pumps, and monitor pipelines. The dredging projects cost millions of dollars, and the cutter suction dredge capital costs are in the millions of dollars. Consequently, it is prudent for dredging companies to invest in training their operators so that they have the best understanding of the hydraulic transport and dredge maneuvering principles.

Digital Automation and Control Systems (DACS 1994) and (Cox et al. 1995) developed dredging simulators for the purpose of training dredge operators. Simulators have been used for a long time to train ship pilots and airplane pilots. The investment in dredge simulator training is expected to improve dredging efficiency and maximize profits for the dredging company and also reduce the costs of dredging projects. Miedema (1999) discussed the principles of developing dredge simulators that interface dredge controls with a personal computer that is the platform for a sophisticated simulation of the entire dredging process including transport, cutting, and advancing the dredge. Randall et al, 2000 described the use of the cutter suction dredge simulator in 1999 and 2000.

The objective of this paper is to discuss the experiences obtained in the training courses sponsored by the Center for Dredging Studies and the Digital Automation and Control Systems (DACS). These courses were presented over a 1-½ day period in 1999 and a 2-½ day period in January 2000 - 2007.

DESCRIPTION OF SIMULATORS

The cutter suction dredge simulator consists of the control console interfaced to a personal computer. The first DACS simulator used a 486/66 MHz personal computer using Windows 3.1. In 1999, the simulator was upgraded to Pentium II/133 MHz computer running in Windows 95, and the current simulators are using the Windows XP operating system. The software simulating the dredging operations is written in Visual Basic. Figure 2 shows two of the three simulators that are used for the cutter suction dredge short course.

DACS

DACS/TAMU

Figure 3. Cutter Suction Dredge Simulators.

The simulator incorporates accepted hydraulic transport theories (Durand, 1953 or Wilson et al., 1997) and combines them with empirical data and a model for soil cutting (Miedema, 1995 and 1996). The user has the capability of specifying channel geometry, geotechnical data (grain size, sand/clay, etc.), pipeline length and diameter, pumping power and pump curves, cutter drive and winch drive, and dredge geometry.

The simulator is designed to show operators and production engineers how to improve their skills and dredge performance through the use of instrumentation. All dredging processes including dredge motions (swing and advance), cutting process, and slurry transport are simulated. The user can experiment with improving productivity without worrying about the consequences of plugging the line and suffering costly downtime. Using the simulator to replicate the dredging process, the operator can learn to achieve maximum production. In fact, the actual dredge characteristics for the dredge that the operator is normally operating can be input.

The large computer screen (Figure 4) shows a panel of gauges, a top view of the channel and dredge with swing wires, and a window that can be toggled between a side and rear view of the dredge. Pertinent information such as swing rate, production rate, total production, cutter depth, spud carrier position, and swing angle are illustrated at the bottom of the window. Error messages and time of dredging are shown at the bottom line of the window. The panel of gauges includes pump speed, pump power, cutter speed, cutter power, slurry specific gravity, slurry velocity, suction pressure, discharge pressure, port winch force, and starboard winch force.

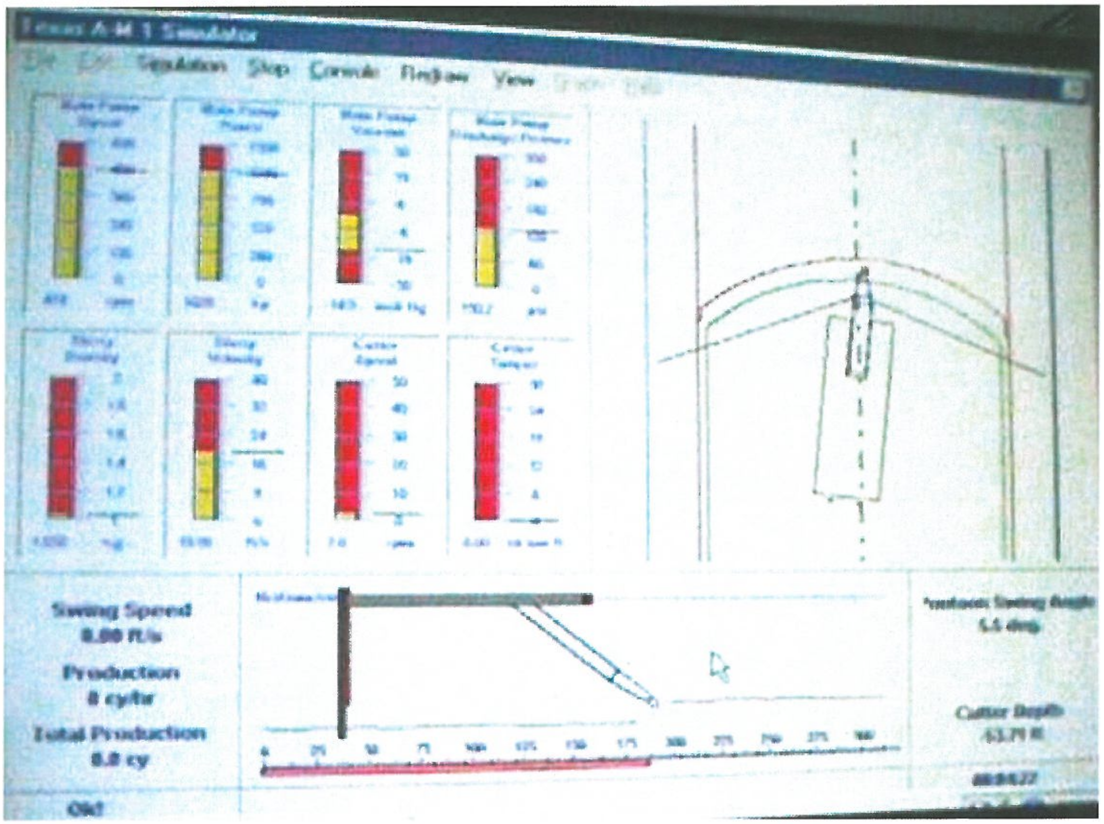

Figure 4. Display on Computer Screen during Simulator Operations.

The dredging simulator uses input files to define the characteristics of the dredge, channel, cutter, pipeline, pumps, spuds, wires, and sediments. These files can be changed to specify a particular dredge and project specific condition. For example the characteristics of the dredge pump and performance curves can be input. The pipeline characteristics and fittings are defined in the pipeline file. An example of selected portions of the pipeline, channel and main pump input files are shown in Table 1.

A very useful capability of the simulator software is its ability to capture data during each simulator exercise, and these data are plotted to show the participant the results of all the data and actions during the exercise. An example of the output for production is illustrated in Figure 5 that shows slurry density, slurry velocity, swing speed, and production as a function of time. A data point is recorded for every time step (~0.5 s) in the simulation. The gray (green) horizontal line represents the average value of the recorded data over the exercise time period. The International System (SI) or US customary units are specified at the start of the simulation.

Table 1. Selected Portions of Simulator Input File (channel, pipeline, and main pump).

Channel	Pipeline	Main Pump
Total width of top view and front view (m) - 150	Theory Used: 0 – Durand, 1 – Wilson fine, 2 – Wilson coarse - 0	Power (kW) - 835
Water level of new channel (m) - 13	Pipe Section 0 Suction	Impeller diameter (m) – 1.35
Width of old channel (m) – 100	Pipe diameter (m) - 0.4	Revolutions (rpm) – 450
Depth of old channel (m) – 10	Pipe length (m) - 26	Maximum Revolutions (rpm) – 500
Slope of old channel (m) – 30	Pipe roughness (m) – 0.0001	Data Points for Performance Curve
Width of new channel (m) – 130	Pipe fittings	Flow (m^3/s) Head (kPa) Eff. NPSH (m)
Depth of New Channel (m) – 15	Number of swivel elbows - 0	0.31 1150 0.55 80
Slope of new channel (m) – 30	Number of swan necks - 0	0.47 1060 0.75 80
Soil type (0=sand, 1=clay) - 0	Pipe Section 1	0.63 980 0.85 78
	Pipe diameter (m) – 0.4	0.79 790 0.87 76

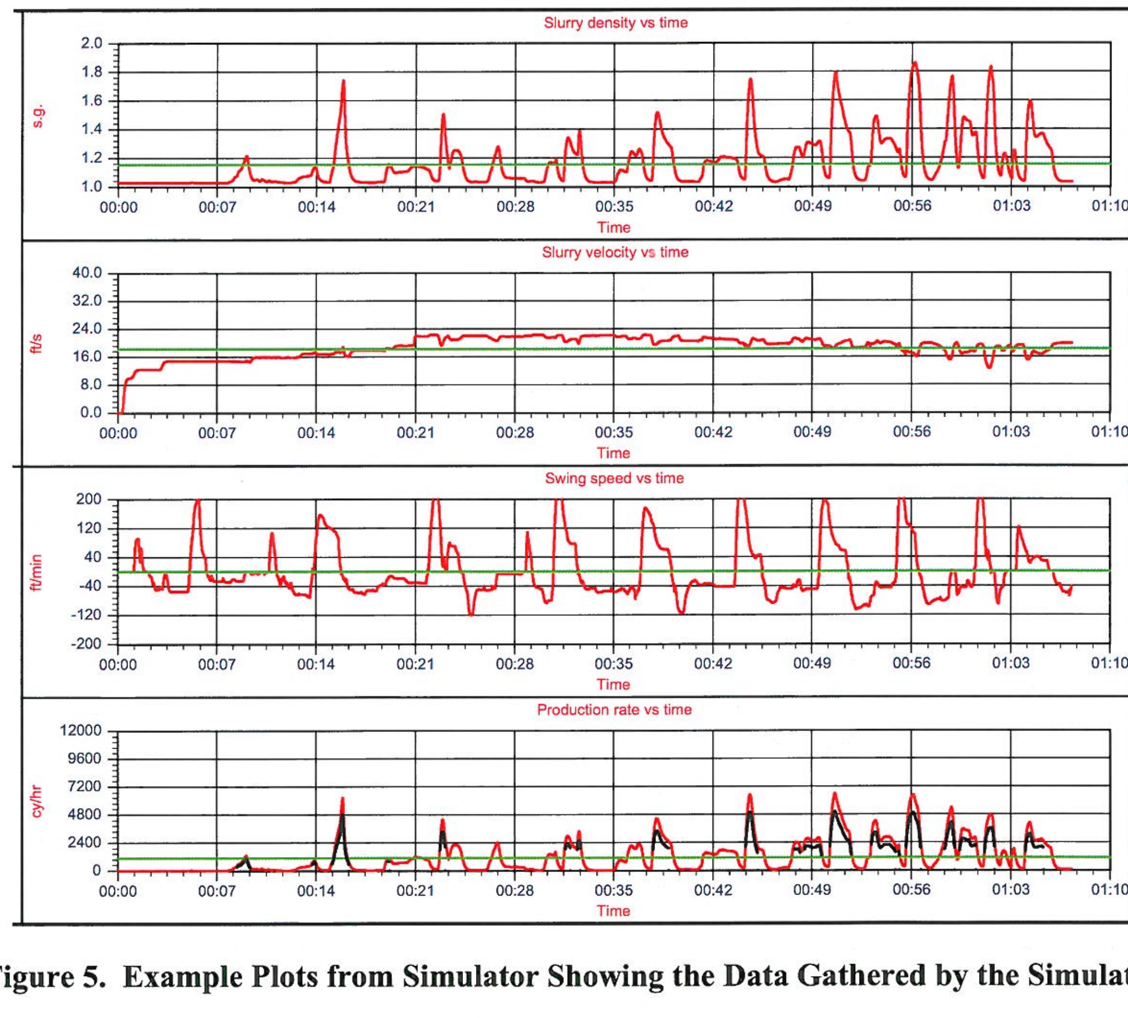

Figure 5. Example Plots from Simulator Showing the Data Gathered by the Simulator.

The actions of the participant using the simulator and error messages are recorded along with the time of the action or message (Table 2). Actions recorded include lowering the ladder, starting pumps, raising and lowering spuds, etc., and error messages such as main pump cavitating, cutter clogged, deposit in the pipeline, pipeline clogged, and no spud on the ground are displayed.

Table 2. Partial Record of Simulator Course Participant Actions.

Date : 01-05-2000
Time : 14:57:37
Student : Name
Company : Name
ID : Student #1
Sessions: 1

0:00:00	Action!	Start of session
0:00:00	Action!	Start of simulation
0:00:00	Action!	Cutter drive enabled
0:00:00	Message!	Suction mouth above water, stop cutter drive
0:00:05	Action!	Main pump enabled
0:00:05	Error!	Suction mouth above water, stop main pump
0:00:25	Action!	Starboard winch in dual operation
0:00:35	Message!	Screen console input
0:00:37	Action!	Starboard winch in single operation
0:00:37	Error!	Suction mouth above water, stop main pump
0:00:48	Action!	Port anchor moved by mouse X = 288.40 ft - Y = 135.27 ft
0:00:48	Error!	Suction mouth above water, stop main pump
0:00:58	Action!	Starboard anchor moved by mouse X = 30.13 ft - Y = 137.94 ft
0:01:18	Action!	Starboard winch in dual operation
0:01:27	Error!	Suction mouth above water, stop main pump
0:01:33	Action!	Ladder lowered
0:01:33	Fatal error!	Pipeline clogged
0:01:54	Action!	Ladder hoisted
0:01:59	Action!	Swing to starboard
0:02:10	Action!	Ladder lowered
0:02:11	Action!	Swing to starboard
0:02:19	Action!	Swing to port
0:02:21	Action!	Swing to port
0:02:35	Action!	Free fall of the step spud
0:02:40	Action!	Step spud lowered
0:02:40	Action!	Work spud hoisted
0:02:43	Action!	Swing to port
0:03:03	Error!	Main pump cavitating, raise ladder
0:03:14	Action!	Swing to port
0:03:21	Error!	Main pump cavitating, raise ladder
0:03:25	Action!	Swing to starboard
0:03:32	Action!	Work spud lowered
0:03:33	Action!	Free fall of the work spud
0:03:34	Action!	Step spud hoisted
0:03:42	Action!	Swing to port
0:04:00	Error!	Main pump cavitating, raise ladder
0:04:01	Error!	Main pump cavitating, raise ladder
0:04:07	Error!	Main pump cavitating, raise ladder

COURSE ORGANIZATION

In 1995 the DACS cutter suction dredge simulator was placed at the Center for Dredging Studies at Texas A&M University, and a set of simulator exercises were developed by the Center with the intention of providing a training course for dredge operators and production engineers. In addition to the simulator exercises, short presentations are given on fundamental dredge hydraulics, the sediment cutting process and a dredge simulator demonstration as shown in Table 3. The first course was presented in January 1999 using one simulator, and experienced operators and production engineers were asked to participate to determine the utility of the simulator. The 1 1/2-day course was successful, but the participants recommended that the course length be extended and offered as training for young operators and production engineers. Subsequent courses were extended to 2 ½ days in 2000 – 2007.

Table 3. Schedule for 2 1/2-day Simulator Short Course.

Time	**First Day Topics**
8:00 – 8:30	Introduction
8:30 – 9:15	Dredge Hydraulics
9:15 – 10:00	Cutting & Dredge Advance
10:00 – 10:20	Refreshment Break
10:20 – 10:40	Simulator Scenarios & Files
10:40 – 11:00	Simulator Demonstration
11:00 – 11:30	Questions
11:30 – 12:30	Lunch
12:30 – 2:00	Simulator Exercise TEXAM 13
2:00 – 2:15	Refreshment Break
2:15 – 3:15	Review Simulator Exercise TEXAM 13
3:15 – 4:45	Simulator Exercise TEXAM 12
5:00	Return to hotel
	Second Day Topics
8:00 – 9:00	Review Simulator Exercise TEXAM 12
9:00 – 10:30	Simulator Exercise TEXAM 8
10:30– 10:45	Refreshment Break
10:45 – 11:45	Review Simulator Exercise TEXAM 8
11:45 – 12:45	Lunch
12:45 – 2:15	Simulator Exercise TEXAM 14
2:15 - 2:30	Refreshment Break
2:30 – 3:30	Review Simulator Exercise TEXAM 14
3:30 – 5:00	Simulator Exercise TEXAM 15
5:00	Return to hotel
	Third Day Topics
8:00 – 9:00	Review Simulator Exercise TEXAM 15 Results
9:00 – 10:30	Simulator Final Exercise (Your Choice of Dredge)
10:30 – 10:45	Refreshment Break
10:45 – 11:45	Review Final Exercise
11:45 – 12:00	Short Course Critique & Certificate Presentation

The course fee is currently $1,500 with a maximum of nine participants using a total of three simulators. Participants arrive the evening before the first day and the cutter suction dredge simulator training manual (CDS, 2007) is given to the participants. The first day of the 2 1/2-day course consists of presentations on dredge hydraulics, cutting of the bottom sediments, and a demonstration of the two simulators. In the afternoon, all participants are given the opportunity to operate the simulator using simulator exercise number 13, which is a 0.61 m (24 in) spud carriage cutter suction dredge. Each participant is given ~30 minutes to complete exercise 13. After all the participants complete the exercise, the data recorded for each participant are reviewed and explained. Exercise 13 has no limitations such as cavitation, long pipeline, and low power to the pump, cutter, or winches, so the participants can become accustom to the simulator, control console and instrumentation information.

On the second day, the exercises are for a 0.61 m (24 in) cutter suction dredge. Exercise 12 has a 5000 m (16,400 ft) pipeline that challenges the participants in controlling the slurry density and velocity within the limits of the pump to maintain production without plugging the pipeline. Participants are expected to have trouble maintaining the same production as achieved in exercise 13. In Exercise 8, the pipeline length is reduced back to 2000 m (6560 ft) and the ladder pump is removed to demonstrate the effect of cavitation on production. Exercise 14 changes from a medium sand sediment to a medium stiff clay and exercise 15 switches back to medium sand and adds a 2 m/s (4 knot) tidal current on the bow. A review of the data recorded is again presented at the conclusion of these exercises for all participants.

SIMULATOR EXERCISES

There are seventeen built-in scenarios, or exercises, provided with the simulator software. The exercises are called TEXAM1 through TEXAM17. The TEXAM1 through 6 are a 0.4 m (16 in) cutter suction dredge with fixed spuds. TEXAM7 is a 0.75 m (30 in) dredge with a spud carriage. The TEXAM8 through TEXAM16 are a 0.61 m (24 in) cutter suction dredge with fixed spuds and TEXAM17 is 0.61 m (24 in) spud carriage dredge. These exercise dredges are briefly described Table 4. Only six of these are commonly used in the short course. Exercise number 7 is a large 0.76 m (30 in) cutter suction dredge that has a spud carriage and is equipped with a ladder pump. The channel sediment in all exercises was sand with a d_{50} of 0.5 mm and the channel water depth and width are 8 m (26.2 ft) and 100 m (328 ft), respectively. The cutter base diameter is 2 m (6.3 ft). The main pump power and the winch power are more than adequate and the pipeline length is 5000 m (16,400 ft). The suction pipe is 0.81 m (32 in). A large dredge with essentially no dredging limitations is best for the participants to start their training and acclimate themselves to the simulator and the controls on the console. Since there are three simulators the class is divided into three groups and each participant completes all their exercises on the same simulator so they don't have to readjust to a different simulator for different exercises. The software is identical on the simulators, but the control consoles are different. All the participants are given about 30 minutes on the simulator with instruction to try to maximize the production without cavitating the pump or plugging the pipeline. These basic exercises are intended to demonstrate the effects of slurry velocity, slurry density, and dredge characteristics on production.

Table 4. Summary of Cutter Suction Dredge Simulator Exercises.

Exercise	Suct Dia	Disch Dia	Pipe Length	Advance Method	Sediment	Critical Velocity	Water Depth	Winch Power	Pump Power	Ladder Pump	Current
TEXAM 1	0.4 m (16 in)	0.4 m (16 in)	2000 m (6560 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	normal	normal	none	none
TEXAM 2	0.5 m (20 in)	0.4 m (16 in)	2000 m (6560 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	normal	normal	none	none
TEXAM 3	0.4 m (16 in)	0.4 m (16 in)	2000 m (6560 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	normal	normal	yes	none
TEXAM 4	0.4 m (16 in)	0.4 m (16 in)	5000 m (16,400 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	normal	normal	none	none
TEXAM 5	0.4 m (16 in)	0.4 m (16 in)	5000 m (16,400 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	normal	high	none	none
TEXAM 6	0.4 m (16 in)	0.4 m (16 in)	2000 m (6560 ft)	Fixed	med sand	4.6 m/s (15 ft/s)	17 m (55.1 ft)	high	high	none	none
TEXAM 7	0.81 m (32 in)	0.75 m (30 in)	5000 m (16,460 ft)	Spud Carriage	med sand	6.5 m/s (21.3 ft/s)	8 m (26.2 ft)	normal	normal	none	none
TEXAM 8	0.61 m (24 in)	0.61 m (24 in)	2000 m (6560 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	none	none
TEXAM 9	0.76 m (30 in)	0.61 m (24 in)	2000 m (6560 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	none	none
TEXAM 10	0.61 m (24 in)	0.61 m (24 in)	2000 m (6560 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	yes	none
TEXAM 11	0.61 m (24 in)	0.61 m (24 in)	2000 m (6560 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	low	normal	yes	none
TEXAM 12	0.61 m (24 in)	0.61 m (24 in)	5000 m (16,400 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	yes	none
TEXAM 13	0.61 m (24 in)	0.61 m (24 in)	5000 m (16,400 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	high	high	yes	none
TEXAM 14	0.61 m (24 in)	0.61 m (24 in)	2013 m (6560 ft)	Fixed	med stiff clay	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	yes	none
TEXAM 15	0.61 m (24 in)	0.61 m (24 in)	2014 m (6560 ft)	Fixed	fine sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	yes	none
TEXAM 16	0.61 m (24 in)	0.61 m (24 in)	2015 m (6560 ft)	Fixed	med sand	5.9 m/s (19.4 ft/s)	20 m (65.6 ft)	normal	normal	yes	yes
TEXAM 17	0.61 m (24 in)	0.61 m (24 in)	6098 m (20,000 ft)	Spud Carriage	med sand	5.9 m/s (19.4 ft/s)	8 m (26.2 ft)	high	high	yes	none

RESULTS OF EXERCISES

An example of the production data curves for exercise 7 is illustrated for one participant in Figure 6. The results show the slurry velocity beginning to drop after 12 minutes into the exercise and at about 19 minutes the sediment began to settle in the pipe. The average specific gravity being pumped is 1.15 and the average velocity is 4.3 m/s (14 ft/s). For sand with a d_{50} of 0.5 mm, the critical velocity for deposit in a 0.76 m (30 in) pipeline is approximately 7 m/s (23 ft/s). The velocity shown in Figure 6 is well below the critical velocity and consequently the sediment settled in the pipe, eventually plugging the pipe. This is evident when the velocity went to zero at about 20 minutes and the program gave a fatal error that the pipeline was plugged.

In recent short courses, the participants are introduced to a 0.6 m (24 in) cutter suction dredge that are numbered TEXAM13, 12, 8, 14, and 15, as shown in Table 5. The purpose of the different exercises is to expose the participants to increasingly more difficult conditions for dredging and to demonstrate the principles of available power, long pipelines, critical velocity, different sediment condition, and cavitation limitations. It is intended to demonstrate the effects of these cutter suction dredge limitations (pipeline length, cavitation, bottom sediment, channel current, and critical velocity) on the production.

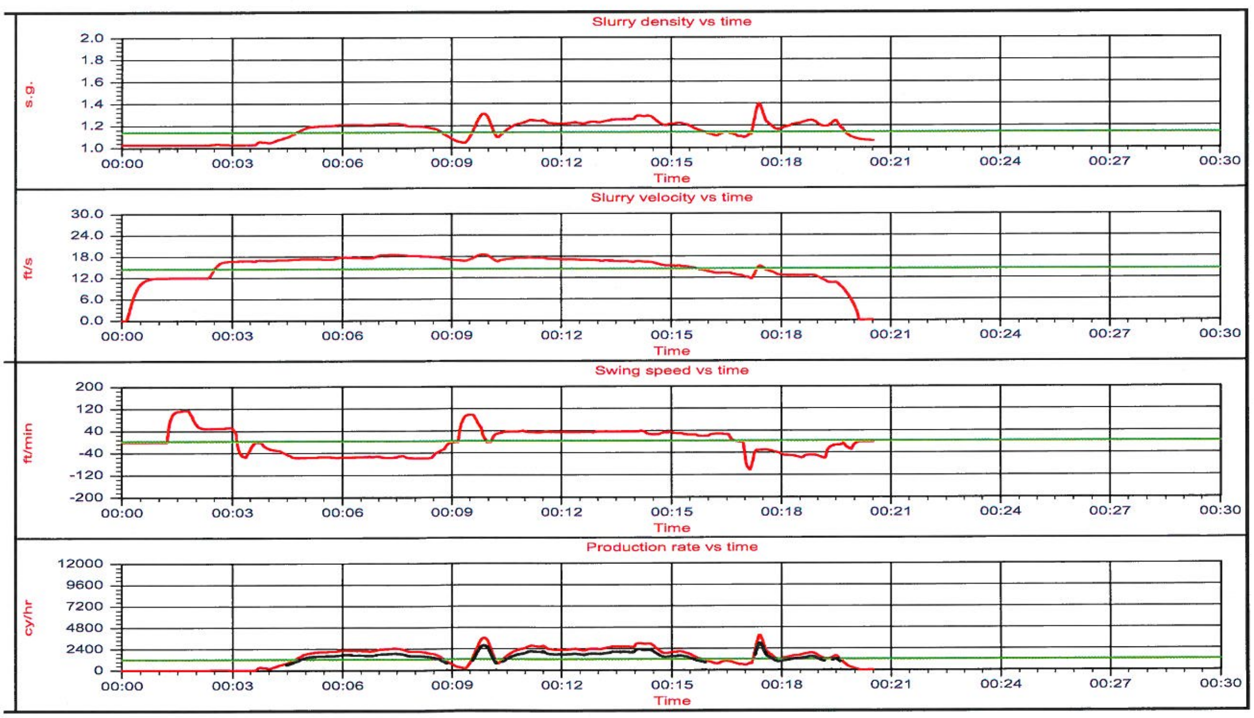

Figure 6. Production Curves Showing Slurry Density, Slurry Velocity, Swing Speed, and Total Production.

Table 5. Comparison of Cutter Suction Dredge Simulator Exercises.

Characteristic	Exercise 13	Exercise 12	Exercise 8	Exercise 14	Exercise 15
Suction Pipe	0.61 m (24 in)	0.61 m (24 in)	0.61 m (24 in)	0.61 m (24 in)	0.61 m (24 in)
Discharge Pipe	0.4 m (16 in)	0.61 m (24 in)	0.61 m (24 in)	0.61 m (24 in)	0.61 m (24 in)
Ladder Pump	Yes	Yes	No	Yes	Yes
Main Pump Power	Maximum	Maximum	Maximum	Maximum	Maximum
Winch Power	Maximum	Maximum	Maximum	Maximum	Maximum
Pipeline Length	2000 m (6560 ft)	5000 m (16,400 ft)	2000 m (6560 ft)	2000 m (6560 ft)	2000 m (6560 ft)
Common Characteristics					
Sand grain size	d_{50} =0.5 mm	d_{50} =0.5 mm	d_{50} =0.5 mm	Med stiff clay	d_{50} =0.5 mm
Water depth	16.8 m (55 ft)	16.8 m (55 ft)	16.8 m (55 ft)	16.8 m (55 ft)	16.8 m (55 ft)
Cutter size	1.2 m base 1.1 m height 1.0 m top	1.2 m base 1.1 m height 1.0 m top	1.2 m base 1.1 m height 1.0 m top	1.2 m base 1.1 m height 1.0 m top	1.2 m base 1.1 m height 1.0 m top
Channel Width	84 m (276 ft)	84 m (276 ft)	84 m (276 ft)	84 m (276 ft)	84 m (276 ft)
Spud Separation	6 m (19.7 ft)	6 m (19.7 ft)	6 m (19.7 ft)	6 m (19.7 ft)	6 m (19.7 ft)
Current	None	None	None	None	2 m/s (4 knots)

Figure 7 shows a summary of the production in cubic yards/hr for nine participants while conducting the five exercises. As illustrated in Figure 7, participant 4 attained the best production over all the exercises. Exercise 13 was meant to have high production because there was maximum power, short pipeline, and a ladder pump. However, when the participants moved to exercise 12, the production for most participants decreased because the pipeline increased from 2000 m to 5000 m (6560 to 16400 ft). In exercise 8, the ladder pump was removed, the pipeline length was reduced back to 2000 m (6560 ft), and everything else remained the same as exercise 12. The effect of cavitation was clearly evident and resulted in the production by all the participants being reduced by 50 % or more. These results show the simulator exercises demonstrate the limitations on production caused by cavitating pumps and increased line length, and power to the pump. Winch and cutter power are also limitations, and exercises can be generated to demonstrate these limitations.

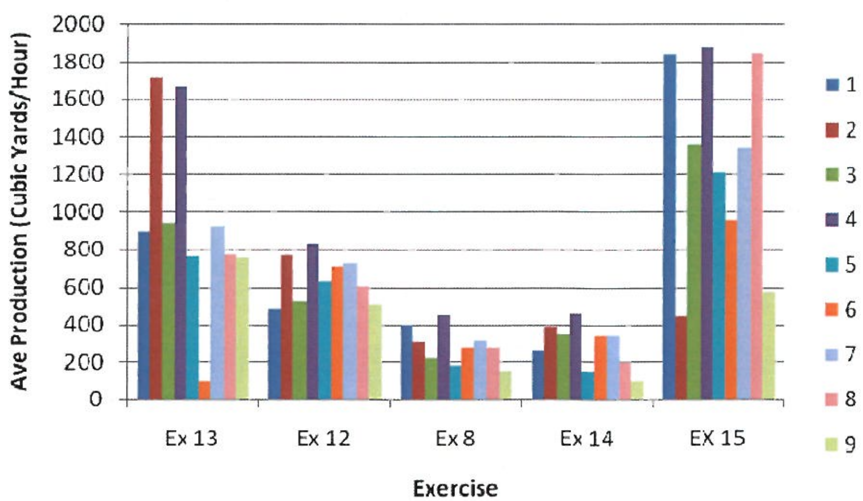

Figure 7. Comparison of Production for Each Participant for the Different Exercises.

Exercises number 13 and 8 illustrated the effects of cavitation on dredge production. In exercise 13, the cutter suction dredge had a ladder pump and the short line (2000 m, 6560 ft). The critical velocity for a 0.61 m (24 in) line transporting material with a d_{50} of 0.5 mm is approximately 4.6 m/s (15 ft/s). Figure 9 illustrates the data collected for exercise 13 and shows an average slurry density 1.15 with maximum specific gravity as high as 1.84. The average slurry velocity was 5.6 m/s (18.4 ft/s) which is about 1.0 m/s (3.3 ft/s) above the critical velocity. During this exercise the average production is about 923 m^3/hr (1200 cy/hr). As shown in Figure 9, the main pump suction pressure is positive over the entire exercise with several drops in pressure due to spikes in slurry specific gravity. The main pump power is at a maximum after 21 minutes, and the maximum swing velocity was 61 m/min (200 ft/min).

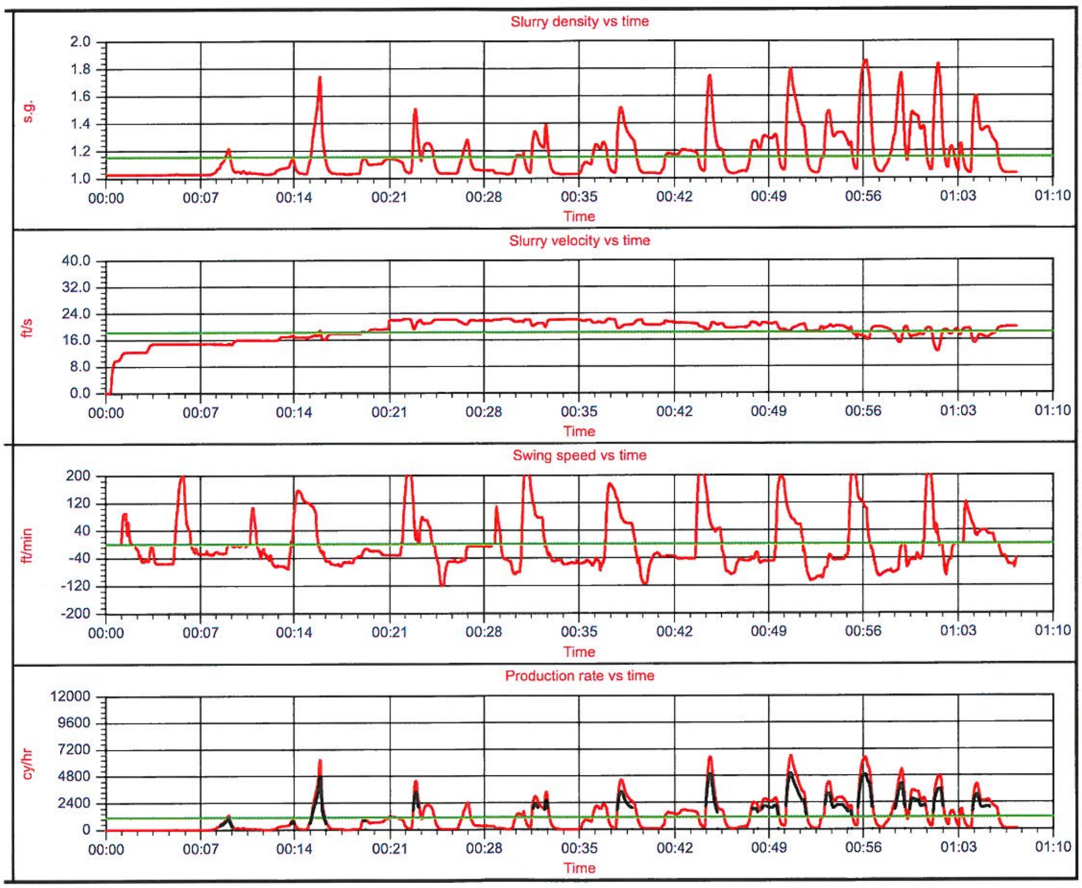

Figure 8. Exercise 13 Example of Production Data (Density, Velocity, Swing Speed, and Production Verses Time) Using Ladder Pump and Short Pipeline.

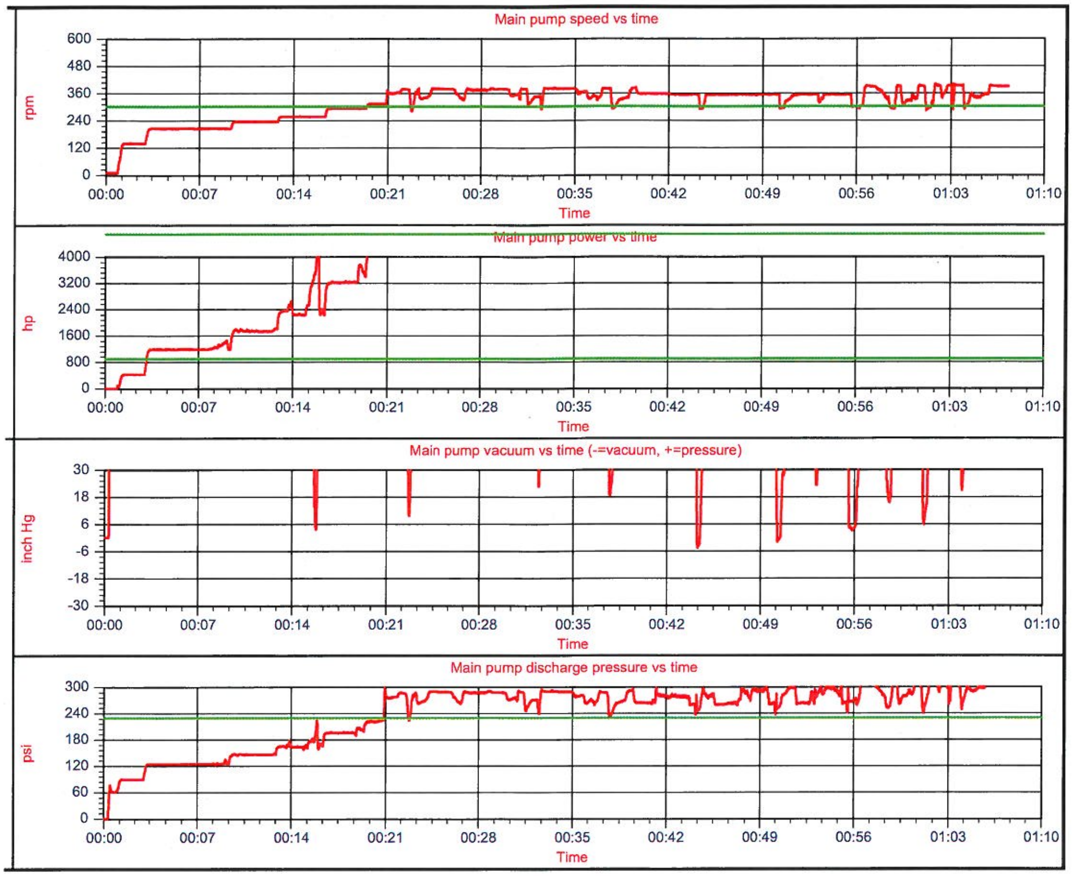

Figure 9. Exercise 13 Example of Main Pump Data (Speed, Power, Vacuum Pressure, and Discharge Pressure Verses Time) Using Ladder Pump and Short Pipeline.

In exercise 8, the ladder pump is removed and the operator tries to maximize the production. As shown in Figure 10 the operator is able to average a 1.1 specific gravity with a few peaks up to 1.4 specific gravity. The slurry velocity drops to an average of 4.9 m/s (16 ft/s) that is just 0.31 m/s (1 ft/s) above the critical velocity. The swing rate is reduced and the production is reduced to about 554 m^3/hr (720 cy/hr), which is a drop of nearly one half. In Figure 11, the main pump suction pressure is always negative and ranges between –152 and –507 mm of Hg (-6 and -20 in of Hg) with an average suction pressure of 365 mm of Hg (14.4 in of Hg). The operator cavitates the pump only a few times throughout the exercise as evidenced by the number of times the suction pressure approaches -760 mm of Hg (-30 in of Hg). The results from Exercises 13 and 8 clearly show the benefit of the ladder pump in maximizing production and reducing wear and tear on the main pump due to excessive cavitation.

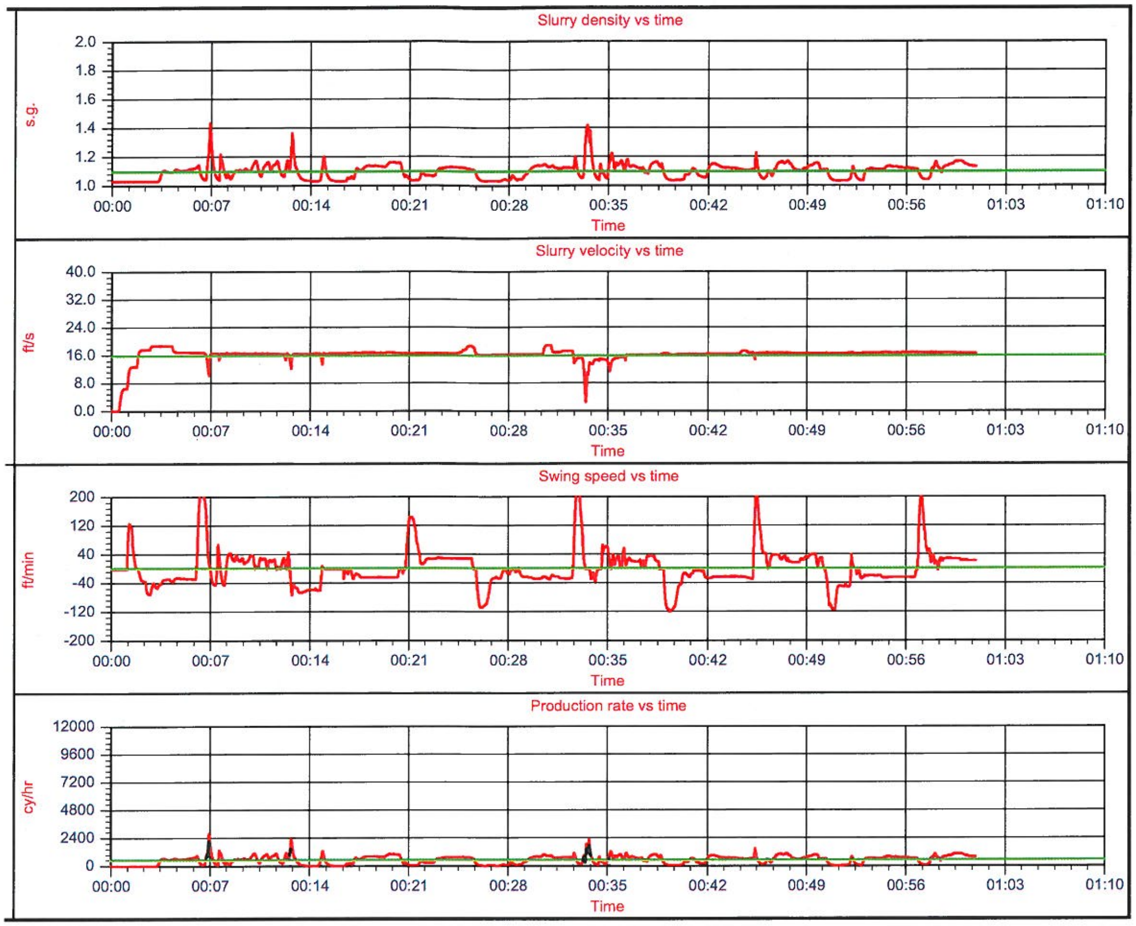

Figure 10. Example of Exercise 8 Production Data (Density, Velocity, Swing Speed, and Production Verses Time) Showing the Effects of Cavitation.

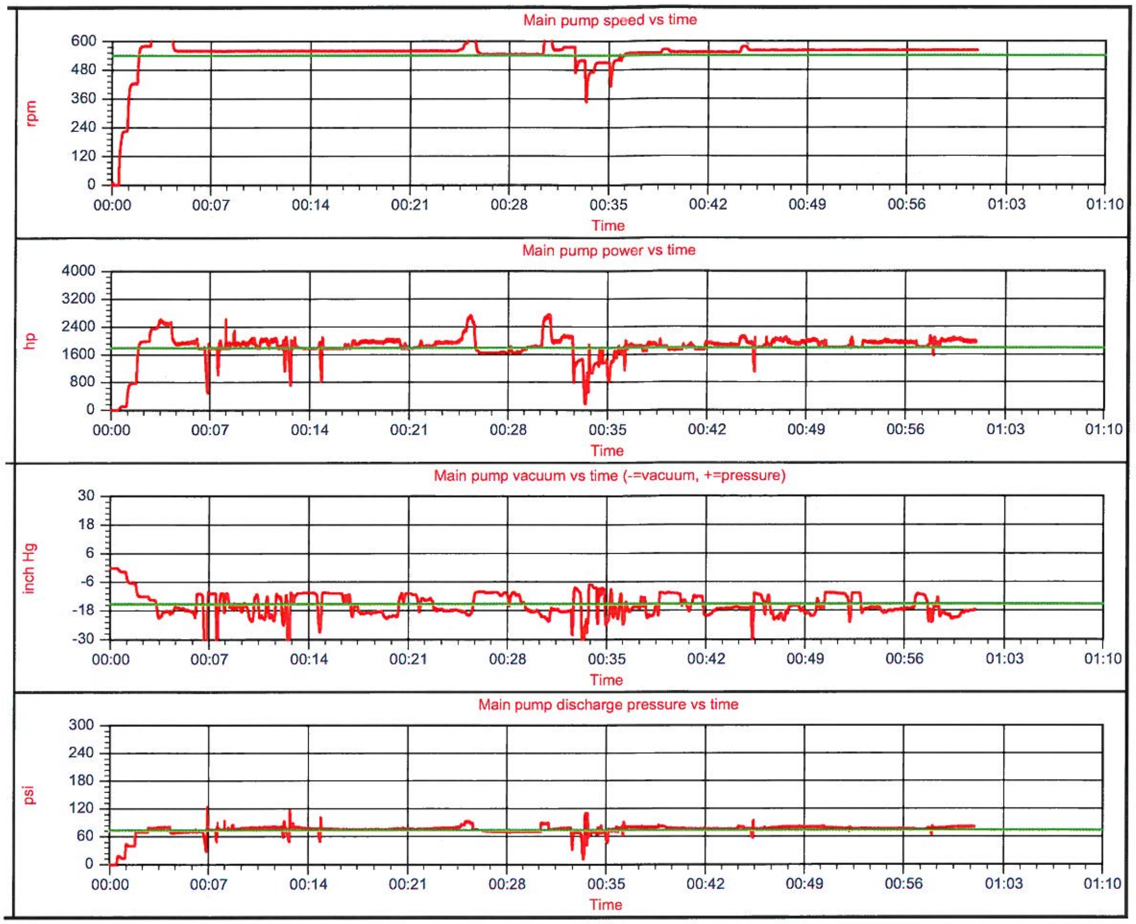

Figure 11. Example of Exercise 8 Main Pump Data (Speed, Power, Vacuum Pressure, and Discharge Pressure Verses Time) Showing the Effects of Cavitation.

Exercise 14 illustrates dredging a channel with the same 610 mm (24 in) cutter suction dredge with the sediment being stiff clay. Figure 12 shows the operator recognized the expected difficulty in excavating the clay so the average slurry specific gravity was 1.1 (solid horizontal gray line) with a maximum instantaneous slurry specific gravity of 1.3. At a time of 40 min, the specific gravity increased rapidly to 1.9 that caused the plugging of the discharge line as evidenced by the slurry velocity going to zero and the discharge pressure dropping to zero. The difficulty of dredging clay is also illustrated by the low production of 554 cm/hr (720 cy/hr) as compared to an average production of 965 cm/hr (1200 cy/hr) when excavating sand with the same dredge. Figure 12 shows the main pump power average 1790 KW (2400 HP) until the pipe line plugged. The main pump cavitated when spikes in the density occurred as shown at 14, 33, 37 minutes. This exercise illustrated the difficulty of dredging clay as compared to sand. In the field, a plugged pipelines can be difficult to unplug and can cause considerable downtime and loss of production. In the case of the simulator, the computer is reset and the participant can try the exercise again without much delay (5 minutes).

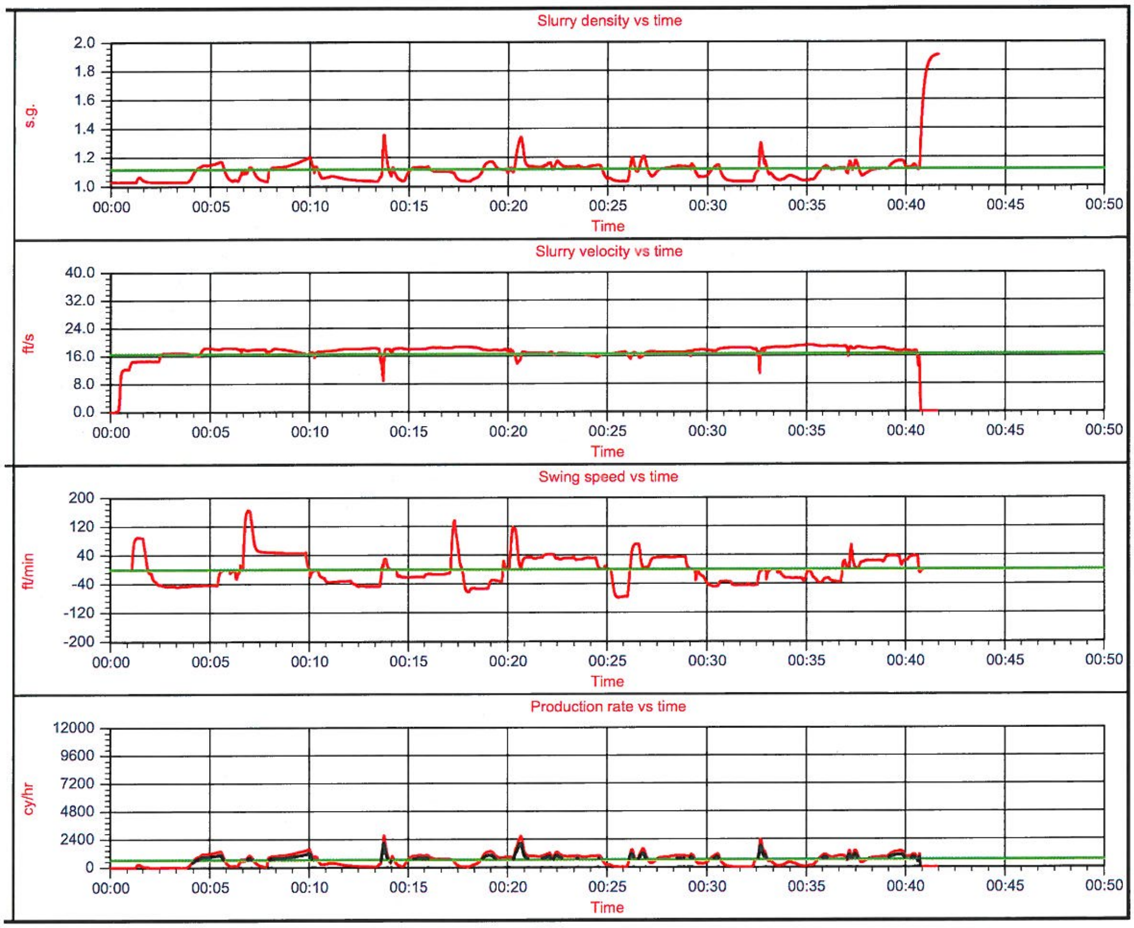

Figure 12. Example Density, Velocity, Swing Speed, and Production Results from Exercise 14 Using Stiff Clay as the Channel Sediment.

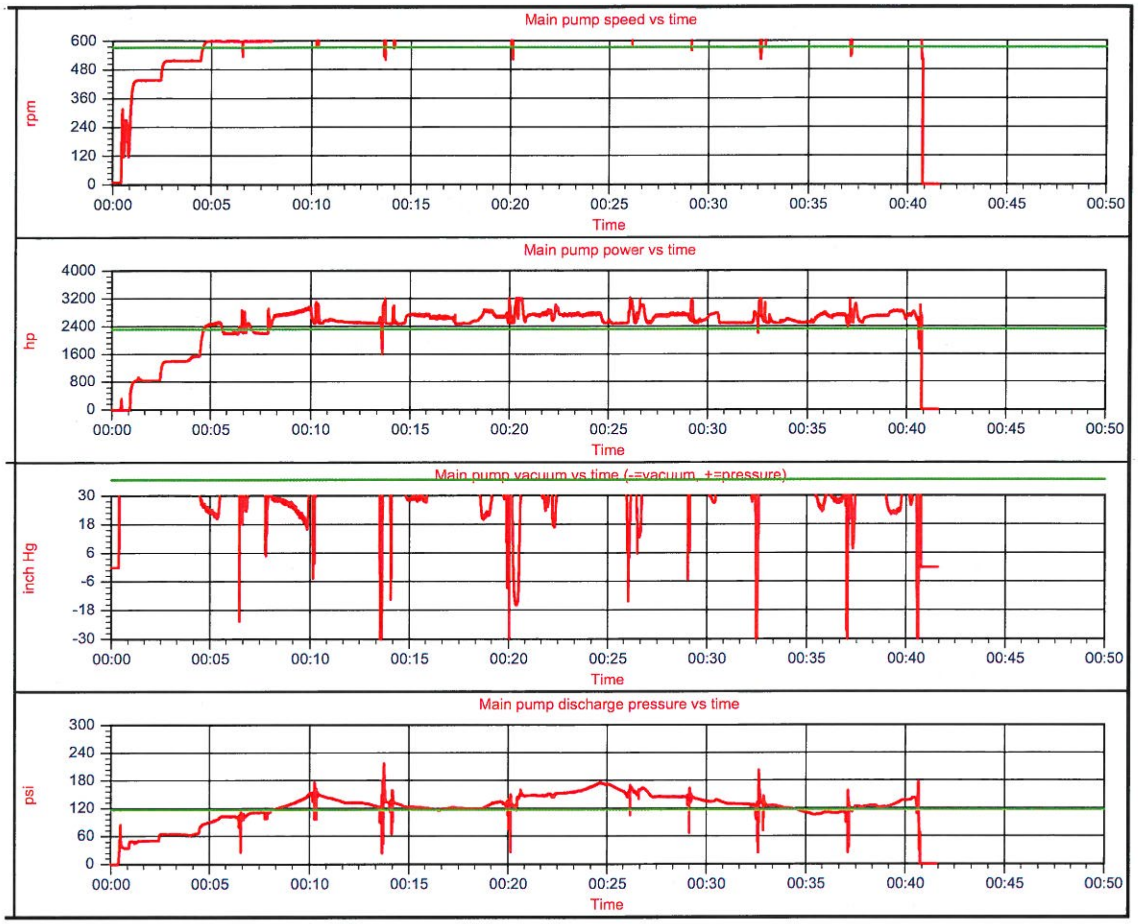

Figure 13. Example Main Pump Speed, Power, Vacuum Pressure and Discharge Pressure Data from the Results of Exercise 14 Using Stiff Clay as the Channel Sediment.

CONCLUSIONS AND RECOMMENDATIONS

The simulator is a very realistic model for cutter suction dredges and has proven to be a reliable simulation of actual cutter suction dredging operations. Participants in the cutter suction dredge simulator short courses indicate that training on the simulator benefits dredge leverman and production engineers. New and experienced dredge company management personnel have also found the short course beneficial.

The exercises that have been developed demonstrate hydraulic transport, cutting and operating principles. The effect of length of pipeline, ladder pump, critical velocity, channel sediment type, channel water current, winch and main pump power limits, and dredge advance equipment are demonstrated. Participants need time to adjust to the control and computer set-up and are given one exercise to acquaint themselves with the controls on the console.

Typically, the three participants working on the same simulator observe each other's activity on the simulator. In some cases, experience operators are able to coach the less experienced participants.

The review of the data and participant actions after each exercise is very useful in showing each participant the results of their exercise and the other participants. Participants also learn from the actions of the other participants since everyone listens to all critiques.

The presentations on fundamentals of slurry transport and cutting of soils proved to be useful to the operators and production engineers. The participants like the question and answer sessions with the course instructors. Most of the operators do not have a formal engineering education and the opportunity to have slurry transport fundamentals explained have been well received.

Critiques by the participants at the close of the short course indicated the course was well received. The length of the course was considered to be about right with a possible extension of one day for additional dredging conditions.

The simulator has the capability to simulate different dredge systems and it is recommended that participants provide actual characteristics of the organization's dredge so that the participants could observe the simulation of an actual company dredge for which the participant is the operator.

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A SENSITIVITY ANALYSIS OF THE PRODUCTION OF CLAMSHELLS

S.A. Miedema[1]

ABSTRACT

Literature reveals little about the prediction of the closing process of clamshell dredging buckets when cutting sand or clay under water. The results of research carried out, mostly relates to the use of clamshells in dry bulk materials. While good prediction of the forces (in dry materials) involved are possible by measuring the closing curve, the very prediction of the closing curve of clamshells in general, seems to be problematic. The research carried out by Becker, Miedema, Wittekoek and de Jong (1992) resulted in a numerical method of calculating the closing process of clamshell grabs in water saturated sand and clay, which simulates the closing of a clamshell so that production and forces can be predicted. The calculation method is based on the non-linear equations of motion of the buckets and the sand cutting theory Miedema presented in 1987 and 2006 and the clay cutting theory presented by Miedema in 1992. The production of a clamshell depends on: the dimensions of the clamshell; the weight and weight distribution of the clamshell; the geometry of the clamshell and especially the cutting edges; the type of soil, the soil mechanical parameters; the water depth and the operational parameters, like the closing speed. A sensitivity analysis has (based on the simulation model) been carried out, varying a number of parameters (weight, speed, geometry, type of soil) resulting in graphs that can be used to optimize the design of clamshells used in dredging. The paper will discuss the sensitivity analysis and show the resulting graphs.

INTRODUCTION TO CLAMSHELL RESEARCH & PRODUCTION

It is important for dredging contractors to be able to predict the production of their dredges. Many studies have been carried out with respect to cutter suction dredges and hopper dredges. From the literature it became clear that, although many researchers have investigated the closing process of clamshell grabs, no one had succeeded in predicting their closing process. Since many clamshell grabs are being used in dredging industry in the U.S.A. and the Far East, it is important to have a good prediction of the production of clamshells in different types of soil.

The first grab reported was designed by Leonardo da Vinci (1452-1519) in the 15th century. Although the basic working principles remained the same, grab designs have improved dramatically as a result of trial and error, though research has had some influence. The following reviews some of the results found of research carried out in this century. Pfahl (1912) investigated the influence of the deadweight of a grab with respect to the payload for grabs of 1 m^3 to 2.25 m^3. He concluded that the payload has a linear relation with the deadweight. Ninnelt (1927) carried out research similar to Pfahl and confirmed Pfahl's conclusions. Niemann (1935) experimented with model clamshells. He investigated the deadweight, the bucket's shape, the soil mechanical properties, the payload and the rope force. Special attention was paid to the width of the grab, leading to the conclusion that the payload is proportional to the width of a grab. The research also led to a confirmation of the work of Pfahl and Ninnelt. Tauber (1959) conducted

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research on prototype and model grabs. Contrary to Nieman, he found that enlarging the grab does not always lead to an increasing payload. The optimum ratio between the grab width and the grab span was found to be in between 0.6 and 0.75. Torke (1962) studied the closing cycle of a clamshell in sand for three different 39.5 kg model grabs. He first determined the closing path of the buckets experimentally, after which he reconstructed the filling process and the rope forces. His results were promising, even though he did not succeed in predicting the closing curve. An important conclusion reached by Torke is, that the payload is inversely proportional to the cutting angle of the bucket edges. In a closed situation, the cutting angle should be as near to horizontal as possible. Wilkinson (1963) performed research on different types of grabs and concluded that wide span grabs are more efficient then clamshell grabs. He also concluded that no model laws for grabs exist and that existing grabs are proportioned in about the best way possible. The best grab is a grab that exerts a torque on the soil that is as high as possible especially towards the end of the closing cycle. Hupe and Schuszter (1965) investigated the influence of the mechanical properties of the soil such as the angle of internal friction. They concluded that grabs intended to handle rough materials like coal should be larger and heavier. Dietrich (1969) tested a 0.6 m^3 grab and measured the payload for different values of the deadweight, the grab area, the cutting angle and the grain size. He concluded that in hard material 80% of the closing force is used for penetrating the soil, while in soft material this takess only 30% of the force. The width/span ratio should be between 0.6 and 0.7 matching Tauber's conclusions, while the cutting angle should be about 11 to 12 degrees with the horizontal in a closed situation matching Torke's conclusions. Gebhardt (1972) derived an empirical formulation for the penetration forces in materials with grain sizes from 30 to 50 mm. Grain size and distribution are parameters in the equation, but the mechanical properties of the soil such as the angle of internal friction are absent. He also concludes that a uniform grain distribution results in relatively low penetration forces. Teeth are only useful in rough materials, but they have a negative effect in fine materials with respect to the penetration forces. Scheffler (1973) made an inventory of grab dimensions and design tendencies in several Eastern European countries. He concludes that most of the grabs are not used to their full potential and also that 80% of the closing force is used for penetration in rough materials confirming the work of Dietrich. Scheffler, Pajer and Kurth (1976) give an overview of the mechanical aspects of several types of grabs. The soil/grab interaction moreover is too simplified or absent. They concluded that after fifty years of research the understanding of grabs is still limited. They refer to Wilkinson as having derived the best conclusions about grab model testing, but regret that prototype results are not available. Bauerslag (1979) investigated the process of grabbing ores of 55 mm with a motor grab. As with Torke he first measured the closing curve (digging path) and then reconstructed the closing process.

In 1992, Becker, Miedema, Wittekoek and de Jong (1992) published a theory to predict the closing behavior of clamshell's based on the equilibrium equations of motions for sand and clay. This theory was further developed in Miedema & Becker 1993 and in Miedema & Vlasblom (2006). The cutting theory for sand cutting now also includes large cutting angles, see Miedema (2006).

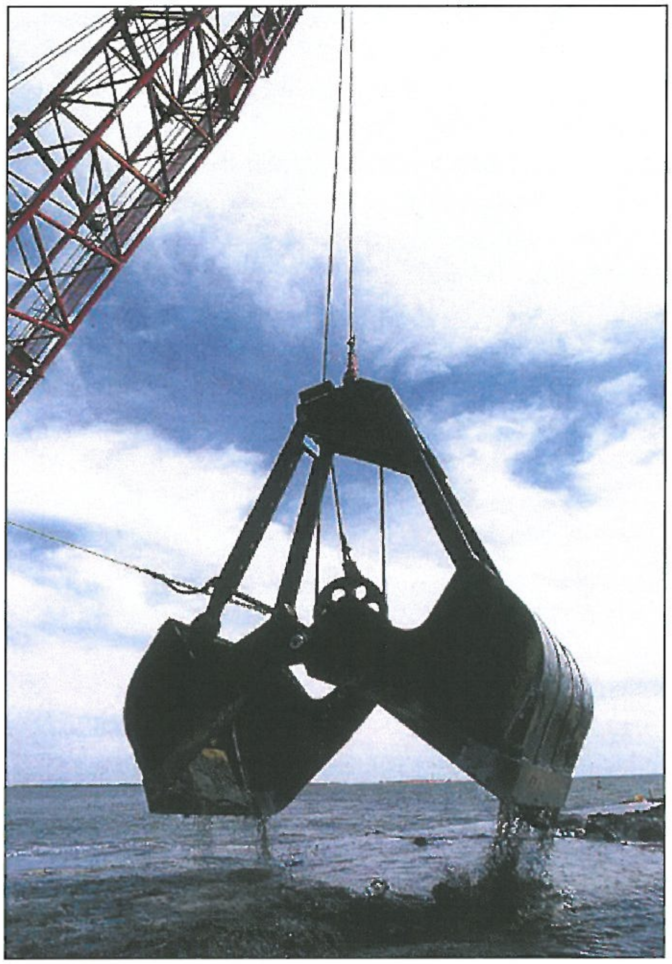

Figure 1: The 50 cubic yard clamshell buckets

Figure 2: The clamshell buckets versus human size

THE EQUATIONS OF MOTION OF A CLAMSHELL.

In order to calculate the closing curve of a clamshell, the equations of motion of the moving parts of the clamshell have to be solved. The type of clamshell considered has six main bodies that are subject to motions. These bodies are the upper sheave block, the lower sheave block, the two arms and the two buckets. Because the arms have a small rotational amplitude and translate vertically with the upper sheave block, they are considered as part of the upper sheave block. The error made by this simplification is negligible. If a clamshell is considered to be symmetrical with respect to its vertical axis, only the equations of motion of one halve of the clamshell have to be solved. The other half is subject to exactly the same motions, but mirrored with respect to the vertical axis. Since there are three main bodies left, three equations of motion have to be derived. In these equations weights are considered to be submerged weights and masses are considered to be the sum of the steel masses and the hydro-mechanical added masses. The weights and the masses as used in the equations of motion are also valid for one half of the clamshell. The positive directions of motions, forces and moments are as depicted in Figure 5.

For the upper sheave block the following equation can be derived from the equilibrium of forces:

$$m_u \cdot \ddot{y}_u = F_r \cdot (i-1) + W_u - F_a \cdot \cos(\alpha) \qquad (1)$$

The motions of the lower sheave block should satisfy the equilibrium equation of forces according to:

$$m_l \cdot \ddot{y}_l = -F_r \cdot i + W_l + W_b - m_b \cdot \ddot{y}_b + m_b \cdot bg \cdot \cos(\varphi+\beta) \cdot \varphi^2 + F_a \cdot \cos(\alpha) + F_{cv} + F_{ev} \qquad (2)$$

For the rotation of the bucket the following equilibrium equation of moments around the bucket bearing is valid:

$$I_b \cdot \ddot{\varphi} = -W_b \cdot bg \cdot \sin(\varphi+\beta) + m_b \cdot y_b \cdot bg \cdot \sin(\varphi+\beta) - F_a \cdot \cos(\alpha) \cdot bc \cdot \sin(\varphi+\theta) + F_a \cdot \sin(\alpha) \cdot bc \cdot \cos(\varphi+\theta) + F_{ch} \cdot ab \cdot \cos(\varphi) - F_{cv} \cdot ab \cdot \sin(\varphi) - M_e \qquad (3)$$

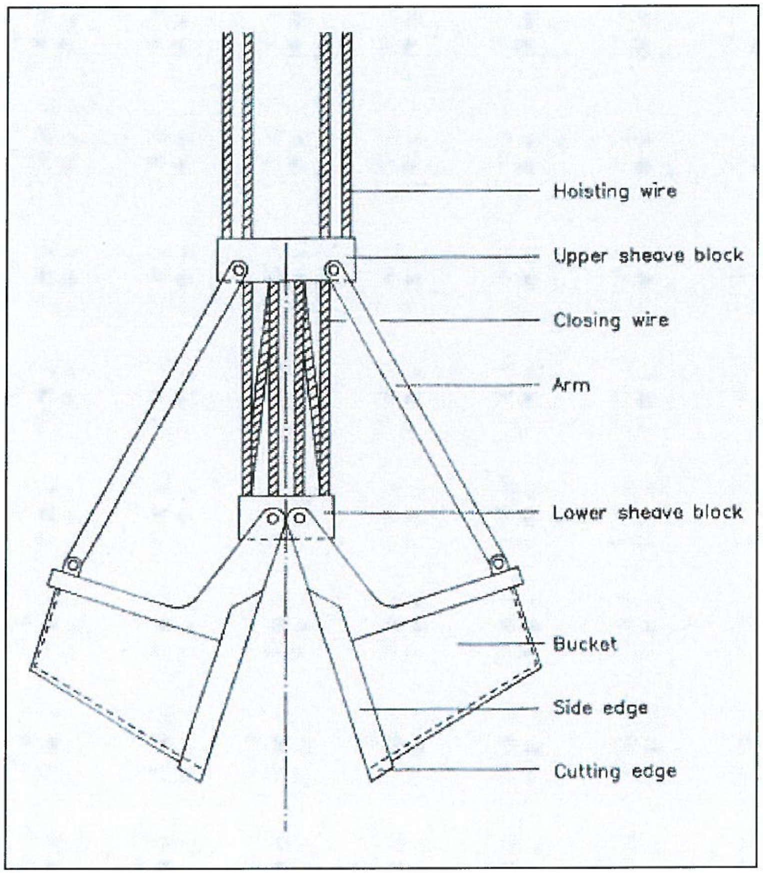

Figure 3: The nomenclature of the clamshell buckets

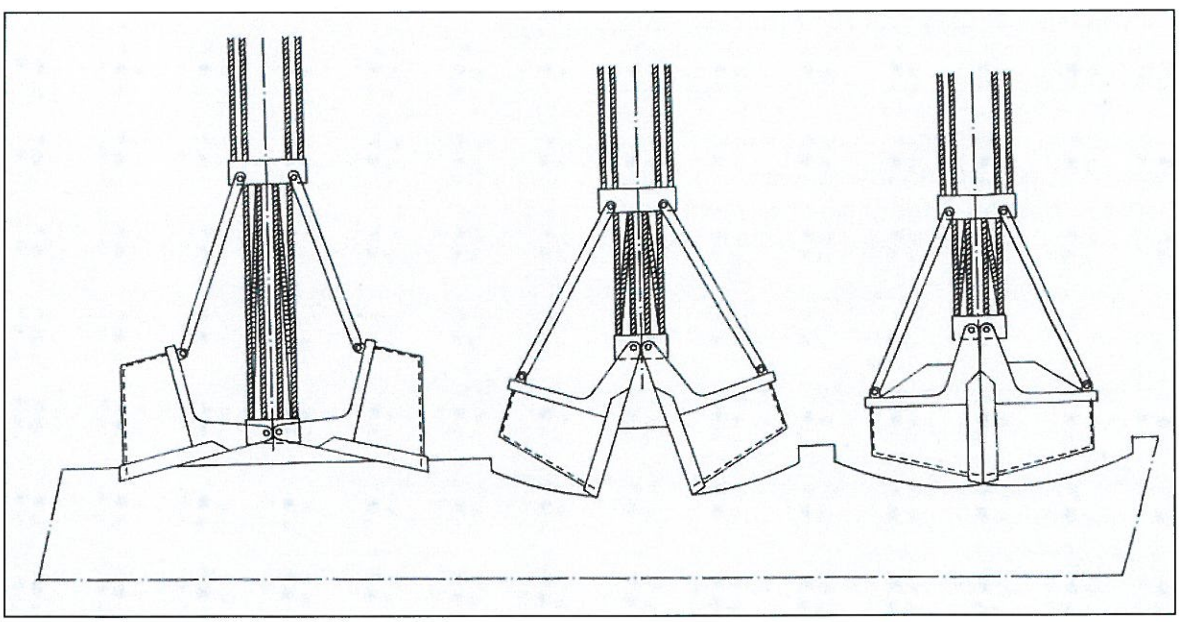

Figure 4: Three stages of the closing process

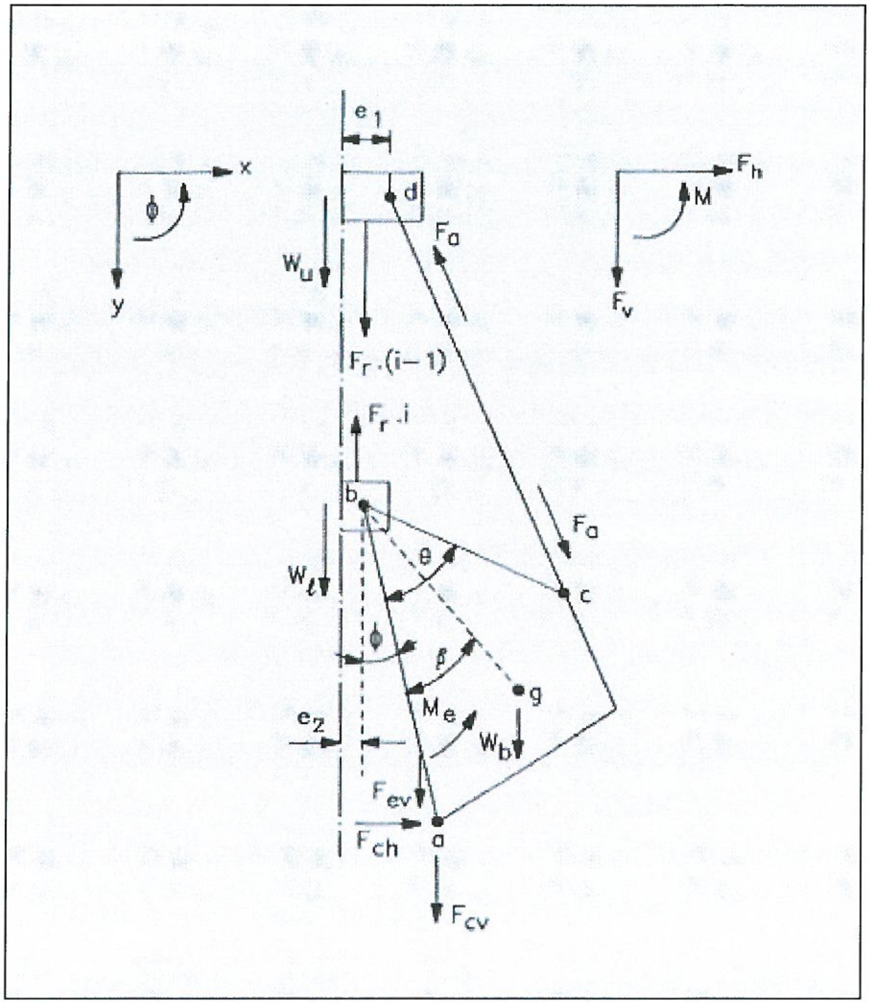

Figure 5: The parameters involved (forces and moments in the clamshell model)

As can be seen, equations (1), (2) and (3) form a system of three coupled non-linear equations of motion. Since in practice the motions of a clamshell depend only on the rope speed and the type of soil dredged, the three equations of motion must form a dependent system, with only one degree of freedom. This means that relations must be found between the motions of the upper sheave block, the lower sheave block and the bucket. A first relation can be found by expressing the rope force as the summation of all the vertical forces acting on the clamshell, this gives:

$$\mathbf{F_r = W_b - m_b \cdot \ddot{y}_b + W_u - m_u \cdot \ddot{y}_u + W_i - m_i \cdot \ddot{y}_i + F_{cv} + F_{ev} + m_b \cdot bg \cdot \cos(\varphi+\beta) \cdot \varphi^2} \qquad (4)$$

Since there are four degrees of freedom in the equations thus derived:

$$\mathbf{\ddot{y}_b, \ddot{y}_l, \ddot{y}_u, \ddot{\varphi}} \qquad (5)$$

One of them has to be chosen as the independent degree of freedom, whilst the other three have to be expressed as a function of the independent degree of freedom. For the independent degree of freedom, φ is chosen as the closing angle of the bucket.

To express the motions of the upper and the lower sheave blocks as a function of the bucket rotation, the following method is applied:

The angle of an arm with the vertical α, can be expressed in the closing angle of the bucket by:

$$\alpha = \arcsin\left[\frac{e_2 - e_1 + bc \cdot \sin(\varphi+\theta)}{dc}\right] \tag{6}$$

The distance between the upper and the lower sheave blocks can now be determined by:

$$|y_u - y_l| = dc \cdot \cos(\alpha) - bc \cdot \cos(\varphi+\theta) \tag{7}$$

As can be seen, the only unknown variable in equations (6) and (7) is the closing angle φ. All other variables are constants, depending only on the geometry of the clamshell. A function $\eta(\varphi)$ can know be defined, which is the derivative of the distance between the sheave blocks with respect to the closing angle of the buckets.

$$\eta(\varphi) = \frac{d\,|y_u - y_l|}{d\varphi} \tag{8}$$

If during a small time interval Δt the length of the closing rope l and the closing angle φ, are subject to small changes Δl and $\Delta\varphi$, the change of the vertical position of the upper sheave block Δy_u can be calculated with:

$$\Delta y_u = \Delta l_r - i \cdot \Delta\varphi \cdot \eta(\varphi) \tag{9}$$

The change of the vertical position of the lower sheave block Δy_l can be expressed by:

$$\Delta y_l = \Delta l_r - (i-1) \cdot \Delta\varphi \cdot \eta(\varphi) \tag{10}$$

In equations (9) and (10) i is the number of parts of line. Dividing the equations (9) and (10) by the time increment Δt gives the equations for the velocities of the upper and the lower sheave block. For the upper sheave block equation (11) is valid.

$$\dot{y}_u = \dot{l}_r - i \cdot \dot{\varphi} \cdot \eta(\varphi) \tag{11}$$

The velocity of the lower sheave block can be calculated with:

$$\dot{y}_l = \dot{l}_r - (i-1) \cdot \dot{\varphi} \cdot \eta(\varphi) \tag{12}$$

The vertical accelerations of the upper and lower sheave block can be calculated by taking the derivative of equations (11) and (12) with respect to the time, this gives for the upper sheave block:

$$\ddot{y}_u = \ddot{l}_r - i \cdot \ddot{\varphi} \cdot \eta(\varphi) - i \cdot \dot{\varphi}^2 \cdot \frac{d\eta(\varphi)}{d\varphi} \tag{13}$$

And, for the lower sheave block:

$$\ddot{y}_u = \ddot{l}_r - (i-1) \cdot \ddot{\varphi} \cdot \eta(\varphi) - (i-1) \cdot \dot{\varphi}^2 \cdot \frac{d\eta(\varphi)}{d\varphi} \tag{14}$$

The vertical acceleration at the centre of gravity of the bucket can be expressed as a function of the vertical acceleration of the lower sheave block and the angular acceleration of the bucket according to:

$$\ddot{y}_b = \ddot{y}_l - \ddot{\varphi} \cdot bg \cdot \sin(\varphi+\theta) \tag{15}$$

The three vertical accelerations can now be expressed as a function of the rotational bucket acceleration. Velocities and motions can be derived by means of integrating the accelerations if boundary conditions are given. The force in the clamshell arm can be calculated from equation (1) if the rope force F_r and the vertical acceleration of the upper sheave block are known. The vertical cutting force F_{cv}, the vertical force on the side edges F_{ev} and the torque on the side edges M_e will be discussed in the next paragraph. Since the equations of motion are non-linear, the equations have to be solved numerically. The solution of this problem is a time domain solution, in this case using the Newton Raphson iteration method and the teta integration method to prevent numerical oscillations.

THE FORCES EXERTED ON THE BUCKETS BY SAND

The buckets of the clamshell are subject to forces and resulting moments exerted out by the sand on the buckets. The forces and moments can be divided into forces and moments as a result of the cutting forces on the cutting edges of the buckets and forces and moments as a result of the soil pressure and friction on the side edges of the buckets.

Figure 5 shows the forces and moments that will be distinguished in the clamshell model. The cutting forces on the cutting edges of the buckets can be calculated with the cutting theory of Miedema (1989) presented at WODCON XII. This theory is based on the equilibrium of forces on the layer of sand cut and on the occurrence of pore under pressures. Since the theory has been published extensively, the theory will be summarized with the following equations: If cavitation does not occur the horizontal force on the cutting edge can be calculated with:

$$F_{ch} = c_1 \cdot \rho_w \cdot g \; v_c \cdot h_i^2 \cdot b \cdot \frac{e}{k_m} \qquad (16)$$

$$F_{cv} = c_2 \cdot \rho_w \cdot g \; v_c \cdot h_i^2 \cdot b \cdot \frac{e}{k_m} \qquad (17)$$

If cavitation does occur the horizontal force on the cutting edge can be calculated with:

$$F_{ch} = d_1 \cdot \rho_w \cdot g \cdot (z+10) \cdot h_i \cdot b \qquad (18)$$

For the vertical cutting force:

$$F_{cv} = d_2 \cdot \rho_w \cdot g \cdot (z+10) \cdot h_i \cdot b \qquad (19)$$

The proportionality coefficients c_1, c_2, d_1 and d_2 can be found in Miedema 1987 [7] or 1989 [8].

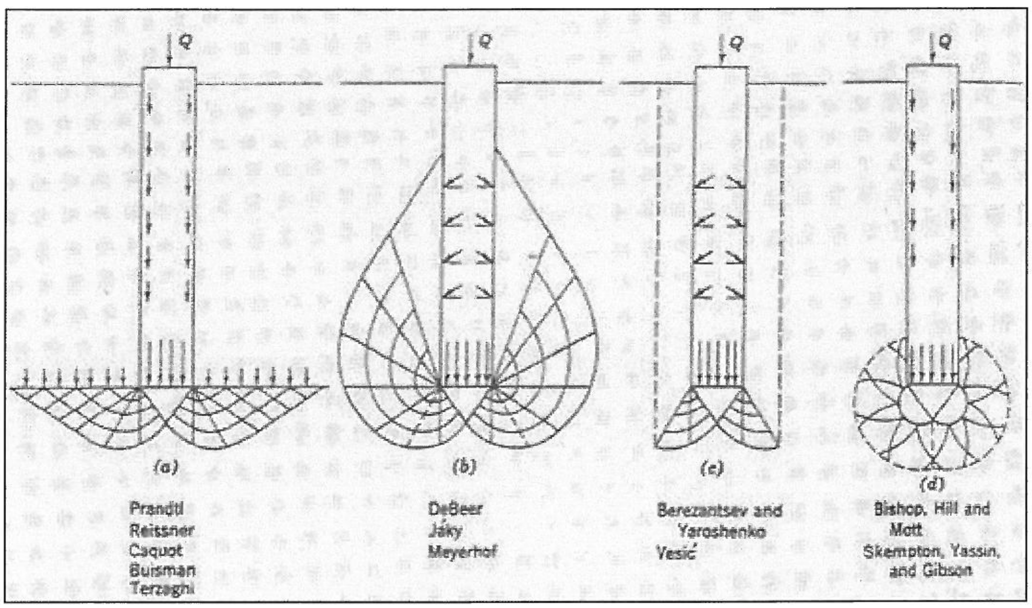

Figure 6: Typical failure patterns that might occur under deep foundations (ref. 23)

The forces and moments on the side edges were unknown when the research started. At first it was assumed that the forces were negligible when cutting sand. From the model experiments Wittekoek (1991) carried out, it appeared that the computer program CLAMSHELL resulted productions that were too high. Changing the mechanical properties of the soil within the accuracy range could not solve this problem. Implementing pressure and friction forces on the side edges improved the calculated results drastically. The forces on the side edges are modeled as the forces on strip footings, Lambe & Whitman (1979). Figure 6 shows some typical failure patterns that might occur under foundations. The general equation for the pressure force on a strip footing is:

$$F_e = A_e \cdot \left(c \cdot N_c + \gamma_s \cdot \delta \cdot N_\gamma / 2 + \gamma_s \cdot h_i \cdot N_q \right) \quad (20)$$

The friction force on the side surfaces of the buckets can be derived by integrating the shear stress over the side surfaces. It appeared from the research that this part of the forces is negligible in sand.

The coefficients N_c, N_γ and N_q can be calculated according to different theories. The best known theory is the theory of Terzaghi for shallow foundations. Theories for shallow and deep foundations have been developed by De Beer, Meyerhof, Brinch Hansen, Caquot-Kerisel, Skempton-Yassin-Gibson, Berantzef, Vesic and Terzaghi. Lambe & Whitman (1979) give an overview of these theories.

The different theories mentioned are based on different failure patterns of the soil. All theories are based on drained conditions, meaning that excess pore pressures can dissipate readily. This assumption is reasonable for static foundations, but not for the digging process of clamshells. During the digging process pore under pressures will occur, increasing the soil pressure on the side edges.

Two problems now occur in modeling the forces on the side edges. The first problem is, which theory to choose for the side edge forces under drained conditions such as those occurring during the initial penetration and the digging process in dry sand. The second problem involves the modeling of the influence of pore pressures on the side edge forces as it occurs when cutting saturated sand.

The first problem was solved by examining the initial penetration and the digging curves that occurred with 8 tests in dry sand. It required some trial and error to find satisfactory coefficients for equation (20). The second problem was solved by examining the initial penetration and the measured digging curves in saturated sand. Although the resulting equation for the force on the side edges is empirical, it is based on a combination of Terzaghi's foundation theory and Miedema's cutting theory.

$$F_e = A_e \cdot \left(\gamma_s \cdot h_i / 2 + \gamma_w \cdot \Delta p \right) \cdot N_q \quad (21)$$

The pore under pressure Δp in equation (21) follows from the sand cutting theory of Miedema (1987). The parts of equation (20) containing N_c and N_γ appeared to be negligible and thus cannot be found in equation (21). To calculate this penetration the empirical formula of Gebhart (1972) can also be used, but does not consider the pore pressures:

$$F_e = 0.14 \cdot e^{0.0019 d_m} \cdot K_f \cdot 1.26^{(\rho_s - 1)} + 0.21 \cdot 10^{-3} e^{(0.0175 d_m)} \cdot (B - 900) + 1.21 \cdot 10^{-3} \cdot e^{(0.0145 d_m)} \cdot (h - 300) \quad (22)$$

RECENT DEVELOPMENTS

When cutting water saturated sand, as is done in dredging, agriculture and soil movement in general, the process is dominated by the phenomenon of dilatancy. Based on pore pressure calculations and the equilibrium of horizontal and vertical forces, equations can be derived to predict the cutting forces. The derivation of this model has been described extensively in previous papers by Miedema et all (1983-2005). In the equations derived, the denominator contains the sine of the sum of the 4 angles involved, the cutting angle α, the shear angle β, the angle of internal friction φ and the soil interface friction angle δ. So when the sum of these 4 angles approaches 180° the sine will become zero and the cutting forces become infinite. When the sum of these 4 angles is greater then 180° the sine becomes negative and so do the cutting forces. Since this does not occur in reality, nature must have chosen a different mechanism for the case where the sum of these 4 angles approaches 180°.

Hettiaratchi and Reece (1975) found a mechanism which they called boundary wedges for dry soil. At large cutting angles a triangular wedge will exist in front of the blade, not moving relative to the blade. This wedge acts as a blade with a smaller blade angle. In fact, this reduces the sum of the 4 angles involved to a value much smaller than 180°. The existence of a dead zone (wedge) in front of the blade when cutting at large cutting angles will affect the value and distribution of vacuum water pressure on the interface. He (1998) proved experimentally that also in water saturated sand at large cutting angles a wedge will occur. The wedge occurs at blade angles larger then 70° and thus has a significant effect on the initial part of the closing process of clamshell's. Figure 7: The static/dynamic wedge gives an impression of the wedge and the velocity distribution in the layer cut.

A series of tests with rake angles 90, 105 and 120 degrees under fully saturated and densely compacted sand condition was performed by Jisong He at the Dredging Technology section of Delft University of Technology. The experimental results showed that the failure pattern with large rake angles is quite different from that with small rake angles. For large rake angles a dead zone is formed in front of the blade but not for small rake angles. In the tests he carried out, both a video camera and film camera were used to capture the failure pattern. The video camera was fixed on the frame which is mounted on the main carriage, translates with the same velocity as the testing cutting blade. Shown in the static slide of the video record, as in fig.1, the boundary wedges exist during the cutting test.

Although the number of experiments published is limited, his research is valuable as a starting point to predict the shape of the wedge. At small cutting angles the cutting forces are determined by the horizontal and vertical force equilibrium equations of the sand cut in front of the blade. These equations contain 3 unknowns, so a third equation/condition had to be found. The principle of minimum energy is used as a third condition to solve the 3 unknowns. This has proved to give very satisfactory results finding the shear angle and the horizontal and vertical cutting forces at small cutting angles. At large cutting angles, a 4th unknown exists, the wedge angle or virtual blade angle. This means that a 4th equation/condition must be found in order to determine the wedge angle. There are 3 possible conditions that can be used: The principle of minimum energy, The circle of Mohr, The equilibrium of moments of the wedge. In fact, there is also a 5th unknown, the mobilized friction on the blade.

On the wedge there is not only an equilibrium of horizontal and vertical forces, but there also has to be an equilibrium of moments. This equilibrium of course should exist around each point of the wedge, but for simplicity reasons the equilibrium equation has been derived around the edge of the blade, resulting in the following equation.

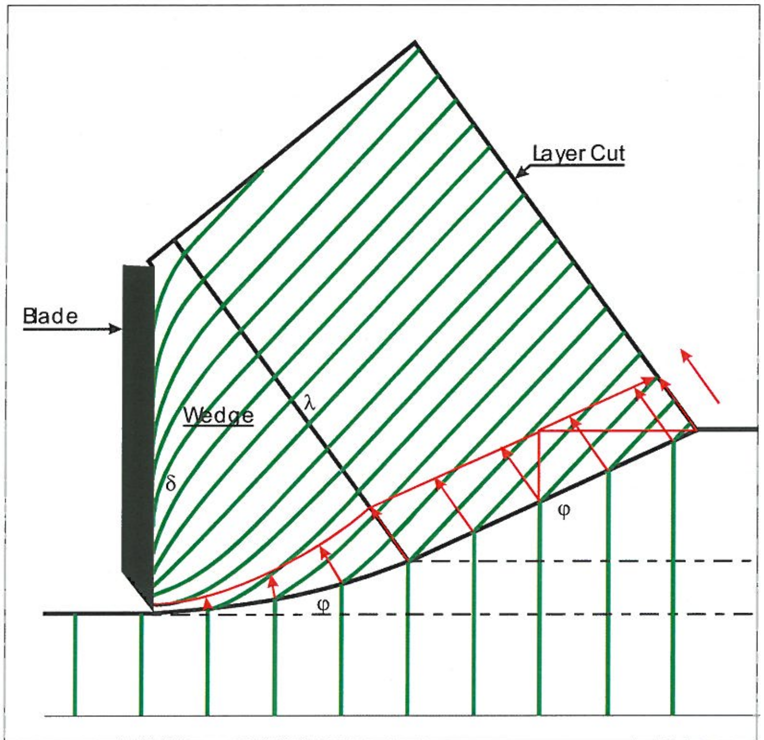

Figure 7: The static/dynamic wedge

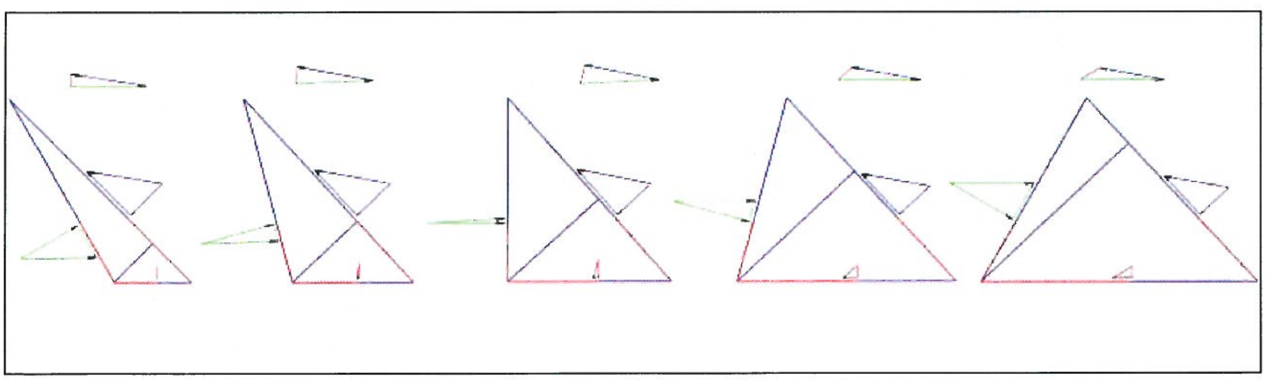

Figure 8: The forces on the wedges at 60°, 75°, 90°, 105° and 120° cutting angles

The resulting moment on the wedge should be zero in the equilibrium situation. Equation 20 contains 3 new parameters e_2, e_3 and e_3 which correspond with the relative positions of the acting points of the forces on the 3 sides of the wedge. The parameter e_2 is the position of the acting point on the interface of the soil cut and the wedge, e_3 on the bottom of the wedge and e_4 on the blade. If an acting point is in the middle of a side the e value would be 0.5.

Figure 8 shows the force triangles on the 3 sides of the wedges for cutting angles from 60 to 120 degrees. From the calculations it appeared that the pore pressures on interface between the soil cut and the wedge and in the shear plane do not change significantly when the blade angle changes. These pore pressures p_1 and p_2 resulting in W_1 and W_2 are determined by the shear angle β, the wedge angle α and other soil mechanical properties like the permeability.

The fact that the pore pressures do not change a lot also results in forces K_2, acting on the wedge that do not change significantly. These forces are shown in figure 8 on the right side of the wedges and the figure shows that these forces are almost equal for all blade angles. These forces are determined by the conventional theory as published by Miedema (1987). Figure 8 also shows that for the small blade angles the friction force on the wedge is directed downwards, while for the big blade angles this friction force is directed upwards.

Now the question is, what is the solution for the cutting of water saturated sand at large cutting angles? From many calculations and an analysis of the laboratory research is described by He (1998), Miedema (2002) and Ma (2001), it appeared that the wedge can be considered a static wedge, although the sand inside the wedge still has velocity, the sand on the blade is not moving. The main problem in finding acceptable solutions was finding good values for the acting points on the 3 sides of the wedge, e_2, e_3 and e_4. If these values are chosen right, solutions exist based on the equilibrium of moments, but if they are chosen wrongly, no solution will be found. So the choice of these parameters is very critical. The values for the acting points of the forces, are $e_2 = 0.35$, $e_3 = 0.55$ and $e_4 = 0.32$, based on the finite element calculations carried out by Ma 2001.The statement that the sand on the blade is not moving is based on two things, first of all if the sand is moving with respect to the blade, the soil interface friction is fully mobilized and the bottom of the wedge requires to have a small angle with respect to the horizontal in order to make a flow of sand possible. This results in much bigger cutting forces, while often no solution can be found or unreasonable values for e_2, e_3 and e_4 have to be used to find a solution. So the solution is, using the equilibrium equations for the horizontal force, the vertical force and the moments on the wedge. The recipe to determine the cutting forces seems not to difficult now, but it requires a lot of calculations and understanding of the processes, because one also has to distinguish between the theory for small cutting angles and the wedge theory.

The following steps have to be taken to find the correct solution:

1. Determine the pore pressures p1, p2, p3, p4 using a finite element calculation or the method described by Miedema (2005), for a variety of shear angles β and wedge angles α around the expected solution.
2. Determine the shear angle β based on the equilibrium equations for the horizontal and vertical forces and the principle of minimum energy, which is equivalent to the minimum horizontal force. This also gives a value for the resulting force K_2 acting on the wedge.
3. Determine values of e2, e3 and e4 based on the results from the pore pressure calculations.
4. Determine the solutions of the equilibrium equations on the wedge and find the solution which has the minimum energy dissipation, resulting in the minimum horizontal force on the blade.
5. Determine the forces without a wedge with the theory for small cutting angles.
6. Determine which horizontal force is the smallest, with or without the wedge.

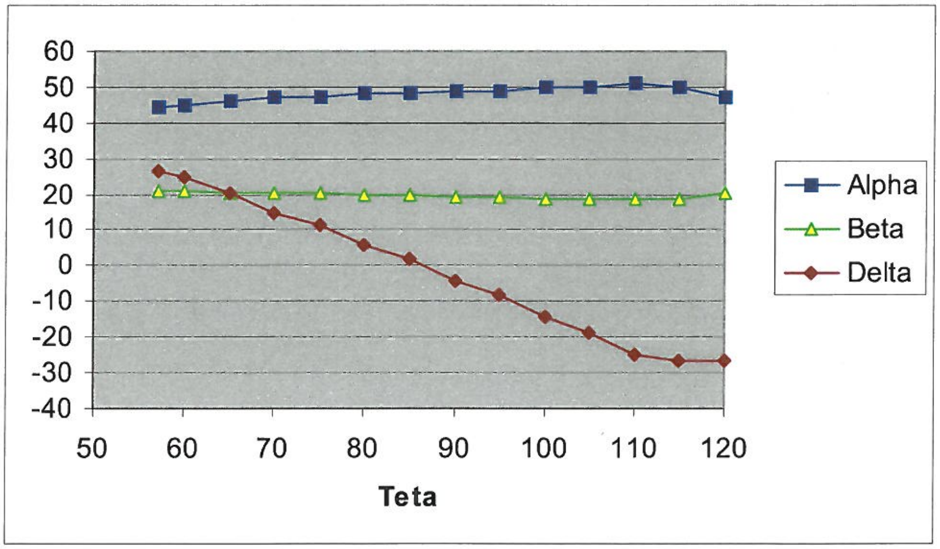

Figure 9: The wedge angle, shear angle and soil interface friction angle as a function of the blade angle (φ of 40°)

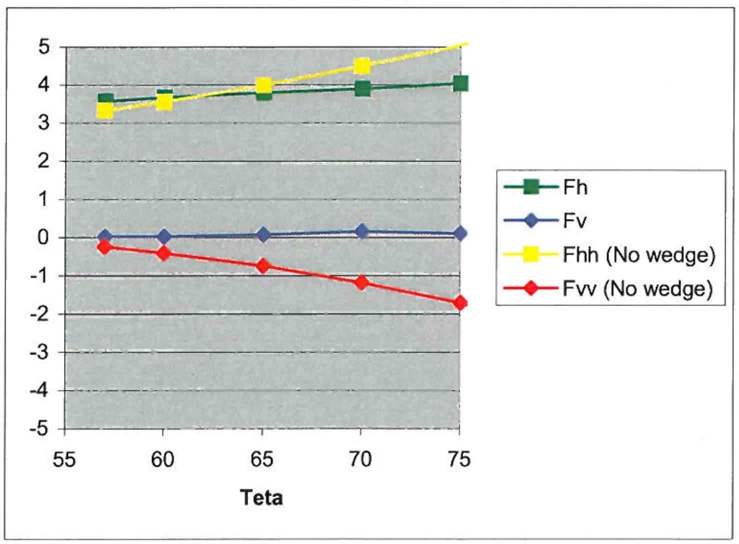

Figure 10: The cutting forces as a function of the blade angle θ, with and without a wedge (φ of 40°)

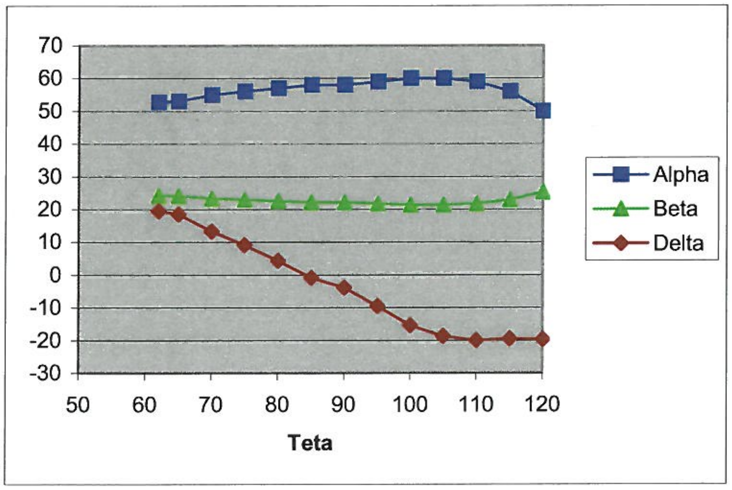

Figure 11: The wedge angle, shear angle and soil interface friction angle as a function of the blade angle (φ of 30°)

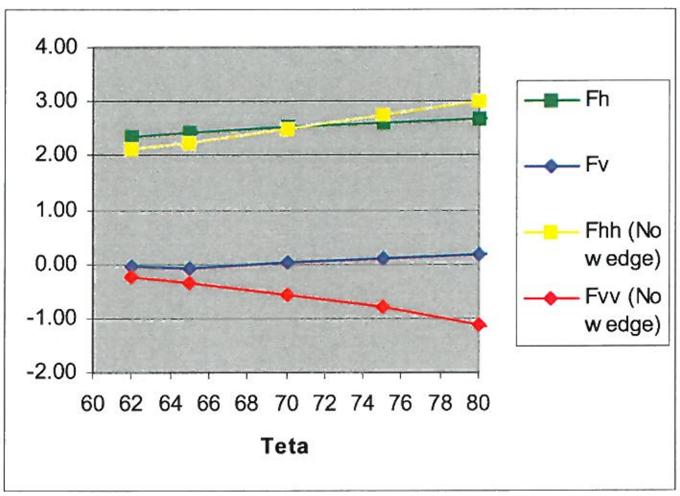

Figure 12: The cutting forces as a function of the blade angle θ, with and without a wedge (φ of 30°)

Figures 9, 10, 11 and 12 show the results of calculations of the non-cavitating cutting process for 2 types of sand. From these calculation the conclusions can be drawn that the wedge angle α can be approximated by 90-φ, while the wedge starts to occur at a blade angle θ of about 63° for the case with an internal friction angle of 40° and at a blade angle θ of about 70° for the case with an internal friction angle of 30°. This gives a first estimate for the occurrence of the wedge for the non-cavitating cutting process according to:

$$\alpha = 90 - \frac{2}{3} \cdot \varphi \tag{23}$$

For the cavitating cutting process the results are similar. In this case the wedge angle α is exactly 90-φ, while the transition of no wedge versus wedge occurs at 68 ° and 77 °, leading to the following transition blade angle:

$$\alpha = 90 - 0.014 \cdot \varphi^2 \tag{24}$$

Equations 23 and 24 are first approximations and will be investigated further in the future. For the non-cavitating cutting process, the cutting forces will continue to increase slightly from the transition blade angle, when the blade angle increases. For the cavitating process however, these forces remain almost constant up to a blade angle larger then 100 °, where they start increasing again. The direction of the cutting forces however does change with an increasing blade angle.

The main conclusion of the cutting theory for large blade angles is, that the occurrence of the wedge influences the initial phase of the cutting process of a clamshell significantly.

CASE STUDIES

For the case studies the 50 cy yd clamshell of the Chicago has been chosen, because detailed data of this clamshell was available. Figure 13 shows the model of this clamshell, while figure 14 shows the clamshell in open position on the soil.

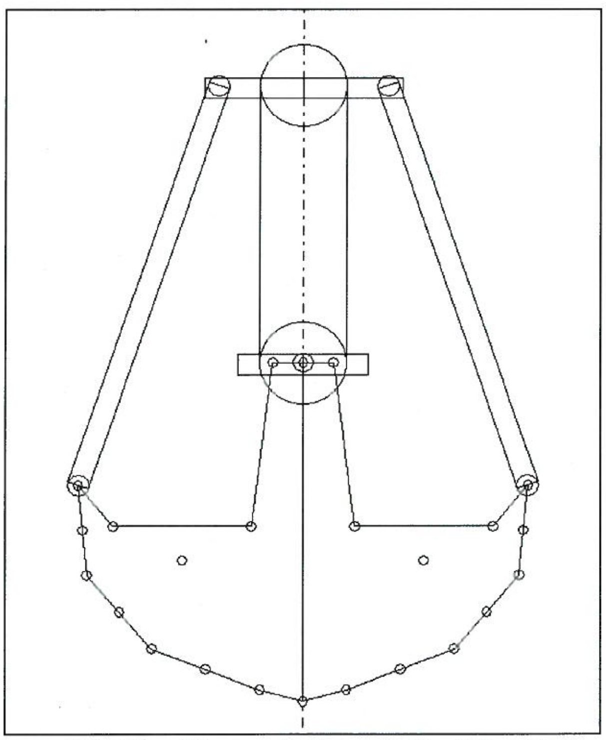

Figure 13: The 50 cu yd clamshell of the Chicago

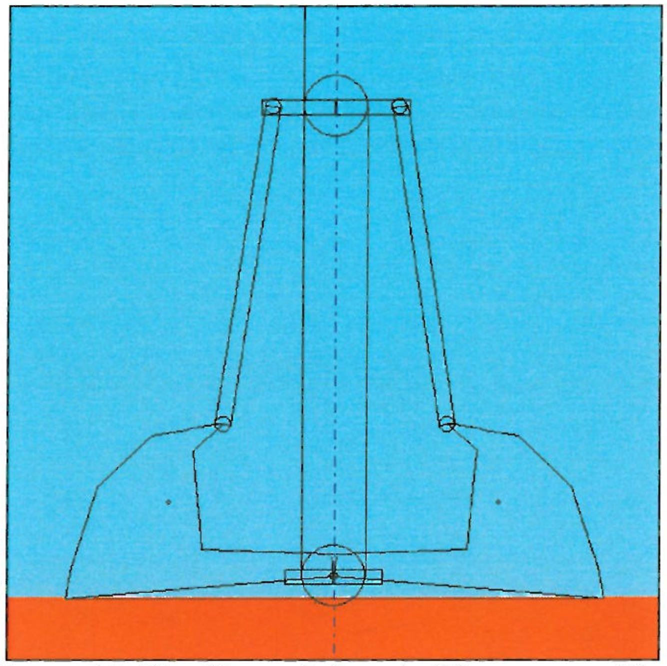

Figure 14: The 50 cu yd clamshell in open position

Some important data of this clamshell is given in table 1, while table 2 gives the soil mechanical parameters of the sands used.

Table 1: Main data of the 50 cu yd clamshell

Total mass	45.6	ton
Total volume	42.7	m^3
Arm	1.0	ton
Lower block	1.5	ton
Upper block	2.3	ton
Bucket	15.0	ton
Sheaves, etc.	4.0	ton
Height	4.14	m
Length	5.20	m
Width	4.11	m

Table 2: The soil mechanical parameters of the sands used

	φ (°)	δ (°)	n (32-50)	k_i (m/sec)	k_{max} (m/sec)
Very loose sand	26	17	48	$4 \cdot 10^{-4}$	$16 \cdot 10^{-4}$
Loose sand	30	20	46	$2 \cdot 10^{-4}$	$8 \cdot 10^{-4}$
Medium sand	34	23	44	$1 \cdot 10^{-4}$	$4 \cdot 10^{-4}$
Dense sand	39	26	42	$0.5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Very dense sand	44	31	40	$0.25 \cdot 10^{-4}$	$1 \cdot 10^{-4}$

With these sands simulations have been carried out with the program CCS (Clamshell Closing Simulation) with rope speeds of 0.5, 1.0 and 1.5 m/sec, blade angles of 12° and 15° and with and without an extra added mass on the upper block of 20 tons. Besides this, a number of simulation have been carried out with an equivalent hydraulic closing mechanism according to figure 15. All the results are compared with the default clamshell case, which has no added mass, a blade angle of 12 °, a rope speed of 1m/s and medium sand. The results of the simulations can be found in table 3.

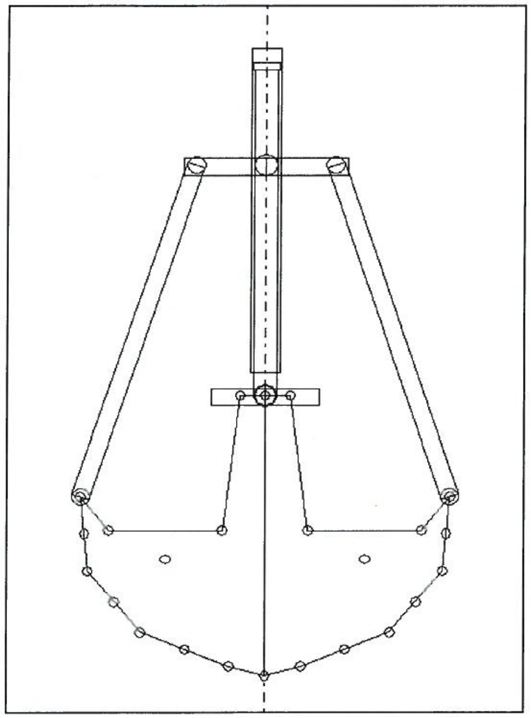

Figure 15: The 50 cu yd clamshell with a hydraulic closing mechanism

Table 3: The results of the simulation

Rope speed	Sand	Default	20 tons added	15 degree blade	H default	H 20 tons added	H 15 deg blade
	vls	81.56	83.94	80.38			
	ls	32.49	40.75	30.33			
0.5	ms	12.95	16.23	12.09			
	ds	5.19	6.49	4.89			
	vds	2.06	2.57	1.95			
	vls	66.03	79.13	60.50	83.67	85.83	82.75
	ls	23.30	28.74	22.76	36.33	43.25	34.66
1.0	ms	9.59	11.75	8.86	12.62	15.34	11.98
	ds	3.82	4.68	3.57	4.34	5.29	4.13
	vds	1.54	1.89	1.45	1.59	1.97	1.48
	vls	52.38	66.71	48.98			
	ls	19.77	23.74	19.53			
1.5	ms	8.21	9.78	7.94			
	ds	3.34	3.91	3.10			
	vds	1.37	1.61	1.26			

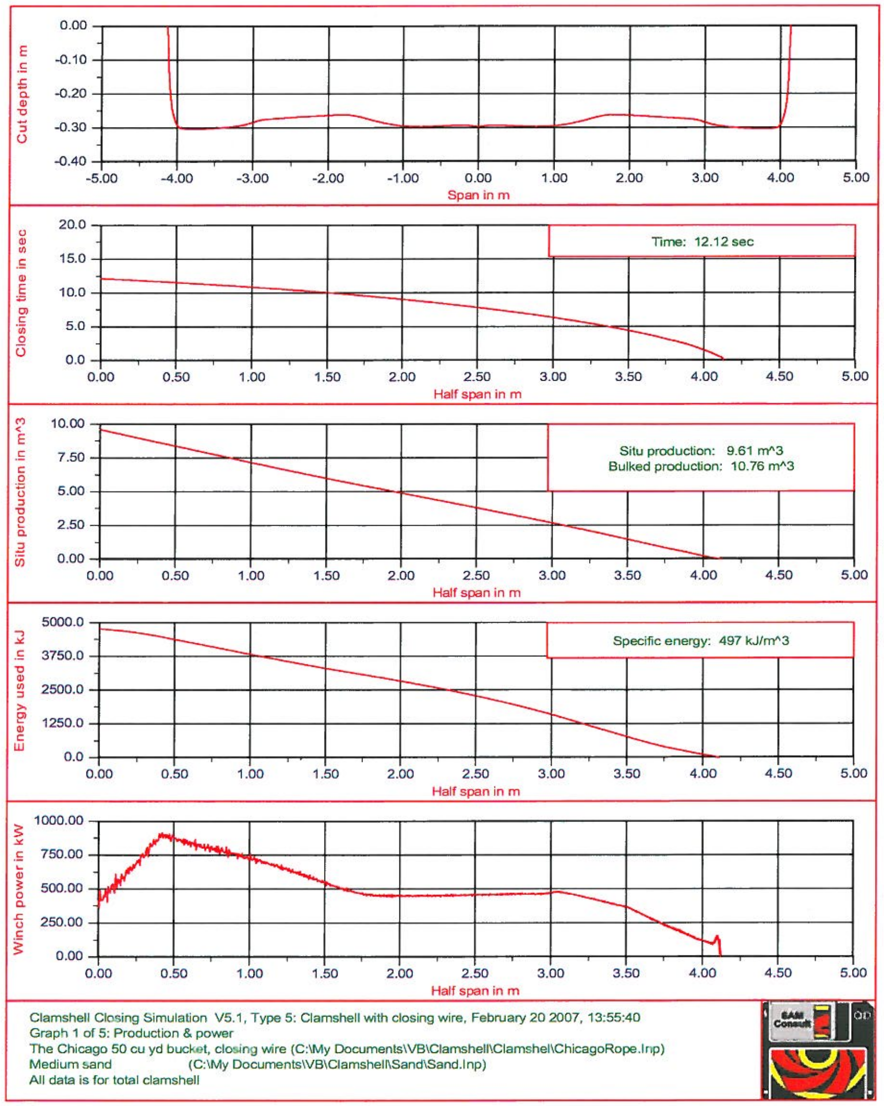

Figure 16: The output of CCS

CONCLUSIONS

Applying the new wedge theory to the closing process of clamshells has a significant effect. The magnitude and the direction of the cutting forces at the start of the closing process when the blade angle is big, will change considerably in relation with the conventional cutting theory, which did not include the wedge mechanism.

From the simulations the following conclusions can be drawn:

1. In general it is only useful to use the clamshell in very loose, loose and medium sands (see the definition in table 2). The production in dense and very dense sand is to low to be economical. For medium sand one can discuss if a filling of about 25% is economical or not.
2. The filling percentage depends strongly on the rope speed, which is caused by the cutting process. From the simulations it appeared that the cutting process is non-cavitating in all cases which results in cutting forces that are proportional to the cutting speed and thus the rope speed. Using a smaller rope speed should be considered, regarding the fact that it may increase the production counted over a full cycle of the clamshell.
3. Adding mass to the upper block has a positive effect on the production, however this effect is limited. The total weight of the clamshell increases from about 46 tons to about 66 tons requiring a stronger winch and a stronger crane. It is the question if this is economical regarding the greater investment.
4. Making the cutting angle bigger reduces the production slightly but not significant. It is advisable to use a blade angle as small as possible, but there will be constraints due to the construction of the clamshell.

Using a hydraulic closing mechanism gives a significant increase of the production in all cases. This is caused by the fact that using a rope with sheaves always gives the upward force in the closing wire, carrying part of the weight of the clamshell. The weight is thus not available entirely for the penetration in the sand. With the hydraulic clamshell 100% of the weight is available for the closing process.

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NOMENCLATURE

Ab	Distance between cutting edge and bucket bearing	m
A_e	Surface of side edges (thickness*length)	m^2
B	Width of the buckets	m
Bc	Distance between bucket bearing and arm bearing	m
Bg	Distance between bucket bearing and centre of gravity	m
B	Width of grab	m
C	Cohesion	Pa
c_1	Proportionality coefficient non-cavitating cutting forces	-
c_2	Proportionality coefficient non-cavitating cutting forces	-
d_1	Proportionality coefficient cavitating cutting forces	-
d_2	Proportionality coefficient cavitating cutting forces	-
Dc	Length of arm	m
d_m	Average grain diameter	μm
E	Volume fraction of dilatational expansion	-
e_1	Eccentricity arm bearing upper sheave block	m
e_2	Eccentricity bucket bearing lower sheave block	m
F_a	Force in one arm	N
F_{ch}	Horizontal force on the cutting edge	N

F_{cv}	Vertical force on the cutting edge	N
F_e	Force on side edges	N
F_{ev}	Vertical force on the side edges	N
F_r	Force in the closing rope (wire)	N
g	Gravitational constant (9.81)	m/s^2
h_i	Thickness of layer cut	m
h	The initial penetration	m
i	Number of parts of line	-
I_b	Mass moment of inertia of bucket	$kg \cdot m^2$
k_m	Average permeability	m/s
K_f	The grain shape factor	-
l	Rope length	m
L	Length of fully opened grab	m
m_b	Mass + added mass of bucket	N
m_l	Mass + added mass of lower sheave block	kg
m_u	Mass + added mass of upper sheave block and arms	kg
M_{bucket}	Mass of grab	kg
M_f	Mass of grab fill	kg
M_e	Moment of side edge forces around bucket bearing	Nm
N_c	Terzaghi coefficient	-
N_γ	Terzaghi coefficient	-
N_q	Terzaghi coefficient	-
p	Pressure	Pa
v_c	Cutting velocity	m/s
W_b	Underwater weight of bucket	N
W_l	Underwater weight of lower sheave block	N
W_u	Underwater weight of upper sheave block and arms	N
y_b	Vertical position of bucket centre of gravity	m
y_l	Vertical position of lower sheave block	m
y_u	Vertical position of upper sheave block	m
z	Water depth	m
α	Angle of arm with vertical	rad
β	Angle between cutting edge, bucket bearing and bucket centre of gravity	rad
φ	Closing (opening) angle of bucket with vertical	rad
θ	Angle between cutting edge, bucket and arm bearings	rad
$\eta(\varphi)$	Function	m
ρ_w	Density water	kg/m^3
γ_w	Specific weight of water	N/m^3
ρ_s	The situ density of material to be dredged	kg/m^3
γ_s	Specific weight of sand under water	N/m^3
δ	Thickness of side edges	m

NOTES FOR CONTRIBUTORS

GENERAL

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Introduction, main body, and following text, conclusions, nomenclature (if necessary), and references.
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$$y = a + b + cx^2 \quad (1)$$

References

References in the text should be given as: Smith (1988), (Smith, 1988) or (Jones et al., 1986). References should be listed alphabetically in the References section at the end of the paper. Give the names and initials of all authors, followed by the title of the article and publication, the publisher and the year of publication. References to conference papers or proceedings should include the name of the organizers. References to articles published in journals should also include the name of the journal, the number of the issue and page numbers (see example below). References to publications in a foreign language should give all details in the original language followed by a translation of the title.

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Figures and Tables

High quality figures and tables should be incorporated into the body of the text. Figures must not be placed at the end of the paper. Leave spaces for photographs. Figure captions should be below the figure; table captions should be above the table.

Line drawings

The lines and lettering on the figures should be clearly legible. If originals cannot be supplied, ONLY BLACK AND WHITE COPIES OF VERY HIGH QUALITY are suitable for reproduction. PENCIL AND PHOTOCOPIES OR COPIES WITH A BACKGROUND COLOR ARE NOT SUITABLE.

Photographs

Photographs must be sharp, high contrast, glossy prints. Please use a pencil to indicate the title of the paper, figure number and title and top edge on the back of each photograph. <u>Paste in the photographs where they should appear in the final manuscript.</u> <u>Place captions under the photograph as part of the text.</u>

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