FACTORS USED IN ESTIMATING THROUGHPUT FOR CUTTER SUCTION DREDGES

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ABSTRACT

Many factors contribute to limitations in the throughput of cutter suctions dredge. While most performance data available from cutter suction dredge manufactures outlines theoretical design throughput, others factors need to be considered when computing expected throughput. This is obviously important for estimating purposes but also to understand what factors cause limitations on the performance of the dredges. This paper will go into detail on understanding the effects on bank height and its relation to throughput rates. The paper will address cutter limitations by showing the affect of throughput on a dredge that is excavating material with high compaction rates with cutter systems under and properly designed to meet the required breakout forces. The paper will address the effects of different material types and how the material classifications affect the performance of the dredge. This paper will also detail pump limitations and the overall system designs required for optimal equipment efficiency. Other factors that will be addressed include; dredge pump location with respect to dredging depth, pipeline choice, pipeline length, dredge repositioning time, cut width and the overall efficiency of the dredging system.

Keywords: Excavation, acquisition, transportation, compaction, limitation

INTRODUCTION

The actual production output of a cutter suction dredge is governed by numerous conditions including atmospheric conditions, the physical site, the design and condition of the dredge and support equipment and the skill of management and operations staff; estimating throughput requires knowledge about each of these. The factors that limit cutter suction dredge production can be broadly grouped into four categories: excavation, acquisition, transportation, and operations. On any given job, one of the first three factors will set the theoretical throughput of the dredge, while the fourth factor, operational efficiency, will lower the production to the level that is actually achieved. It is important to clearly define and understand and apply each of these factors to accurately estimate cutter suction dredge throughput.

This paper will provide an introductory look at the physical limitations of different types of dredges in varying types of deposits. Three bank failure models are introduced: partial shear, thin shear, or sliver, and full shear with cave-in. All of these models are idealized, but combined represent conditions that are represented in normal operation.

Five different dredge types are explored as well: conventional spud dredge, spud carriage dredge, kicking spud dredge, single stern wire dredge, and three stern wire (Christmas tree) dredge. Each of these dredges advantages and disadvantages that can be explored through the bank failure calculations.

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Excavation

The excavation limitation of a dredge encompasses all of the conditions that are involved in controlling the maximum rate at which sediments can be sheared loose from the in-situ soil so that it can readily be acquired by the dredge pump. The most prevalent of these conditions are the soil geology and the dredge cutter, swing and mooring systems. The excavation rate for a cutter suction dredge can be defined by:

$$V_e = 60 * Z_e * L_e * S_e \quad (1)$$

V_e = excavated volume in m^3/hr
Z_e = average depth of cut in m
L_e = average length of cutter engaged in m
S_e = average swing speed perpendicular to the channel in m/min

Soil strength, consistency, and geometry are all factors that must be investigated to estimate the dredge throughput. Soils can vary greatly from fine grained to coarse grains to solid rock; for simplicity, this paper will only consider soils that are granular (sandy) in nature and will not directly address fatty clays or materials with definite cleavages like un-blasted rock. Soil strength, or shear stress, is influenced by both the geometry of interlocking particles and chemical action that has or is occurring between these particles. It is often difficult to get accurate shear stress values when estimating dredging jobs, but Standard Penetration Test (SPT) results are often provided with borings. SPT values, commonly recorded in blows per foot, N_{SPT}, may be unreliable but can provide clues to the materials strength. From field experimentation in sandy soils, shear stress can be approximated as follows:

$$\sigma_e = 3{,}900 * N_{SPT} \quad (2)$$

σ_e = excavation shear stress in N/m^2
N_{SPT} = number of blows per foot

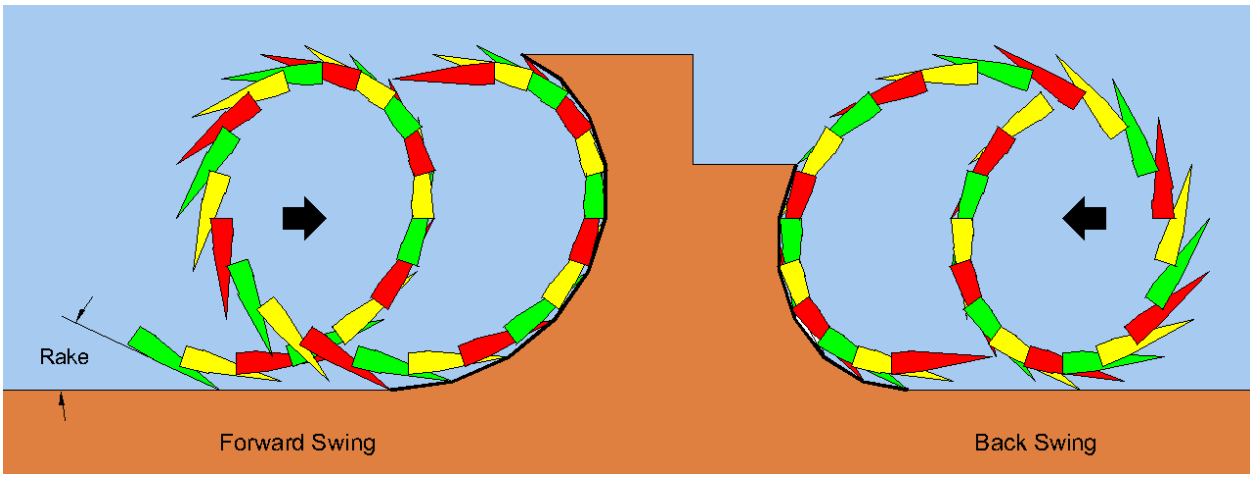

Figure 1. Cutter Tooth Path

Figure 1 depicts the path that a single cutter tooth scribes during both the forward and back swing of the cut. The motion is complicated in that there is both rotational and linear motion taking place simultaneously. The forward cut can be described as a reverse cycloid and the back swing as a sliding cycloid (similar to a Spirograph curve). The tooth is alternatively colored every 18 degrees from green to yellow to red for clarity; several other features are evident in this figure.

A highlighted curve is illustrated along the surface of both the forward cut and back swing. The area created by extruding this arc along the length of the cutter engagement is the shear area and, along with the soil shear stress, determines the cutter torque and the swing force required. The equation for this exact arc length involves high level Calculus and specific cutter geometry and is not easily attainable without an equation solver; however, under normal dredging conditions, the maximum height of cut can be estimated as follows:

$$Z_{fe} \cong 0.5 * D_e * (1 - \cos(3.625 * T_e / (\sigma_e * L_e * D_e^2))) \quad (3)$$

Z_{fe} = forward swing depth of cut in m
T_e = available cutter torque in N-m
D_e = cutter outside diameter in m

The cosine term in equation 3 should be evaluated in radians; if a calculator with a radians function is not available and degrees must be used, then the term in cosine parenthesis must be multiplied by 57.296. Most modern cutter drives are constant torque devices where the cutting power increases with speed and the torque remains unchanged; some older AC electric cutter drives may have variable torque where both power and torque increase with speed. For equation 3, it is important to know the available cutter torque at the operational speed selected; this information is readily available from dredge manufacturers and suppliers. A typical value for the length of cutter engagement or set, L_e, is 0.4 to 0.5 times the cutter outside diameter.

In Figure 1, the forward swing height is shown much higher than the back swing height; this is common in dredging since the back swing tooth forces tend to lift the ladder out of the cut if there is not sufficient dredge ladder mass or external force from a cylinder to hold it down; the cutter tooth forces also push the cutter into the cut causing the swing force to be low and the braking force on the opposite winch to be high to prevent run-away. The opposite is true of the forward swing as the cutter forces pull the cutter downward; the swing winch force increases as the cut height approaches the half diameter height and then reduce as the cut deepens. This paper will not explore cutting on the back swing in detail or the required swing forces as current model dredge designs take this into account; the assumption will be made that the height of the cut during the back swing will be one half of the forward swing and the swing speed will be similar.

$$Z_e = (Z_{fe} + Z_{be}) / 2 \quad (4)$$

Z_{be} = back swing depth of cut (0.5 * Z_{fc} for this paper) in m

Cutter rotational speeds are usually variable and should be adjusted for the various materials encountered. The rotational speed also varies with the cutter diameter. This relationship can be expressed as:

$$N_e = S_t / (D_e * 3.1416) \quad (5)$$

S_t = cutter tip speed in m/min

Typical values for the cutter tip speed are: 75 m/min for silty or loose materials, 125 m/min for sand and gravel materials, and 175 m/min for cemented soils or rock. A typical value for the cutter rake angle is 20 - 30 degrees; this angle controls the maximum perpendicular cutter speed achievable without having the back sides of the cutter blade come into contact with the bank. The perpendicular swing speed is a function of cutter rotational speed, cutter diameter, number of cutter blades, and the cutter rake angle. This speed is generalized for a common rake angle in the following:

$$S_{fe} = N_e * D_e * b_e / 10.67 \quad (6)$$

S_{fe} = forward swing speed perpendicular to the channel in m/min
N_e = cutter rotational speed in RPM
b_e = number of cutter blades

$$S_e = (S_{fe} + S_{be}) / 2 \quad (7)$$

S_{be} = back swing speed perpendicular to the channel (S_{fe} for this paper) in m/min

Figure 1 shows the cutter traveling at the maximum speed that is possible for the rotational speed as the backside of the cutter blade is nearly in contact with the soil.

Finally, since the dredge travels in an arc, the actual travel distance is the length of the arc which is longer than the perpendicular channel distance. Depending on the swing anchor position and length of the dredge or ladder, the swing winch speed may be much greater than S_e. A safe assumption on the maximum swing winch speed is S_e / 0.7; if the swing winches are not capable of this rate, than S_e should be reduced to 0.7 * the swing winch speed.

With values for L_e, S_e, and Z_e computed, equation 1 can now be solved for the excavation limitation for the dredge.

Acquisition

The acquisition, or suction, limitation of a cutter suction dredge controls the volume of water and solids that can be slurrified and made available to the dredge pump; the factors involved in limiting acquisition throughput are varied and include atmospheric conditions, site conditions, and the design of the dredge and dredge pump. The acquisition rate of any hydraulic dredge can be defined by:

$$V_a = Q_a * cv_a \quad (8)$$

V_a = acquired volume in m^3/hr
Q_a = acquisition flow rate in m3/hr
cv_a = acquisition concentration of solids by volume

The values for flow and concentration that the acquisition system is capable of are dependent solely on conditions on the suction side of the first dredge pump. Centrifugal pumps require a certain amount of positive suction head at their inlets in order to operate. The amount required is determined by the pump manufacturer and varies with the type of impeller inlet, impeller design, pump flow rate, pump rotational speed, and the nature of the liquid. For smaller higher speed pumps, the $NPSH_r$ can be as high as 6 meters and for larger, slower turning pumps as low as 1 meter. The amount of suction head available, $NPSH_a$, must always be equal or greater than what is required by the pump.

$$NPSH_a >= NPSH_r \quad (9)$$

$NPSH_a$ = net positive suction head available in m of liquid
$NPSH_r$ = net positive suction head required by the pump in m of liquid

The $NPSH_a$ value is comprised of the atmospheric pressure, vapor pressure, static or vertical head, and dynamic head. The static head term influenced by the slurry concentration and the dynamic head term is a function of both the flow rate and the slurry concentration:

$$NPSH_a = h_{atm} – h_{vap} - h_{sta} – h_{dyn} \quad (10)$$

h_{atm} = atmospheric pressure in m of liquid
h_{vap} = vapor pressure in m of liquid
h_{sta} = static pressure in m of liquid
h_{dyn} = dynamic pressure in m of liquid

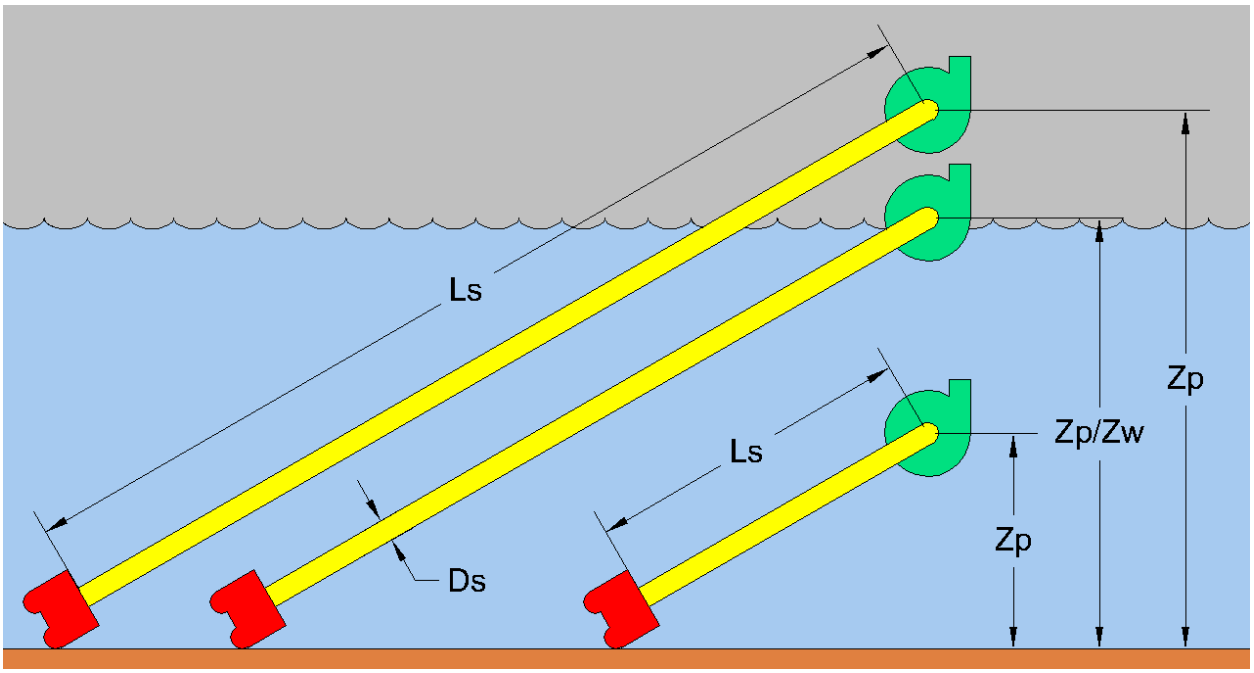

Figure 2. Acquisition Layout

Both atmospheric pressure and vapor pressures are available in tables for a given altitude and temperature. At sea level and 20 degrees Centigrade, the atmospheric pressure is 10.35 meters of liquid and the vapor pressure is 0.24 meters of liquid (liquid is water). It should be noted that vapor pressure rises with rising liquid temperature and atmospheric pressure decreases with increasing altitude.

Figure 2 depicts the layouts of three different dredge systems, an above deck pump system, a surface mounted pump system and a submerged pump system. While still popular in some older mine sites, above deck pump dredges have fallen out of favor due to their poor acquisition systems. These dredges must rely on jet pumps to add net positive suction head; unfortunately most jet pumps operate at an efficiency level of less than 25 percent. Because of this, jet pumps will not be considered in this paper.

The static head term is dependent on the dredge pump location with respect to the bottom, the water level with respect to the bottom, the solids specific gravity, the fluid specific gravity, and the solids concentration.

$$h_{sta} = Z_p * cv_a * (SG_s - SG_l) + SG_l * (Z_p - Z_w) \quad (11)$$

Z_p = pump height above bottom in m
Z_w = water height above bottom in meters in m
SG_s = specific gravity of solids in g/cm^3
SG_l = specific gravity of liquid in g/cm^3

The dynamic head term contains three distinct parts, an acceleration loss, an entrance loss, and a friction loss. Each of these losses is evaluated for the carrying liquid and the solids portion. The combinations of these losses results in the following equation:

$$h_{dyn} \cong L_s * (f_s * Q_a^2 / (156849727 * D_s^5) + 0.22 * L_s * cv_a * (SG_s - SG_l) * (w * (8/f)^{0.5} * \cosh (60 * d_{50} / D_s) / (2827 * Q_a * D_s^2))^{1.7} + 1.5 * (cv_a * (SG_s - SG_l) + SG_l) * Q_a^2 / (49926819 * D_s^2) \quad (12)$$

L_s = length of suction in m
f_s = suction friction factor for Darcy-Weisbach formula
D_s = suction pipe inside diameter in m
w = particle associated velocity in m/sec
d_{50} = average particle diameter in m

The value for w requires solving for a number of equations as it varies with the particle mean diameter, shape factor, fluid density, and terminal velocity. w can be estimated by Equation 13 for particles that are shaped and have a density similar to sand; this equation should not be used for materials such a coal, fly ash, clays, etc.

$$w \cong (0.068611073 + 98.247385 * d_{50}) / (1+175.902 * d_{50} - 1273.5009 * d_{50}^2) \quad (13)$$

The dynamic head term varies with both the concentration of solids and the flow rate for a specific suction pipeline. An iterative process is often employed to accurately maximize the throughput; for estimating purposes, research done by Durand provides a relationship between the minimum flow rate for a given pipeline inside diameter with sand-water suspensions at common concentration levels seen in dredging as follows:

$$Q_a \cong 21557 * D_s^{2.5} \quad (14)$$

D_s = pipeline inside diameter in m

With Q_a estimated, the friction factor can be computed or found on the Moody Diagram.

$$f_s = (1 / (\log (\varepsilon_s / (3.7 * D_s) + 2.51 / (R_s * f_s^{0.5}))^2 \quad (15)$$

ε_s = absolute roughness of suction pipe in m
R_s = Reynolds number, $Q_a / (2827 * D_s * \upsilon)$
υ = kinematic viscosity in m^2/sec

Typical values for the relative roughness, ε, of steel and plastic pipeline is 0.00004572 and 0.00001524 respectively; the kinematic viscosity of water at 20 degrees Centigrade is 1.00E-6. The friction factor, f_s, can be calculated by

iteratively substituting the previously calculated value of f several times, starting with a value of 0.012 or it can be estimated by the following:

$$f_s \cong a * b^{(1/Ds)} * D_s^{c} \quad (16)$$

a = 0.010720544 for steel or 0.0094755416 for plastic pipe
b = 1.0118545 for steel or 1.0124177 for plastic pipe
c = -0.19113378 for steel or -0.19675875 for plastic pipe

The maximum acquisition concentration can be computed at the minimum flow rate from equation 14 by equating the $NPSH_a$ and $NPSH_r$ by the following equation:

$$cv_a = (h_{atm} - h_{vap} - NPSH_r - SG_l * (Z_p - Z_w) - L_s * f_s * Q_a^2 / (156849727 * D_s^5) - SG_l * 1.5 * Q_a2 / (49926819 * D_s^2)) / (Z_p * (SG_s - SG_l) + 0.22 * L_s * (SG_s - SG_l) * (w * (8 / f_s)^{0.5} * \cosh (60 * d_{50} / D_s) / (2827 * Q_a * D_s^2))^{1.7} + (SG_s\, SG_l) * 1.5 * Q_a^2 / (49926819 * D_s^2)) \quad (17)$$

There are physical limitations to the concentration that can be carried in both the acquisition and transport systems. A good practical maximum is 0.3; this value should be used in equation 8 if it is computed as a higher value.

Transportation

The transportation limitation of a cutter suction dredge includes all factors that influence the discharge capability of the system, primarily head and power restrictions. Properly placed booster pumps add energy and head to the system such that the powers and heads are additive; while not necessarily practical, boosters can be placed so that there is no transportation limit regardless of pipeline length or terminal elevation. Similar to acquisition limitation equation 8, the discharge throughput can be equated as:

$$V_t = Q_t * cv_t \quad (18)$$

V_t = transportation production in m^3/hr
Q_t = transportation flow rate in m3/hr
cv_t = transportation concentration of solids by volume

The head produced by the dredge pump or pumps must be equal or greater than the head required to transport the slurry.

$$TH_a >= TH_r \quad (19)$$

TH_a = transportation head available in meters of liquid
TH_r = transportation head required in meters of liquid

The head produced by a centrifugal pump varies with the type of impeller inlet, impeller design, pump flow rate, pump rotational speed, and the nature of the liquid; Pump manufactures publish performance curves that graphically show this value; when not available the head produced can be approximated by:

$$TH_a \cong (D_i * N_i / 70.54)^2 \quad (20)$$

D_i = diameter of impeller in m
N_i = maximum rotational speed of impeller in RPM

The head required by the pipeline system is a function of the pipeline, terminal elevation, particle size and concentration, and the fluid velocity. As in the acquisition limitation calculations, the calculations are complex and require an iterative approach for an exact solution.

$$TH_r \cong L_d * (f_d * Q_t^2 / (156849727 * D_d^5) + 0.22 * L_d * cv_{th} * (SG_s - SG_l) * (w * (8/f)^{0.5} * \cosh (60 * d_{50} / D_d) / (2827 * Q_t * D_d^2))^{1.7} + Z_d * (cv_{th} * (SG_s - SG_l) + SG_l) \quad (21)$$

L_d = length of discharge in m
f_d = discharge friction factor for Darcy-Weisbach formula
D_d = discharge pipe inside diameter in m
cv_{th} = transportation concentration of solids for head limit

Z_d = discharge terminal elevation above primary dredge pump in m

Again using the Durand minimum flow rate, a simple approximation presents itself.

$$Q_t \cong 21557 * D_d^{2.5} \quad (22)$$

Q_t = minimum slurry flow rate in m3/hr
D_d = pipeline inside diameter in m

With Q_t approximated, the friction factor can be calculated, estimated or read from the Moody Diagram as in the acquisition section. The maximum transportation concentration based on pump head can be computed at the minimum flow rate from equation 22 by equating the TH_a and TH_r by the following equation:

$$cv_{th} = (TH_r - L_d * f_d * Q_t^2 / (156849727 * D_d^5) - Z_d * SG_l) / (0.22 * L_d * (SG_s - SG_l) * (w * (8 / f_d)^{0.5} * \cosh (60 * d_{50} / D_d) / (2827 * Q_t * D_d^2))^{1.7} + Z_d * (SG_s - SG_l)) \quad (23)$$

The power available at the dredge pump or pumps must also be greater than or equal to the power required by them.

$$TP_a >= TP_r \quad (24)$$

TP_a = transportation power available in kW
TP_r = transportation power required in kW

The power available at the pump can be usually be found on a power versus speed curve provided by the manufacturer of the prime mover. The power required by the pump can be evaluated as:

$$TP_r = Q_t * TH_r * (cv_{tp} * (SG_s - SG_l) + SG_l) / (367.6 * \eta_p) \quad (25)$$

η_p = pump mechanical efficiency
cv_{tp} = transportation concentration of solids for power limit

The pump mechanical efficiency should also be found on the pump curve; it is commonly dependant on the flow rate and rotational speed. It should be evaluated at the minimum flow rate and the maximum rotational speed of the impeller. If no curve is available, a value of 0.65 can be safely be used. By equating the available and required power, the maximum concentration at the minimum flow rate can be calculated.

$$cv_{tp} = (TP_a * 367.6 * \eta_p - Q_t * TH_a * SG_l) / (Q_t * TH_a * (SG_s - SG_l)) \quad (26)$$

The lesser of the two transportation concentrations should be used in equation 18, provided it is less than 0.3, with the minimum flow rate to solve for the transportation limited production.

Operations

The lesser of the three production rates found in equations 1, 6, and 14 can now be used in the operation efficiency equations in this section for an estimate of cutter suction dredge throughput. This rate will be further reduced due to soil geometry, dredge design, and finally dredge operation and site conditions. In production estimating, the soil geometry primarily refers to the angle of repose (rise over run) that the sediment bank will shear at. High angles of repose are often desirable in mining applications because it allows the dredge to operate in a confined area without stepping forward for long periods of time; banks with high angles of repose also often cave-in, again desirable in mining because this mixes the various layers and sizes of soils together for processing.

Using the lowest throughput value of

$$V_{dredge} = \min (V_e, V_a, V_t) \quad (27)$$

V_{dredge} = theoretical throughput of dredge in m^3/hr

$$Z_o = V_{dredge} / (60 * Le * Se) \quad (28)$$

Z_o = average depth of cut in m
L_e = average length of cutter engaged in m

S_e = average swing speed perpendicular to the channel in m/min

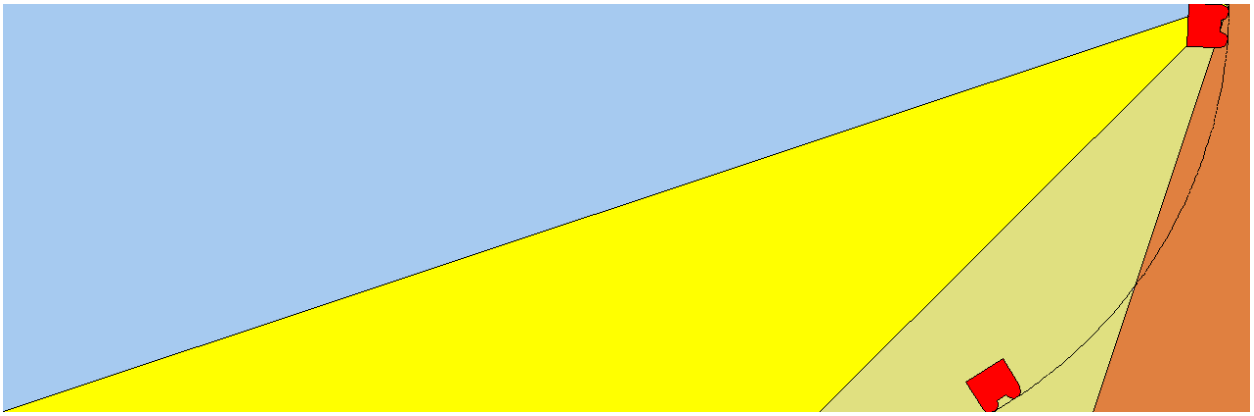

Figure 3. Angle of Repose

Figure 3 portrays the path a dredge cutter will follow as the dredge ladder is lowered. Three distinct regions are highlighted in this figure: the yellow area shows the bank with a 1 on 3 slope commonly found in navigational dredging, the tan region illustrates a 1 on 1 slope, and the brown trapezoid depicts a 3 on 1 slope commonly found in mining operations. While the cutter could not be lowered without the ladder dragging, it is important to note that the cutter path is much steeper than the 1 on 3 or 1 on 1 slope throughout its travels and steeper than the 3 on 1 slope for half its travel. This figure was included to illustrate that stair-stepping, or bench dredging, often does not lead to the desired result as the bank will prematurely fail leaving material behind the dredge. A more sound and efficient approach is for the dredge to dig to an intermediate of final depth and advance forward at that level.

In this paper, three common bank failure models will be investigated: partial bank shear, thin layer or sliver bank shear, and full bank shear resulting in a cave-in. As mention previously, the assumption is made that the cutter back swing excavates one half of the material of the forward swing and the perpendicular swing speed is equal to that of the forward swing speed. Each of these models results in very different dredge throughput because of differing amounts of cutter engagement and dredge relocation or moving.

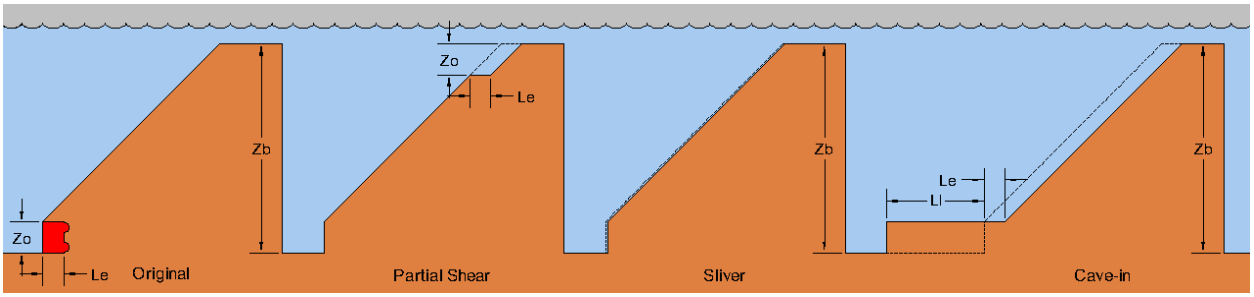

Figure 4. Bank Failure Models

Figure 4 illustrates the cutter engagement that precipitates the bank failure as well as the three bank failure models. These models do not require the entire cutter to be engaged, but use the same criterion as used in the excavation section, namely Z_o and L_e.

In the partial bank shear model, the bank shears at the tip of the cutter, L_e, along its angle of repose just enough to refill the area removed by the cutter; the bank height, Z_b, is reduced by the cut depth, Z_o, each digging pass until it is even with the bottom at which time the dredge must step forward as distance L_e; this movement is called a short step. This model has the highest throughput since the cutter has access to full bank each swing.

In the case of sliver shear model, a thin layer of the bank shears over the entire bank height along its angle of repose just enough to refill the area removed by the cutter; the bank height, Z_b, remains the same throughout, but the bank recedes by the thin layer distance, l. Each successive cutter pass has a reduced cutter engagement length, L_e, by a

geometric progression until the dredge steps forward; in this model, it is up to the estimator, or operator, to decide when to make a short step.

The full bank shear model results in the entire bank height shearing at the tip of the cutter, L_e, resulting in a cave-in and material falling behind the dredge, forcing the dredge to retreat to remove this material; this retreat is called a long set. Each successive swing cycle requires a short set until the excavation causes the next cave-in; in each swing cycle, the cutter has access to the full bank.

Table 1. Bank Failure Equations

	Bank Model		
Variable	**Partial shear**	**Sliver**	**Cave-in**
η_e	1	$(1 - (1 - (Z_o / Z_b))^{ps}) / (p_s * Z_o / Z_b)$	1
p_s	Z_b / Z_o	operator	1
L_s	L_e	$L_e * (1 - Z_o / Z_b)^{ps}$	L_e
p_l	infinity	infinity	Z_b / Z_o
L_l	0	0	$(Z_b - 2 * Z_o) * L_e / Z_o$

η_e = excavation efficiency
p_s = number of cutter passes prior to a short step
L_s = length of short step in m
p_l = number of passes prior to a long step
L_l = length of long step in

Table 2. Dredge Type Equations

	Dredge Type				
Movement	**Conventional spud**	**Spud carriage**	**Kicking spud**	**Stern wire**	**3 Stern wire**
T_s	$20 * Z_o / S_w$	$(20 * Z_o / S_w + L_{car} / S_{car}) * L_s / L_{car} + L_s / S_{car}$	$20 * Z_o / S_w + 2 * L_s / S_{car}$	L_s / S_w	$3 * L_s / S_w$
T_l	$L_l / L_{spud} * (20 * Z_o / S_w + 2 * W_c / S_e)$	$L_l / L_{car} * (20 * Z_o / S_w + L_{car} / S_{car})$	$20 * Z_o / S_w + 2 * L_l / S_{car}$	L_l / S_w	$3 * L_l / S_w$
T_a	$2 * T_m * L_s / L_m$	$2 * T_m * L_s / L_m$	$2 * T_m * L_s / L_m$	$3 * T_m * L_s / L_m$	$5 * T_m * L_s / L_m$

T_s = time required for a short set in min
T_l = time required for a long set in min
T_a = time required to reset anchors or dredge per short step in min
S_w = stern or spud winch wire speed in m/min
W_c = width of dredge cut (channel width) in m
L_{spud} = distance between spuds in m
L_{car} = length of carriage or kicker travel in m
S_{car} = carriage or kicker speed in m/min
T_m = time required to reset anchors or move dredge min
L_m = length between anchor of dredge sets in m

$$T_d = W_c / S_e \quad (29)$$

T_d = dredging time for forward and back swing in min

$$T_t = T_d + T_s / p_s + T_l / p_l + T_a / p_s \quad (30)$$

T_t = total operating time for forward and back swing

$$V_o = V_{dredge} * \eta_e * T_d / T_t \quad (31)$$

V_o = maximum dredge throughput in m3/hr

$$V = V_o * \eta_o * \eta_u \quad (32)$$

V = expected cutter suction throughput in m3/hr
η_o = dredge master efficiency
η_u = dredge up-time efficiency

Example

This example is shown to clarify the calculations that need to be performed to evaluate cutter suction dredge throughput as well as to compare two different type of dredges, a 450mm submerged pump dredge with a spud carriage (Dredge 1) and a 500mm in-hull pump dredge with conventional spuds (Dredge 2). The sensitivity of soil shear stress, or blow counts, digging depth, bank height, and channel width will also be explored.

Given: borings reveal uniform coarse sand with an average d_{50} of 0.5mm a particle specific gravity of 2.65 g/mm. Standard Penetration Test was performed and an average of 15 blows/ft was required.
15 meter average digging depth with an average bank height of 5 meters and a channel with of 40 meters.
1000 meters of discharge pipeline with a terminal elevation of 20 meters.
maximum anchor placement of 50 meters.

Table 3. Example Dredge Characteristics

	Dredge 1	**Dredge 2**
Dredge type	Spud carriage	Conventional spud
Pump location	submerged	water line
D_e, cutter diameter	1.27	1.42
L_e, cutter length	0.635	0.71
T_e, cutter torque	46563	78375
N_e, cutter RPM	31	27
b_e, number of blades	6	6
swing winch speed	30	30
$NPSH_r$	4.5	4
Z_p, pump height above bottom	6	15
D_s, suction diameter	0.4318	0.4826
L_s, suction length	8.5	25
D_i, impeller diameter	1.12	1.17
Ni, impeller RPM	572	547
Dd, discharge diameter	0.4318	0.4826
Tpa, available pump power	840	1100
hp, pump mechanical efficiency	0.8	0.8
Sw, Spud winch speed	20	20
Lcar, carriage length	5	0
Scar, carriage speed	5	0
Lspud, distance between spuds	0	5

Steel pipeline will be selected due to the wear characteristics of this sand. Average operator efficiency, η_o, of 0.8 and dredge up-time, η_u, of 0.95 will also be used in the estimate. Additionally, since anchor access is good, 15 minutes per anchor set will be estimated. Since the exact nature of the soil is not revealed from the boring, all three bank failure models will be explored.

Table 4. Dredge Excavation, Acquisition, and Transportation Throughput Calculations

	Dredge 1	Dredge 2
Excavation		
Z_{fe}	1.237	1.398
Z_e	0.928	1.048
S_{fe}	21.425	23.955
S_e	21.000	21.000
V_e	742	938
Acquisition		
Q_a	2641	3488
f_s	0.013	0.013
w	0.108	0.108
cv_a	1.120	0.132
V_a	792	460
Transportation		
TH_a	70.057	69.915
Q_t	2641	3488
f_t	0.013	0.013
cv_{th}	0.356	0.379
cv_{tp}	0.203	0.198
cv_t	0.203	0.198
V_t	536	690
Operational		
V_{dredge}	536	460
Z_o	0.670	0.514

It is clear for Table 4 that the smaller, less powerful dredge has a higher theoretical production. This dredge is limited by its transportation system while the larger dredge is limited by its acquisition system.

Table 5. Estimated Throughput per Dredge per Bank Model Calculations

	Dredge 1 Bank Model			Dredge 2 Bank Model		
Variable	**Partial Shear**	**Sliver**	**Cave-In**	**Partial Shear**	**Sliver**	**Cave-In**
η_e	1.000	0.933	1.000	1.000	0.949	1.000
p_s	7.459	2.000	1.000	9.724	2.000	1.000
L_s	0.635	0.476	0.635	0.710	0.571	0.710
p_l	infinity	infinity	7.459	infinity	infinity	9.724
L_l	0.000	0.000	3.467	0.000	0.000	5.484
T_s	0.339	0.254	0.339	0.514	0.514	0.514
T_l	0.000	0.000	1.158	0.000	0.000	4.742
T_a	0.381	0.286	0.381	0.426	0.343	0.426
T_d	1.905	1.905	1.905	1.905	1.905	1.905
T_t	2.001	2.175	2.780	2.001	2.333	3.333
V_o	510	438	367	438	356	263
V	412	354	297	354	288	212

With each dredge, the partial shear model yielded the highest throughput, and the cave-in model the least; the cave-in model is particularly poor for dredges with spuds since large movements, even with a carriage, are quite slow. Dredges with stern wires operate much more efficiently in this environment. The ratio of the estimated production to the theoretical production also sheds light on how the different spud systems operate under different bank models. For the carriage dredge it is 0.77, 0.66, and 0.55 for the partial shear, sliver, and cave-in models respectively. For the carriage dredge it is 0.77, 0.63, and 0.46 for the partial shear, sliver, and cave-in models respectively. The justification for a spud carriage is easy to make on the last two models, but not on the first.

Expanding on these results, four graphs were generated to show different sensitivities to environmental conditions.

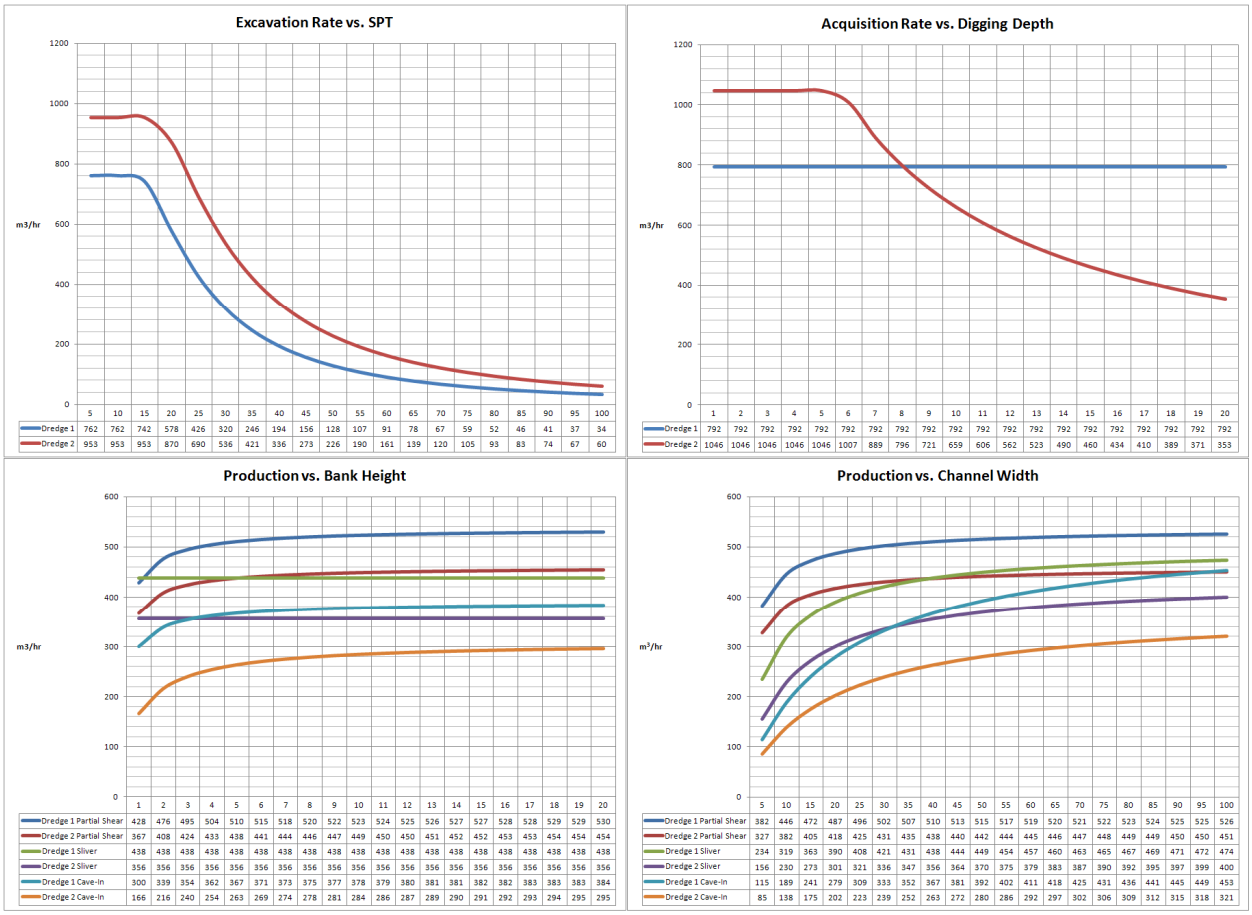

Figure 5. Sensitivity Graphs

CONCLUSIONS

The equations and example contained in this paper provide results that are in agreement with what is actually found in the field. Specific site conditions, like boat traffic and debris, would need to be applied separately. The sensitivity graphs at the end of the example provided some unexpected result in terms of bank height and channel width. The influence of bank height on total production decreases rapidly after just a few cutter diameters; the expectation was that the result would be more linear.

The same can be said for the channel width. The channel width affected different bank failure models and different dredges differently, but increasing channel width (lengthening the dredge), had diminishing returns. The models did not address the challenges with boat traffic where setting up the dredge off center and swinging the entire waterway allows for more up-time.

The example certainly demonstrated that a smaller, more modern, dredge can easily outperform a large dredge with older technology. The example quickly showed each dredge's strong points (acquisition for the smaller submerged

pump dredge, and excavation for the larger dredge), but neither dredge was able to take full advantage of that due to short-coming in the other areas; this represents the true nature of the dredges in the field today.

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