PARAMETRIC ANALYSIS ON OFF-SHORE DREDGING PROCESS USING CUTTER SUCTION DREDGERS

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Abstract

Nowadays, cutter-suction dredgers are widely used in off-shore tin mining around South East Asia region, especially in Indonesia. So far, the effectiveness of the dredging process is arguably due to the skills and experience of individuals who operate the dredgers. No sufficient guidelines, standard operating procedures exist on how to operate the dredgers effectively based on scientific facts and factual data on the mining environment. This paper discusses the effectiveness of the dredging process in a cutter suction dredger (CSD). The influence of various parameters is studied through parametric simulation based on theoretical approach developed by Miedema and Vastbloom, with a number of adaptations from the original model in order to obtain a better approximation. A specific CSD design is used as a case study. From the parametric analysis, it is found that, dredging capacity is highly affected by the cutting thickness and swing speed, rather than the dredging depth. With the limit of pump capacity and dredge power, the optimum cutting thickness is approximately 75% for the dredger in question, adjustable through the swing speed during operation. Moreover, the dredging forces are highly affected by the cutter rotational speed and soil type, whilst lightly affected by the dredging depth. For dredging harder soils, the dredge forces increase by up to 68%, for the dredger in question, hence the operational parameters must be adjusted, i.e. by lowering the swing speed, however maintaining higher rotational speed, in order to have a safe and optimum operation.

Keywords: Cutter suction dredgers, Offshore mining, Tin/Mineral mining

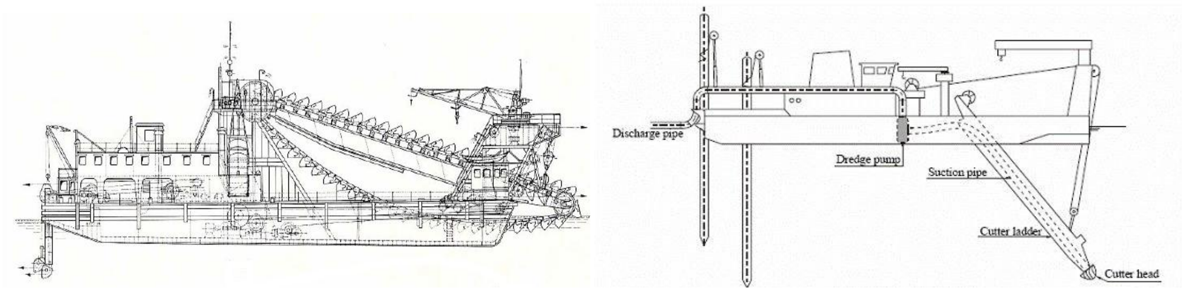
Introduction

Indonesia is one of the largest tin producers in the world. The tin deposit lies on the area of the-so-called "tin belt", that is spread from the east cost of Indo-china to Bangka islands and the west coast of South Kalimantan in Indonesia. The tin mining industry in Indonesia dated back from as early as pre-colonial period in 1852, when van den Berg secured a concession from the Riau ruler to mine tin in Bangka and Belitung islands [1]. With the increase of electronic and other consumer products, and limited resource of tin-deposit inland, as well as new environmental regulations, the tin-mining is now driven off-shore.

Bucket line dredgers (BLD), as can be seen in Figure 1a, was then used even until today for off-shore mining. By using BLD, in-situ compacted soil containing tin deposits from the seabed is dredged by means of a line of buckets acting as a digging equipment as well as conveyor, conveying the dredged soil to the surface and on the dredger, where it would be processed through washing and refining to become mineral soil with higher grade of tin. In terms of dredging, the equipment performance is measured in dredging capacity (m^3/hour, or ton/hour), whereas in washing plant, the performance is measured in recovery level, that represents amount of tin-ore recovered from the dredged soil. As an alternative to the becoming-obsolete Bucket Line Dredgers (BLD), Cutter Suction Dredgers (CSD) are also used in Indonesia and other neighboring countries for off-shore tin-mining (See Figure 1b).

In a BLD, in order to transport the soil, it requires additional power to rotate and move a chain consisting of more than 100 buckets, weighing approximately 1.5 tons each. On the other hand, a CSD uses hydraulic transportation, where compacted soil at the sea-bed is dredged by means of a crown-shaped cutters on a rotating cutter head. Then, the disintegrated soil is then pumped by a slurry pump, or here called dredge pump, and delivered up to the surface through a pipe. The dredger movement is made possible by swing propeller attached at the pontoon. With this hydraulic delivery, the need for heavy bucket chain conveyor is vanished, reducing the total power that is previously used to rotate the bucket-chain. For deeper dredging operation, a BLD would require even longer chain and more buckets, hence heavier and require even more power. The weight reduction, power reduction and potentially higher dredging capacity and reliability are among the main advantages of CSD over BLD.

For a rough illustration of the study significance, currently, an average-sized CSD could produce approximately 25 ton of tin (Sn) equivalent, worth USD 370,000 a month. To do so, it would require a combination of rich deposit and effective dredging. So far, the effectiveness of the dredging process is, arguably, due to the skills and experience of individuals who operate the dredgers. No sufficient guidelines, standard operating procedures exist on how to operate the dredgers effectively based on scientific facts and factual data on the mining environment. As an initial stage of research to tackle this problem, this paper discusses the effectiveness of the dredging process in a cutter suction dredger (CSD) through parametric analysis. The influence of various parameters is studied through parametric simulation based on theoretical approach developed by Miedema [2]. A number of adaptations from the original model have been made, namely: the use of a more realistic crown-shaped cutter-head, rather than a truncated cone in the original model, and a more realistic estimate on the cut soil volume using solid model. The simulation is based on data and information of the existing dredger operated by an Indonesian tin-mining company. With a comprehensive understanding, combined with experience of the field-operators of the dredgers, dredging process can be carried out more optimally.



(a) (b)

Figure 1. Two types of tin-mining off-shore dredgers: a) bucket line dredger, b) cutter suction dredger [3]

Analysis Method

Dredging Model

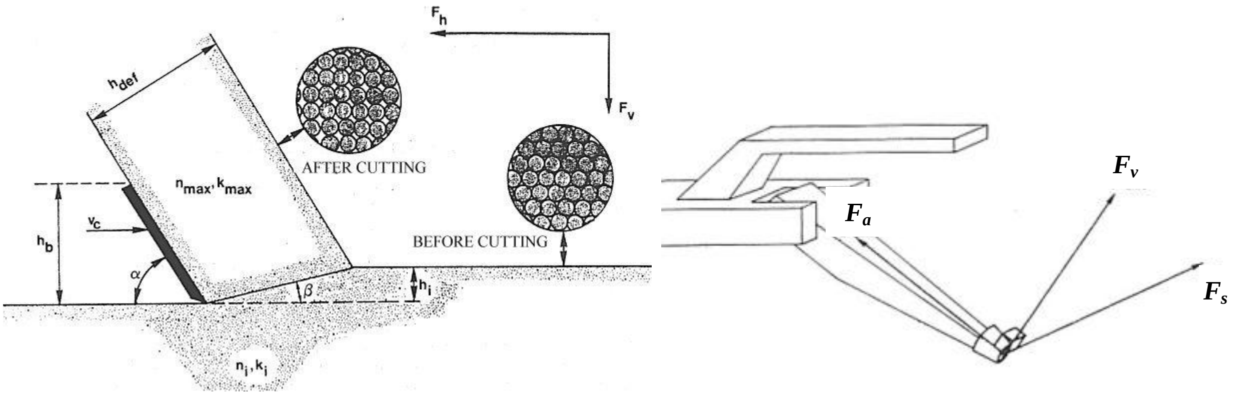
Theories on underwater dredging began to develop since the 1970s, and continued in the 1980s with the result of quantitative relationship between various parameters, such as the dredging forces and the soil characteristics. Os and van Leussen [4], among others, investigated the forces required in the dredging process on saturated sand, in the range of 0.01 to 5 m/s cutterhead blade speed. Miedema [2] independently studied underwater dredging, especially for the speed of the blades 0.5 to 5 m/s. The results of their research were reported further in Miedema [6,7]. More recent research results from other researchers can refer to Patel [8], who developed the theory of the cutting blade speed range < 0.5 m/ s.

Based on the data of cutter-head rotational speed and radius, it is concluded that the cutter blade speed that occur in the design of the CSD in-question varies between 1 to 3 m/s.

Among various models, that of Miedema [2] still provides the most comphrehensive mixed analytical-experimental approach, albeit using a simplified 2D mechanism to model complex 3D underwater dredging process by cutter head against soil layers. Figure 2a shows a blade making a rake angle,α, while cutting saturated soil with blade speed of v_c. Previously, the thickness of the soil is h_i, and becomes h_{def}, after cutting process. In the figure, it can be seen that for a given mass, the soil density is reduced, with illustrations of hypothetical soil composition for the two conditions, i.e. before and after the cutting process. As a result, there are reaction forces by the soil ground to the cutter blades both in horizontal and vertical directions, F_h and F_v, respectively, as follows.

$$F_h = c_1 \cdot \rho_w \cdot g \cdot v_c h_i^2 \cdot b \cdot \frac{e}{k_m} + d_1 \cdot \rho_w \cdot g \cdot (z+10) \cdot h_i \cdot b \tag{1}$$

$$F_v = c_2 \cdot \rho_w \cdot g \cdot v_c h_i^2 \cdot b \cdot \frac{e}{k_m} + d_2 \cdot \rho_w \cdot g \cdot (z+10) \cdot h_i \cdot b \tag{2}$$



(a) (b)

Figure 2. Illustration of 2-D cutting process, and coordinate system of dredging forces, F_{st}, F_{vt}, F_{at}, with respect to the dredger ladder axis [2]

Here, parameters c_1, c_2, d_1, d_2 are cutting coefficients obtained empirically by Miedema [2], and as functions of soil characteristics (δ and ϕ), and the rake angle, α. Whilst, e is volumetric strain, that represents the volume ratio between before and after cutting condition, and k_m is soil permeability. The cutting thickness is represented by h_i, blade width, b, whilst, ρ_w and g are seawater density and gravity constant, respectively. The 2-dimensional cutting forces, may be transformed into 3-dimensional forces with respect to the cutter-head axis, as illustrated in Figure 2b, and taken as an integral of the forces along the cutting-blade curve to become average cutting force in axial direction, F_{at}, vertical-direction, F_{vt}, and lateral-direction, F_{st}, as follows.

$$F_{at} = \frac{p}{2\pi}\left[\left(F_v \cos\xi \pm F_h \sin\iota \cos\xi\right)\left(1-\cos\Omega_0\right) \pm F_h \cos\iota \sin\Omega_0\right] \tag{3}$$

$$F_{vt} = \frac{p}{2\pi}\left[-\left(F_v \cos\xi \pm F_h \sin\iota \sin\xi\right)\left(\sin\Omega_0\right) \pm \left(F_h \cos\iota\right)\left(1-\cos\Omega_0\right)\right] \tag{4}$$

$$F_{st} = \frac{p\Omega_0}{2\pi}\left[-\left(F_v \sin\xi\right) \pm \left(F_h \sin\iota \cos\xi\right)\right] \tag{5}$$

Equation (3) to (5) are derived from the transformation matrix, and is applicable to a crown cutter-head shape, rather than the original truncated-conical shape, as in Figure 3. Operator ± in the formulation depend on the mode of cutting, i.e. overcutting or undercutting.

Overcutting process is when the cutter-blade touches the soil from above downward, and vice-versa for undercutting. Face angle, ξ, and tooth angle, ι, are the contact angle between cutter blade and soil surface, and the angle between blade and cutter-head axis, respectively. Unlike in the original assumption of truncated-conical shape by Miedema [2], in a crown-shaped cutter-head, these angles are estimated through scaled-model in a laboratory and vary to dredging depth. Illustration of the angles can be seen in Figure 3. The axial force, F_{at}, pushes/pulls the ladder through its axis, whilst the vertical force, F_{vt}, tries to rotate the ladder with respect to the ladder pivot. With sufficient weight of the ladder structure, a full contact between the cutter-head and the sea-bed is maintained. Moreover, the swing force, F_{st}, tries to drag the ladder, and hence the whole dredger, sidewise. In order to maintain the position, or to provide the dredging effect, the dredger must provide sufficient sidewise propelling power.

Furthermore, cutting torque, cutting power and specific cutting energy can be expressed as follows.

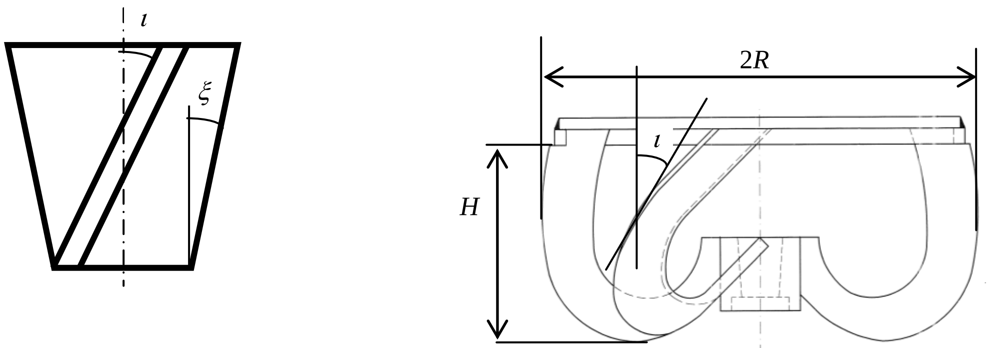
$$M_t = \frac{pR}{2\pi} F_h \cos \iota \Omega_0 \quad \text{(N.m)} \tag{6}$$

$$P = M_t \omega \quad \text{(Watt)} \tag{7}$$

$$E_s = \frac{M_t v_{ciR}}{v_s B_v B_a R} \quad \text{(J/kg)} \tag{8}$$

Ω_0, represents a non-cavitation cuting angle, and taken as total cutting angle since no cavitation assumption is assumed, whereas R is the avaregae radius of cutter-head, and B_v and B_a, are cutting thickness in vertical and horizontal directions, respectively. From the cutting specific energy, E_s (Equation (8)), dredging capacity can be estimated based on the available cutter-shaft power, P_a as follows.

$$Q_s = 3600 \frac{P_a}{E_s} \quad \text{(m}^3\text{/hr)} \tag{9}$$

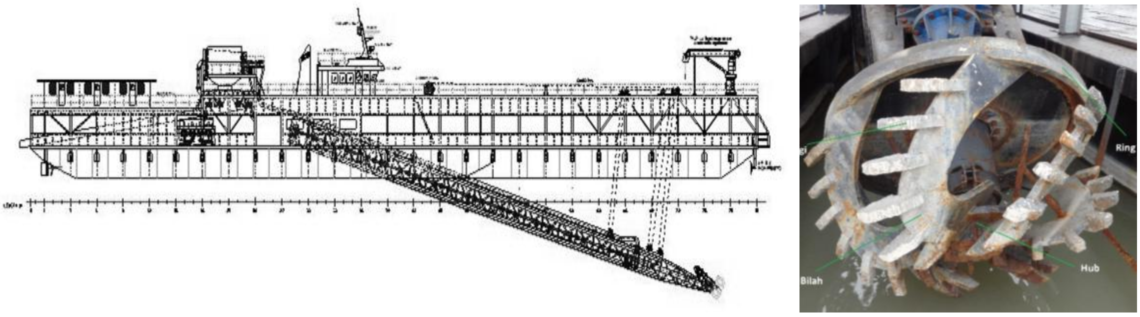


(a) (b)

Figure 3. Cutter-head model: a) original model of truncated-conical shape [2], b) actual geometry of crown-shape

Dredger Data and Information

In order to simulate the effects of various conditions in operation, the above theory is applied to an existing dredger. Figure 4 shows the dredger used for simulation and the cutter-head design. The cutter is in form of a crown of 6 cutter blades. Important dimensions are shown in Table 1. In cutter-suction dredgers, the cutterhead axis is alligned or in-plane with the axis of the ladder. In this study case, the axis of the cutter makes 30^0 angle in-plane with the axis of the ladder. The in-plane condition makes it possible for the dredger to be operated overcutting and undercutting.



(a) (b)

Figure 4. Cutter suction dredger for simulation: a) overall dredger: b) actual cutter head [8]

Table 1. Cutter Main Data [8]

Symbol	Name	Value	Unit	Symbol	Name	Value	Unit
	Crown height	990	Mm	P	No. of blades	6	
	Outter diameter	1820	Mm	R	Radius	0,9	m
	Inner diameter	1580	Mm	α	Rake Angle	45	°
B	Blade width	0,5	M	ι	Tooth angle	32	°
h_b	Blade height	0.192	M	ξ	Face Angle	35	°

The dredger operates using side propellers in order to provide dredger's swing movement that in turns provides swing movement of the cutter head. According to the spcification, the propellers could provide up to 20 m/min of swing speed, whereas the cutter-head is rotated by a hydraulic driver system by up to 24 rpm.

Soil Characteristics

Five soil types are simulated here, using the company-owned classification system with equivalence with the Unified Soil Classification System, USCS, based on the observation, as in Table 2. In general, before reaching the tin deposit, i.e. tin layer, dredging must be carried out to open the overburden. Tin layer may fall into the category of PHAKS (SW), although it is possible to take form of PHAPKA (SP). On the other hand, the overburden soil is close to PHALP (ML) or LPLT (CH). In between, there could be a number of layers found, one of which is a hard layer called Humicrite. Based on the SPT number, i.e. 47, this layer may be categorized as PKAKS (GP) and presumably the hardest layer in the mining area.

Table 2. Soil Data Used in The Simulation

No	Soil Code	USCS equivalent	Avg. Internal Friction Angle, ϕ[1]	Avg. Soil to Metal Friction Angle, δ[2]	Soil Permeability (m/s)[1]
1	PHAKS	Well graded sands – dense (SW)	47^0	24^0	10^{-6}
2	LPLT	Inorganic clays of high plasticity (CH)	42^0	24^0	10^{-8}
3	PHAPKA	Gravelly sands (SP)	37^0	30^0	5.35×10^{-4}
4	PKAKS	Sandy gravels – Dense (GP)	47^0	30^0	5×10^{-4}
5	PHALP	clayey silts – compacted (ML)	37^0	24^0	5×10^{-9}

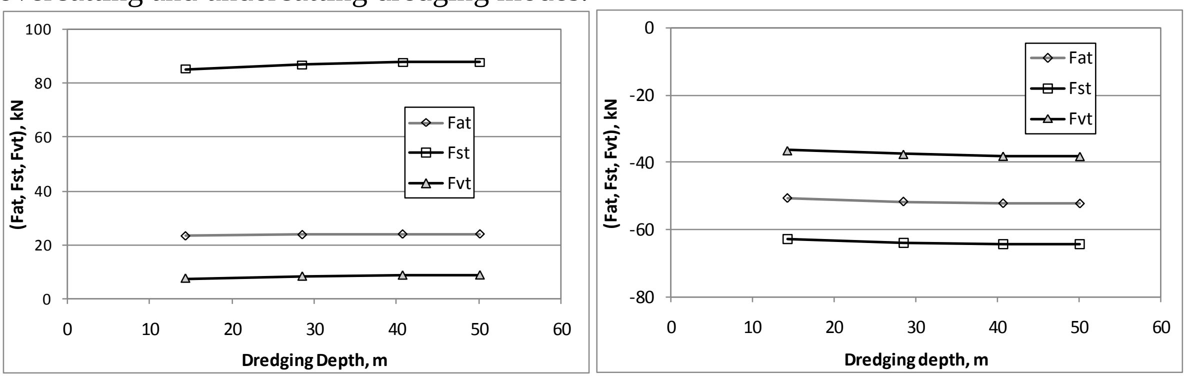
[1] Source: Geotechdata.info [9]
[2] Source: NAVFAC [10]

Result and Discussion

The dredging performance is simulated through parametric study based on the theory described previously. The effects of dredging depth, soil types and operations on the dredging forces, power and capacity are simulated and the results are discussed subsequently.

Effect of Dredging Depth

The previous model by Miedema [2] uses an assumed truncated-conical geometry for the cutter head, whereas the actual cutter head is crown-shaped. Hence, in this investigation, the cutting thickness in Miedema model, i.e. B_a, and B_v are estimated using a solid geometry model for various dredging depth. The effects of dredging depth is simulated by observing the dredge forces, i.e. axial force, F_{at}, vertical force, F_{vt}, swing force, F_{st}, and dredging capacity, Q, for the case of PHAKS soil type, at cutter speed, n_c, of 20 rpm, and dredger swing speed, v_s, of 16 m/minute. Equations (3) through (5) are used to calculate the dredge forces, and Equations (9) and (11) for dredging force and capacity, respectively, both for overcutting and undercutting dredging modes.



(a) (b)

Figure 5. Effect of dredging depth to dredge forces for well graded sands – dense (PHAKS), at 20 rpm rotational speed and 16 m/min swing speed: a) overcutting, b) undercutting

In most cases, swing forces, F_{st}, give the highest absolute values, followed by axial and vertical forces (F_{at} and F_{vt}). At higher depth, the absolute value of all forces tend to increase, for both overcutting and undercutting dredging methods, though insignificantly. The difference between 14.3 and 50.1 m dredging depth in forces is only 2.9% and 2.3%, for overcutting and undercutting, respectively. In overcutting mode at 50.1 m depth, vertical force is estimated to be 8.65 kN upward. In order the dredging process to take place effectively, the ladder weight must be sufficient to compensate the upward vertical dredge force. Whereas, in undercutting mode, the dredging produces 38.2 kN vertical dredge force downward, hence tends to pull the ladder down, adding the loading to the ladder hanger system. The design of ladder hanger system must consider this.

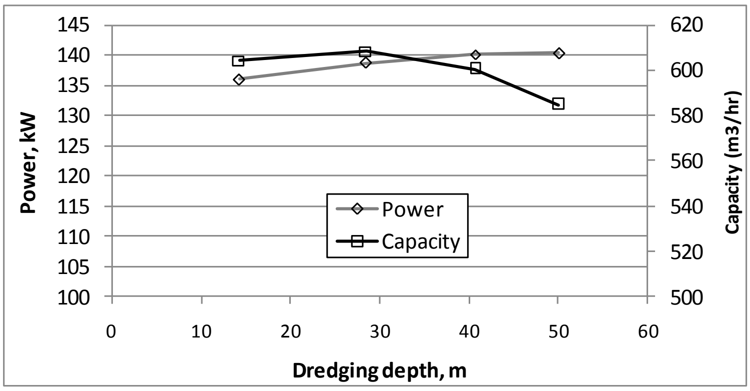


Figure 6 shows the effect of the dredging depth to dredging power and capacity. In general, the power increases in higher depth, however, opposite occurs in the capacity. Different dredging depth affects the cutting thickness on the soil, represented by B_a and B_v. For higher dredging depth the cutting thickness is expected to be smaller, resulting in a lower dredge capacity. For dredging depth up to 50 m, the required power is estimated to be 140.3 kW and theoretical dredging capacity of 585 m^3/hr. By accounting for the assumed mechanical efficiency of the dredge driver of 0.7, the required power is estimated to be 200.5 kW or 268 HP, whereas the available power in the dredger is 226 HP. Hence, for the case of PHAKS soil type at the depth of 50 m, the maximum theoretical capacity cannot be achieved. Moreover, referring to the dredge pump, the maximum capacity is limited to 250 m^3/hr of soil, hence it can be concluded that with current condition, the dredge pump is the limitting factor.

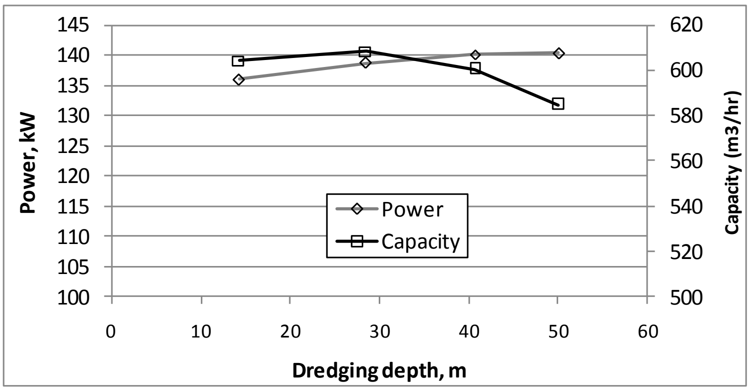


Figure 6. Effect of dredging depth to dredging power and capacity for PHAKS soil type, at 20 rpm rotational speed and 16 m/min. swing speed

Effect of Soil Type

The effect of soil type is simulated on relatively shallow and deep dredging cases, i.e. 28 and 50 m, respectively. In general, the swing force, F_s, is consistently higher than axial forces, F_a, followed by vertical force, F_v. For undercutting dredging mode, dense - sandy gravels

(PKAKS), with the highest internal friction angle, ϕ, requires the highest dredging forces and, clayey compacted silts (PHALP), the lowest. For a comparison, swing forces for PKAKS are approximately 62.4% higher than those of the softest. This could become a guide during operation when dredging hard soil. With the limit of the dredger's capability in providing swing force, the dredging process must use lower cutting thickness, B_a and B_v, resulting in lower dredging capacity. The vertical force is associated with the weight of the ladder and its hoisting system. The vertical force is estimated to be 26.2 kN for soft soils and 39.4 kN for hard soils, a difference of 50.4%, for undercutting dredging method (Figure 7). The vertical force adds to the ladder hoist loading. Using otherwise overcutting method, too high vertical force could cause the ladder to lift hence reducing the effectiveness to dredge, hence reducing the dredging capacity. In the same graph, the required power can also be seen. It requires 170.9 kW to dredge hard soil (PKAKS), a 68.4% higher than that of soft soil (PHALP) for the same dredging capacity. With the limit of power, the dredging capacity will also be limited. Further on the soil types, hard soil such as PKAKS is sometimes found between overburden and tin layers, so that it requires more attention. The tin layer, on the other hand, could be classified as PHAPKA or PHALP, and requires lower power and forces to dredge.

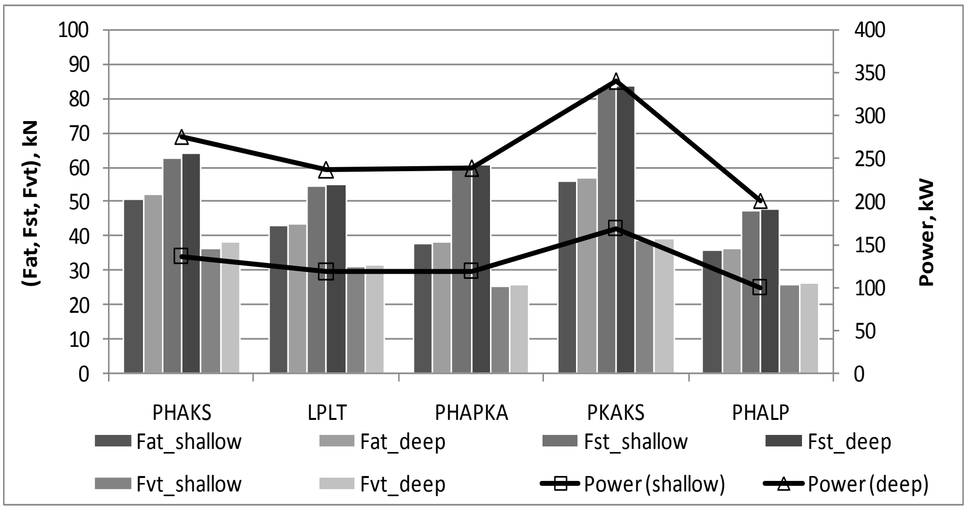


Figure 7. Effect of soil types to dredging forces, for shallow (28.5m) and deep dredge (50.1m), at a rotational speed of 20 rpm and swing speed of 16 m/min, undercutting

Effect of Operation

The effect of various parameters disscussed above uses the same operational parameters, i.e. cutter rotating speed of 20 rpm and swing speed of 16 m/min, and with the maximum possible cutting thickness for various dredging depth. In this part, the operational parameters will be varied, including cutting thickness, that is affected by the skills of the operator, cutter rorational speed and swing speed. The simulation is carried out at the dredging depth of 50.1 m and for dense-well graded sands type (PHAPKA).

The effect of cutting thickness on the dredging power and capacity can be seen in Figure 8. With less-effective dredging process, the cutting thickness ratio, i.e. percentage ratio between actual and maximum possible cutting thickness, the dredging capacity and power drops. With only 25% cutting thickness, the required power is much less than the available power, i.e. 135 kW, and the dredging capacity is also much less than the targetted capacity, i.e. 250 m^3/hr. Hence, the condition is considered ineffective. On the other hand, considering the available power and target capacity, the optimum cutting thickness is approximately

75%, obtainable through modifying the cutting volume, represented here by B_a and B_v, during operation. Cutter rotational speed and swing speed also affect the dredging forces, as illustrated in Figure 9. For the same swing speed, the higher the rotational speed the lower the dredging forces are. With higher rotational speed, the cutting thickness per rotation will be smaller, resulting in a significantly lower force needed. As an example, for 20 m/min. swing speed, the swing force is 117.8 kN at 16 rpm rotational speed, compared with 78.5 kN at 24 rpm. The power required remains the same since the force is inversely proportional to the speed.

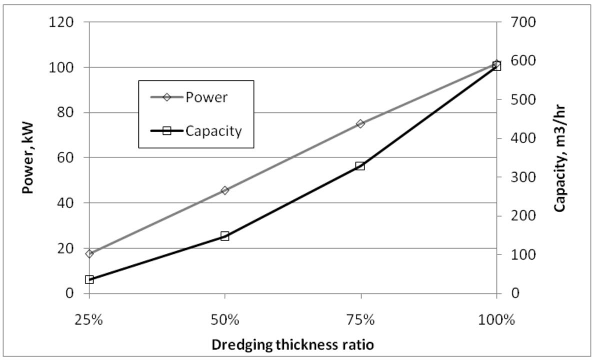


Figure 8. Effect of cutting thickness ratio on the power and capacity

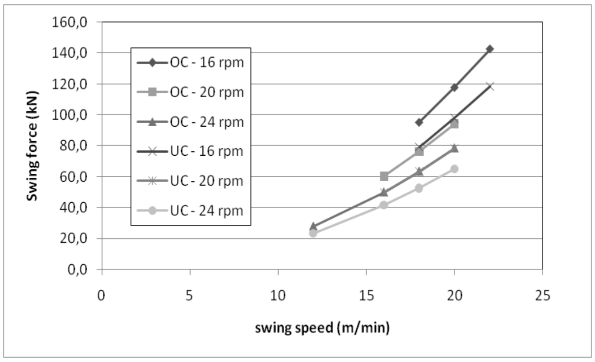


Figure 9. Effect of swing speed and rotational speed to the swing forces, for PHAPKA

Conclusions

In this paper, an adaptation from a dredging model of Miedema has been carried out, by a 3-dimensional directional transformation based on its original 2-dimesional model and the use of solid modelling to estimate the cutting volume more accurately based on actual cutter-head geometry. Parametric simulation from the analytical solution formulated here has been carried out, leading to the following conclusions,

- In general, the dredging forces are highly affected by cutter rotational speed and soil type, whilst lightly affected by dredging depth. For dredging presumably hardest soils, the dredge forces increase by up to 62% compared to dredging soft soils, for the dredger in question. Hence, the operational parameters must be adjusted, i.e. by lowering the swing speed, while maintaining higher rotational speed, in order to have a safe and optimum operation.
- Dredging capacity is highly affected by the cutting volume, represented here by B_a and B_v, and swing speed, rather than the dredging depth. For the dredger in question, with the limit of pump capacity of 250 m^3/hr, and dredge power of 226 HP, it is found that the optimum cutting thickness is approximately 75%. This can be done by adjusting the swing speed and cutter-head position during operation. The current cutter-head has a potential to produce higher capacity, however using a dredge pump with higher capacity to match with.

For the future development, in order to increase the accuracy of the model, an empirical model of the dredger needs to be improved based on actual condition. A field trial requires an accurate measurement of forces and cutting power in order to update the dredging constants, such as c_1, c_2, d_1, d_2, currently obtained from Miedema [2].

With a better understanding on the dredging process including the effects of the dredging parameters on the dredging performances, the dredging process can be designed automatically to achieve optimum operation condition for a certain dredger and cutter-head design.

Another direction of research would be to obtain characteristics of various cutter-head design and relate them to dredging performances.

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