A SENSITIVITY ANALYSIS OF THE PRODUCTION OF CLAMSHELLS

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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 (1992). The production of a clamshell depends on:

1. The dimensions of the clamshell.
2. The weight and weight distribution of the clamshell.
3. The geometry of the clamshell and especially the cutting edges.
4. The type of soil, the soil mechanical parameters.
5. The water depth.
6. 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 m³ to 2.25 m³. 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 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

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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 Schusztet (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 m³ 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 takes 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.

Figure 1. The 50 cubic yard clamshell buckets.
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 and Figure 2 give an impression of the size of modern clamshells as used in dredging. Figure 3 gives the definition of the different parts of the clamshell, while Figure 4 gives the stages of the closing process of Clamshells.

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 half 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:

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

(1)

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

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

(2)
Figure 3. The nomenclature of the clamshell buckets.

Figure 4. Three stages of the closing process.
For the rotation of the bucket the following equilibrium equation of moments around the bucket bearing is valid:

\[ I_b \cdot \ddot{\phi} = -W_b \cdot b_g \cdot \sin(\phi + \beta) + m_b \cdot y_b \cdot b_g \cdot \sin(\phi + \beta) - F_a \cdot \cos(\alpha) \cdot b_c \cdot \sin(\phi + \theta) + F_a \cdot \sin(\alpha) \cdot b_c \cdot \cos(\phi + \theta) + F_{ch} \cdot a_b \cdot \cos(\phi) - F_{cv} \cdot a_b \cdot \sin(\phi) - M_e \]  

(3)

Figure 5. The parameters involved (forces and moments distinguished 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:

\[ F_r = W_b - m_b \cdot \ddot{y}_b + W_u - m_u \cdot \ddot{y}_u + W_l - m_l \cdot \ddot{y}_l + F_{cv} + F_{ev} + m_b \cdot b_g \cdot \cos(\phi + \beta) \cdot \phi^2 \]  

(4)

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

\[ \ddot{y}_b, \ddot{y}_l, \ddot{y}_u, \ddot{\phi} \]  

(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, $\varphi$ 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 $\alpha$, can be expressed in the closing angle of the bucket by:

$$\alpha = \arcsin \left( \frac{e_2 - e_1 + b \cdot \sin(\varphi + \theta)}{d_c} \right)$$  \hspace{1cm} (6)

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

$$|y_u - y_l| = d_c \cdot \cos(\alpha) - b \cdot \cos(\varphi + \theta)$$  \hspace{1cm} (7)

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

$$\eta(\varphi) = \frac{d}{d\varphi} \left| y_u - y_l \right|$$  \hspace{1cm} (8)

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

$$\Delta y_u = \Delta l_r - i \cdot \Delta \varphi \cdot \eta(\varphi)$$  \hspace{1cm} (9)

The change of the vertical position of the lower sheave block $\Delta y_l$ can be expressed by:

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

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

$$\dot{y}_u = \dot{l}_r - i \cdot \dot{\varphi} \cdot \eta(\varphi)$$  \hspace{1cm} (11)

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

$$\dot{y}_l = \dot{l}_r - (i-1) \cdot \dot{\varphi} \cdot \eta(\varphi)$$  \hspace{1cm} (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:

$$\ddot{y}_u = \ddot{r}_r - \ddot{\phi} \cdot \eta(\phi) - \dddot{\phi} \cdot \frac{d\eta(\phi)}{d\phi}$$ (13)

and for the lower sheave block:

$$\ddot{y}_u = \ddot{r}_r - (i-1) \cdot \ddot{\phi} \cdot \eta(\phi) - (i-1) \cdot \dddot{\phi} \cdot \frac{d\eta(\phi)}{d\phi}$$ (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:

$$\ddot{y}_b = \ddot{y}_1 - \ddot{\phi} \cdot b \cdot g \cdot \sin(\phi+\theta)$$ (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 presented at WODCON XII in 1989. 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:

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

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

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

$$F_{ch} = d_1 \cdot \rho_w \cdot g \cdot (z+10) \cdot h_i \cdot b$$ (18)
For the vertical cutting force:

\[ F_{cv} = d_2 \cdot \rho_w \cdot g \cdot \left( z + 10 \right) \cdot h_l \cdot b \]  \hspace{1cm} (19)

The proportionality coefficients \( c_1, c_2, d_1 \) and \( d_2 \) can be found in Miedema 1987 or 1989.

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 in production 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:

\[ F_p = A_e \left( c \cdot N_c + \gamma_s \cdot \delta \cdot N_s / 2 + \gamma_s \cdot h_l \cdot N_q \right) \]  \hspace{1cm} (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 \( N_c, N_s \) 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 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.

\[
F_e = A_e \left( \gamma_w \cdot h_0 / 2 + \gamma_w \cdot \Delta p \right) \cdot N_q
\]  

(21)

The pore under pressure \( \Delta p \) in equation (21) follows from the sand cutting theory of Miedema (1987). The parts of equation (20) containing \( N_c \) and \( N_t \) 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:

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

(22)

**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 al. (1983-2005). In the equations derived, the denominator contains the sine of the sum of the 4 angles involved, the cutting angle \( \alpha \), the shear angle \( \beta \), the angle of internal friction \( \varphi \) and the soil interface friction angle \( \delta \). 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 than 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 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 figure 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.](image)

The resulting moment on the wedge should be zero in the equilibrium situation. Equation 20 contains 3 new parameters $e_2$, $e_3$ and $e_4$ 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. The forces on the wedges at 60°, 75°, 90°, 105° and 120° cutting angles.](image)

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 $\beta$, the wedge angle $\alpha$ 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 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 $p_1$, $p_2$, $p_3$, $p_4$ using a finite element calculation or the method described by Miedema (2005), for a variety of shear angles $\beta$ and wedge angles $\alpha$ around the expected solution.
2. Determine the shear angle $\beta$ 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 $e_2$, $e_3$ and $e_4$ 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 (\(\varphi = 40^\circ\)).](image-url)
Figure 10. The cutting forces as a function of the blade angle \( \vartheta \), with and without a wedge (\( \varphi \) of 40\(^\circ\)).

Figure 11. The wedge angle, shear angle and soil interface friction angle as a function of the blade angle (\( \varphi \) of 30\(^\circ\)).

Figure 12. The cutting forces as a function of the blade angle \( \vartheta \), with and without a wedge (\( \varphi \) of 30\(^\circ\)).
Figures 9, 10, 11 and 12 show the results of calculations of the non-cavitating cutting process for 2 types of sand. From these calculations the conclusions can be drawn that the wedge angle $\alpha$ can be approximated by $90 - \varphi$, while the wedge starts to occur at a blade angle $\theta$ of about 63° for the case with an internal friction angle of 40° and at a blade angle $\theta$ 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:

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

(23)

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

$$\alpha = 90 - 0.014 \cdot \varphi^2$$

(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 than 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 38 m³ (50 cu yd) clamshell of the Chicago.](image)
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.**

<table>
<thead>
<tr>
<th>Total mass</th>
<th>45.6 ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total volume</td>
<td>42.7 m³</td>
</tr>
<tr>
<td>Arm</td>
<td>1.0 ton</td>
</tr>
<tr>
<td>Lower block</td>
<td>1.5 ton</td>
</tr>
<tr>
<td>Upper block</td>
<td>2.3 ton</td>
</tr>
<tr>
<td>Bucket</td>
<td>15.0 ton</td>
</tr>
<tr>
<td>Sheaves, etc.</td>
<td>4.0 ton</td>
</tr>
<tr>
<td>Height</td>
<td>4.14 m</td>
</tr>
<tr>
<td>Length</td>
<td>5.20 m</td>
</tr>
<tr>
<td>Width</td>
<td>4.11 m</td>
</tr>
</tbody>
</table>

**Table 2. The soil mechanical parameters of the sands used.**

<table>
<thead>
<tr>
<th></th>
<th>φ (°)</th>
<th>δ (°)</th>
<th>n (32-50)</th>
<th>k₁ (m/sec)</th>
<th>kₘₐₓ (m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very loose sand</td>
<td>26</td>
<td>17</td>
<td>48</td>
<td>4·10⁻⁴</td>
<td>16·10⁻⁴</td>
</tr>
<tr>
<td>Loose sand</td>
<td>30</td>
<td>20</td>
<td>46</td>
<td>2·10⁻⁴</td>
<td>8·10⁻⁴</td>
</tr>
<tr>
<td>Medium sand</td>
<td>34</td>
<td>23</td>
<td>44</td>
<td>1·10⁻⁴</td>
<td>4·10⁻⁴</td>
</tr>
<tr>
<td>Dense sand</td>
<td>39</td>
<td>26</td>
<td>42</td>
<td>0.5·10⁻⁴</td>
<td>2·10⁻⁴</td>
</tr>
<tr>
<td>Very dense sand</td>
<td>44</td>
<td>31</td>
<td>40</td>
<td>0.25·10⁻⁴</td>
<td>1·10⁻⁴</td>
</tr>
</tbody>
</table>

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.
Table 3. The results of the simulation.

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

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 too 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.

5. 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.

Figure 16. The output of CCS.

Clamshell Closing Simulation V5.1, Type 5: Clamshell with closing wire, February 20 2007, 13:55:40
Graph 1 of 5: Production & power
The Chicago 50 cu yd bucket, closing wire (C:\My Documents\VB\Clamshell\Clamshell\ChicagoRope.Inp)
Medium sand (C:\My Documents\VB\Clamshell\Sand\Sand.Inp)
All data is for total clamshell
REFERENCES

Tauber, B.A., "The effect of the design of a cable grab on its scooping capacity". Coll. of scientific works of MLTI 8 (1958), page 30-34.
He, J. & W.J.Vlasblom, “Modelling of saturated sand cutting with large rake angle”. 15th world dredging congress, June 1998, Las Vegas, Nevada, USA
# LIST OF SYMBOLS USED

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ab</td>
<td>Distance between cutting edge and bucket bearing</td>
<td>m</td>
</tr>
<tr>
<td>Ae</td>
<td>Surface of side edges (thickness*length)</td>
<td>m²</td>
</tr>
<tr>
<td>b</td>
<td>Width of the buckets</td>
<td>m</td>
</tr>
<tr>
<td>bc</td>
<td>Distance between bucket bearing and arm bearing</td>
<td>m</td>
</tr>
<tr>
<td>bg</td>
<td>Distance between bucket bearing and centre of gravity</td>
<td>m</td>
</tr>
<tr>
<td>B</td>
<td>Width of grab</td>
<td>m</td>
</tr>
<tr>
<td>c</td>
<td>Cohesion</td>
<td>Pa</td>
</tr>
<tr>
<td>c₁</td>
<td>Proportionality coefficient non-cavitating cutting forces</td>
<td>-</td>
</tr>
<tr>
<td>c₂</td>
<td>Proportionality coefficient non-cavitating cutting forces</td>
<td>-</td>
</tr>
<tr>
<td>d₁</td>
<td>Proportionality coefficient cavitating cutting forces</td>
<td>-</td>
</tr>
<tr>
<td>d₂</td>
<td>Proportionality coefficient cavitating cutting forces</td>
<td>-</td>
</tr>
<tr>
<td>dc</td>
<td>Length of arm</td>
<td>m</td>
</tr>
<tr>
<td>dm</td>
<td>Average grain diameter</td>
<td>μm</td>
</tr>
<tr>
<td>e₁</td>
<td>Volume fraction of dilatational expansion</td>
<td>-</td>
</tr>
<tr>
<td>e₂</td>
<td>Eccentricity arm bearing upper sheave block</td>
<td>m</td>
</tr>
<tr>
<td>e₃</td>
<td>Eccentricity bucket bearing lower sheave block</td>
<td>m</td>
</tr>
<tr>
<td>Fₘ</td>
<td>Force in one arm</td>
<td>N</td>
</tr>
<tr>
<td>F₈h</td>
<td>Horizontal force on the cutting edge</td>
<td>N</td>
</tr>
<tr>
<td>Fₚv</td>
<td>Vertical force on the cutting edge</td>
<td>N</td>
</tr>
<tr>
<td>Fₚe</td>
<td>Force on side edges</td>
<td>N</td>
</tr>
<tr>
<td>Fₚₜv</td>
<td>Vertical force on the side edges</td>
<td>N</td>
</tr>
<tr>
<td>Fₚr</td>
<td>Force in the closing rope (wire)</td>
<td>N</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational constant (9.81)</td>
<td>m/s²</td>
</tr>
<tr>
<td>h₁</td>
<td>Thickness of layer cut</td>
<td>m</td>
</tr>
<tr>
<td>h₂</td>
<td>The initial penetration</td>
<td>m</td>
</tr>
<tr>
<td>i</td>
<td>Number of parts of line</td>
<td>-</td>
</tr>
<tr>
<td>Iₖb</td>
<td>Mass moment of inertia of bucket</td>
<td>kg·m²</td>
</tr>
<tr>
<td>kᵥ</td>
<td>Average permeability</td>
<td>m/s</td>
</tr>
<tr>
<td>Kₚ</td>
<td>The grain shape factor</td>
<td>-</td>
</tr>
<tr>
<td>l</td>
<td>Rope length</td>
<td>m</td>
</tr>
<tr>
<td>L</td>
<td>Length of fully opened grab</td>
<td>m</td>
</tr>
<tr>
<td>mₕ</td>
<td>Mass + added mass of bucket</td>
<td>N</td>
</tr>
<tr>
<td>m₁</td>
<td>Mass + added mass of lower sheave block</td>
<td>kg</td>
</tr>
<tr>
<td>mₐ</td>
<td>Mass + added mass of upper sheave block and arms</td>
<td>kg</td>
</tr>
<tr>
<td>Mₕb</td>
<td>Mass of grab</td>
<td>kg</td>
</tr>
<tr>
<td>Mₙ</td>
<td>Mass of grab fill</td>
<td>kg</td>
</tr>
<tr>
<td>Mₙc</td>
<td>Moment of side edge forces around bucket bearing</td>
<td>N·m</td>
</tr>
<tr>
<td>Nₕc</td>
<td>Terzaghi coefficient</td>
<td>-</td>
</tr>
<tr>
<td>Nₙp</td>
<td>Terzaghi coefficient</td>
<td>-</td>
</tr>
<tr>
<td>Nₙₗ</td>
<td>Terzaghi coefficient</td>
<td>-</td>
</tr>
<tr>
<td>p</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
</tbody>
</table>
\[v_c\] Cutting velocity \[\text{m/s}\]
\[W_h\] Underwater weight of bucket \[\text{N}\]
\[W_l\] Underwater weight of lower sheave block \[\text{N}\]
\[W_u\] Underwater weight of upper sheave block and arms \[\text{N}\]
\[y_b\] Vertical position of bucket centre of gravity \[\text{m}\]
\[y_l\] Vertical position of lower sheave block \[\text{m}\]
\[y_u\] Vertical position of upper sheave block \[\text{m}\]
\[z\] Water depth \[\text{m}\]
\[\alpha\] Angle of arm with vertical \[\text{rad}\]
\[\beta\] Angle between cutting edge, bucket bearing and bucket centre of gravity \[\text{rad}\]
\[\varphi\] Closing (opening) angle of bucket with vertical \[\text{rad}\]
\[\theta\] Angle between cutting edge, bucket and arm bearings \[\text{rad}\]
\[\eta(\varphi)\] Function \[\text{m}\]
\[\rho_w\] Density water \[\text{kg/m}^3\]
\[\gamma_w\] Specific weight of water \[\text{N/m}^3\]
\[\rho_s\] The situ density of material to be dredged \[\text{kg/m}^3\]
\[\gamma_s\] Specific weight of sand under water \[\text{N/m}^3\]
\[\delta\] Thickness of side edges \[\text{m}\]