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THE CLOSING PROCESS OF CLAMSHELL DREDGES IN WATER-SATURATED SAND.

Dr.ir. S.A. Miedema[1]
Prof.ir. W.J. Vlasblom[2]

ABSTRACT.

The 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. Because the dredging business is concerned with water saturated sand or clay has to be dredged, the research into the closing process of clamshell grabs had to start from scratch (except for the kinematics of clamshells). In 1989 the research carried out by Great Lakes Dredge & Dock Company 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. A clay cutting theory is implemented in the numerical model but will not be taken into consideration in this paper. In 1991, Great Lakes and the Delft University of Technology carried out laboratory research in which a scale model clamshell was used. This research, carried out in dry and in water saturated sand, resulted in a verification and validation of the calculation method with respect to the closing curve, the angular velocity and the pulling force in the closing wire. This paper contains results of the lecture notes of Vlasblom [22], a literature survey, the equations of motion of a clamshell grab, background to the sand cutting theory, results of the computer program CLAMSHELL, and it will give some of the results of the research carried out with respect to verification and validation of the computer program, whilst a short preview into future research is given.

INTRODUCTION TO CLAMSHELL DREDGING.

The grab dredger is the most common used dredger in the world, especially in North America and the Far East. It is a rather simple and easy to understand stationary dredger with and without propulsion (Figure 2). In the latter the ship has a hold which it stores the dredge material, otherwise barges transport the material. The dredgers can be moored by anchors or by poles (spuds).

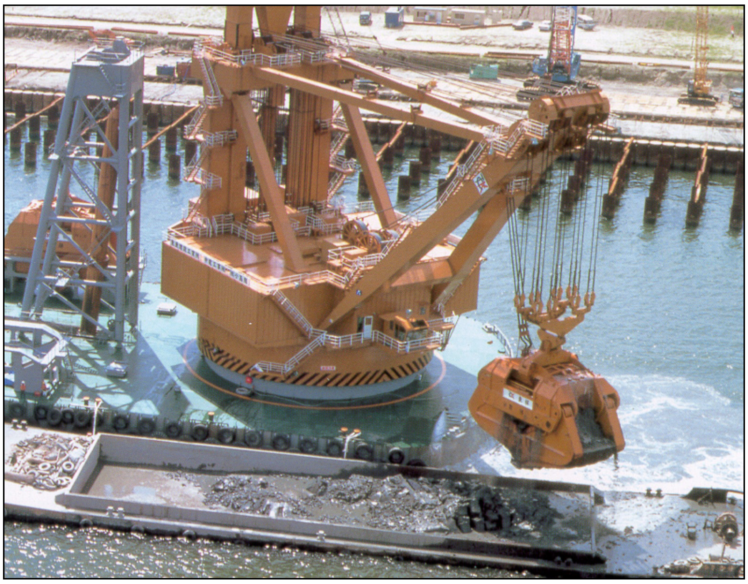

Figure 1: The largest grab in the world (200 m3).

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[1] Delft University of Technology, Faculty 3mE, The Netherlands. s.a.miedema@3me.tudelft.nl
[2] Delft University of Technology, Faculty 3mE, The Netherlands. w.j.vlasblom@3me.tudelft.nl

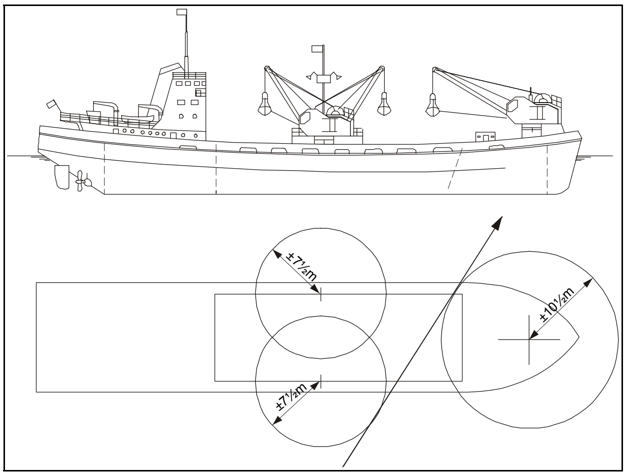

Figure 2: Self propelled grab hopper dredge .

The most common types are boom type clamshell dredgers with a boom that can swing around a vertical axis. Beside these, but considerably less in number, are the overhead cranes (Figure 3), with the trolleys, like the ones used for the transshipment of bulk goods in ports. The capacity of a grab dredger is expressed in the volume of the grab. Grab sizes varies between less than 1 m^3 up to 200 m^3 (Figure 1).

Figure 3: Grab bucket reclaimer.

The opening of the grab is controlled by the closing and hoisting wires or by hydraulic cylinders. To ensure that the grab does not spin during hoisting and lowering many crane are equipped with a tag line, running from half way the boom straight to the grab. For clamshell dredgers the method of anchoring and the positioning system plays an important role for the effectiveness of the dredger. The volume to be dredged at a position decreases with the angle from the centerline. So dredging areas from -90° to +90 ° from the centerline is not always effective. In Figure 5 a top view and a projection of the dredging area is shown. The width of the dredging area is $R \cdot \sin(\zeta)$ and the width of the cut is L, so the surface of the effective dredging area is: $A_{eff} = L \cdot R \cdot \sin(\zeta)$ which equals: $A_{eff} = \zeta \cdot \frac{2 \cdot \pi}{360^\circ} \cdot R \cdot L'$.

The mean dredging (swing) efficiency as a function of the swing angle of the crane being $\frac{L'}{L}$ follows from equalization of both equations: $\frac{L'}{L} = \frac{\sin(\zeta)}{\zeta} \cdot \frac{360^\circ}{2 \cdot \pi}$ (Figure 6).

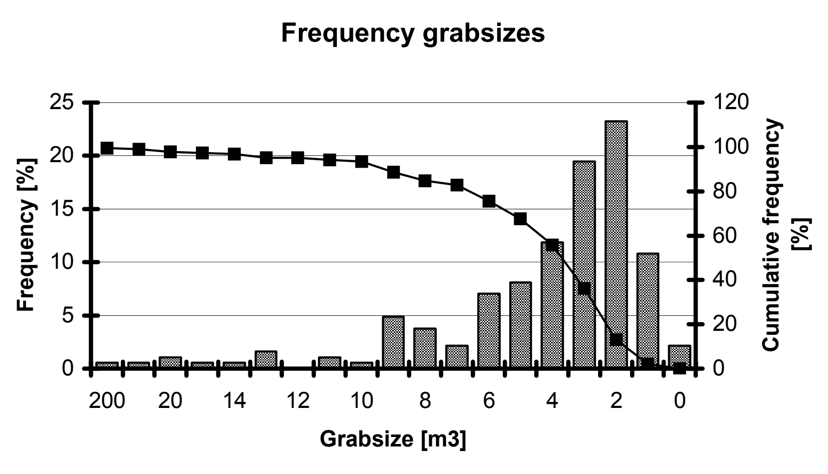

Figure 4: A rough overview of the most common grab sizes.

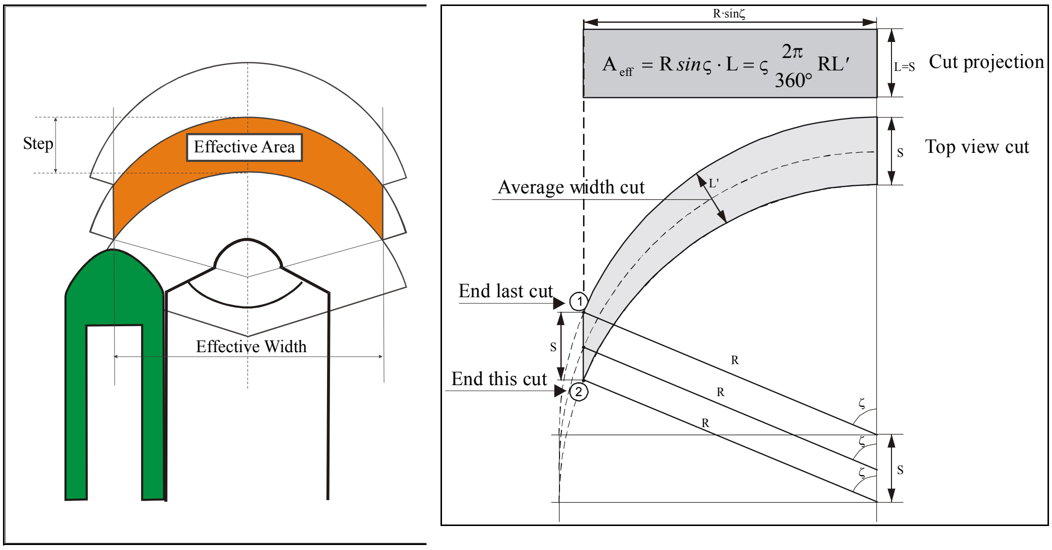

Figure 5: The effective dredging area.

Figure 6: The swing efficiency.

It is important to localize every bite of the grab by means of a positioning system. This helps the dredge master to place the next bit after the foregoing. The dredging process is discontinuously and cyclic:

- Lowering of the grab to the bottom
- Closing of the grab by pulling the hoisting wire
- Hoisting starts when the bucket is complete closed
- Swinging to the barge or hopper
- Lowering the filled bucket into the barge or hopper
- Opening the bucket by releasing the closing wire.

Releasing the aft wires and pulling the fore wires does the movement of the pontoon. When the dredgers have spud poles, this movement is done by a spud operation, which is more accurate than executed by wires. The principle of this hoisting operation is given in Figure 7 below. For a good crane-working behavior the cable cranes have two motors:

- The hoisting motor, which drives the hoisting winch and
- The closing motor, which controls the closing and the opening the grab.

In order to avoid spinning of the clamshell a so-called tag wire is connected to the clamshell.

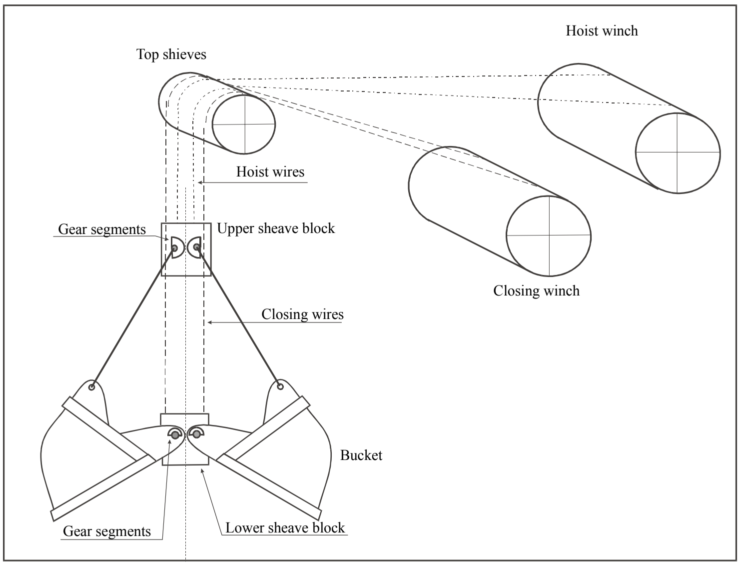

Figure 7: Hoisting system of cable clamshells.

The crane-working behavior is now as follows:

no.	Cycle Part	Position Yaws	Hoisting Winch	Closing Winch
1	ease	open	eases	eases
2	dig	closing	hoists	hoists
3	hoist	closed	hoists	hoists
4	swing	closed	rest	rest
5	ease	closed	eases	eases
6	dump	opening	eases	rest
7	hoist	open	hoists	hoists
8	swing	open	rest	rest

The large grab dredgers are used for bulk dredging. While the smaller ones are mostly used for special jobs, such as:

- Difficult accessible places in harbors
- Small quantities with strongly varying depth.
- Along quay walls where the soil is spoiled by wires and debris
- Borrowing sand and gravel in deep pits
- Sand and gravel mining
- Dredging in moraine areas where big stones can be expected.

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The production of a grab depends strongly on the soil. Suitable materials are soft clay, sand and gravel. Though, boulder clay is dredged as well by this type of dredger. In soft soils light big grabs are used while in more cohesive soils heavy small grabs are favorable. The dredging depth depends only on the length of the wire on the winches. However the accuracy decreases with depth. For mining of minerals dredging depths can reach more than 100 m.

IMPORTANT DESIGN ASPECTS.

The clamshell (Figure 8) most common and is used in silty, clayey and sandy materials. In mud the yaws in general have flat plates without teeth. In sand, clay and gravel, the yaws are fitted with in each other grabbing teeth. The two halves, shells, rotate around a hinge in the **lower sheave block** and are connected with the **upper sheave block** by rods. The closure/hoist cable is reefed several times between the head and the disc block to generate enough closing force. In mud the yaws in general have flat plates without teeth. In sand, clay and gravel, the yaws are fitted with in each other grabbing teeth. For the removal of contaminated soil closed clamshells are used to avoid spillage.

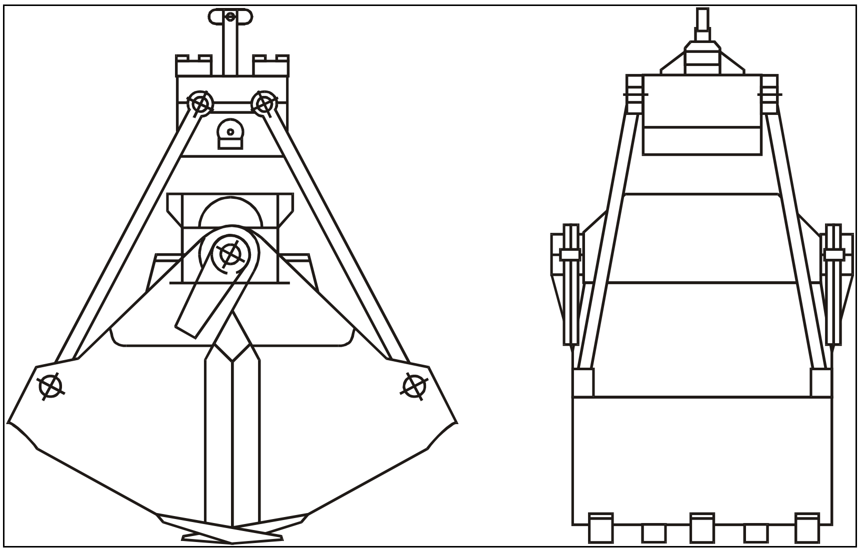

Figure 8: The clamshell.

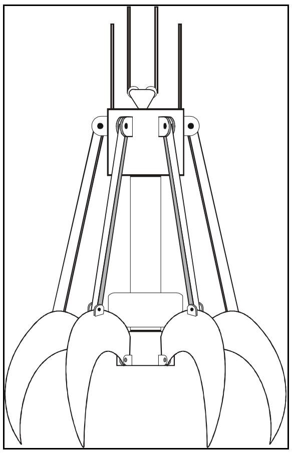

Figure 9: The orange peel grab.

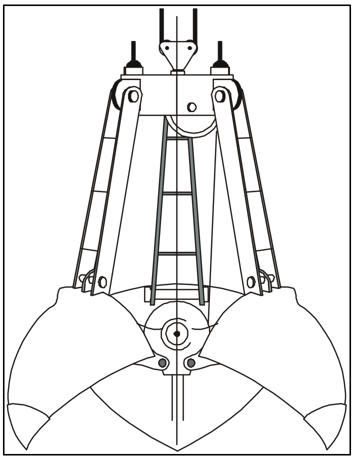

Figure 10: The cactus grab.

The orange peel grab (Figure 9) is often used for the removal of large irregular pieces of rock and other irregular pieces. This type of grab has 8 yaws that in general do not close very well. The **cactus bucket** (Figure 10) is used in the occurrence of both coarse and fine material at the same time. This grab has 3 or 4 yaws that close well in the closed position and form a proper bucket. The size of the bucket depends on the required production capacity of the crane.

The size of the grab depends on the capacity of the crane. The construction weight is determined, besides by the size also by the required strength and therefore by the type of soil to be dredged. So a grab suitable for the dredging of silt will be relatively large in volume and light in weight, while for the dredging of heavy clay or rocks a relative small but heavy bucket will be used. However, because the hoist force remains constant, with increasing weight of the grab the load weight must decrease. For this reason the efficiency of the grab is expressed as $\eta = \frac{\text{paying load in tons}}{\text{paying load} + \text{grab weight}}$. Research carried out in Japan has found the following relation between the ratio of the mass of the material in and the mass of the bucket: $K_s = L \cdot \sqrt{\frac{B}{2 \cdot M_{bucket}}}$ (Figure 11).

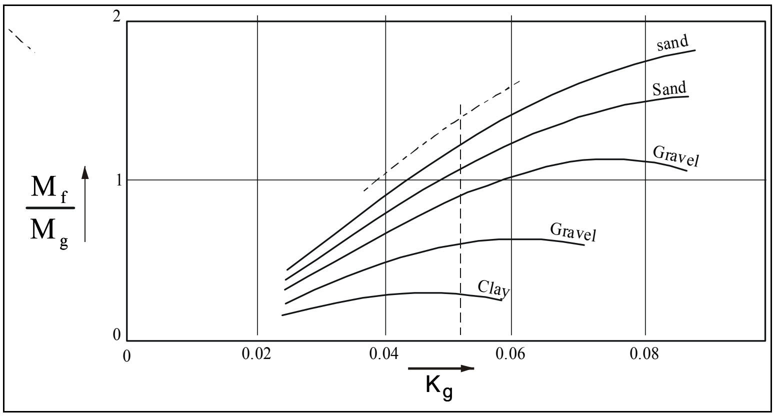

Figure 11: Fill mass and bucket mass ratio.

The winch drive systems are mainly electric (direct current or thyristor-controlled d-c motor connect to the 3 phase board net system) and has the 4 quadrants system (Figure 12).

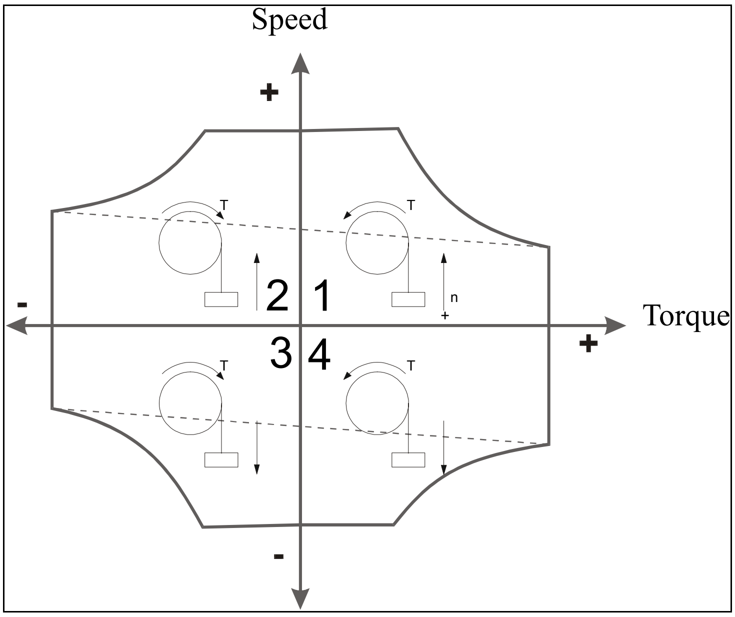

Figure 12: Four quadrants system. winch drive.

Non self-propelled grab dredgers consist of simple pontoons on which the crane is positioned. The deck is heavy reinforced no only for foundation of the crane but also where heavy loads can be expected, in particular where the grabs are stored. Winces for the movement of the pontoon are placed on deck as well as the accommodation for the crew when necessary. In many cases a standard crane is placed on the pontoon. The boom of the crane is movable with a simple wire system. During dredging the boom is kept in a fixed position as much as possible. This avoids the need for a horizontal load path. The length of the pontoon is in many cases longer than necessary in order to keep barges along side. The positioning of the pontoon is either by anchors (4 to 6) or by 2 or 3 spud poles.(Figure 13). In the last case 2 fixed spuds are situated at on the sides of the pontoon and one walking spud aft.

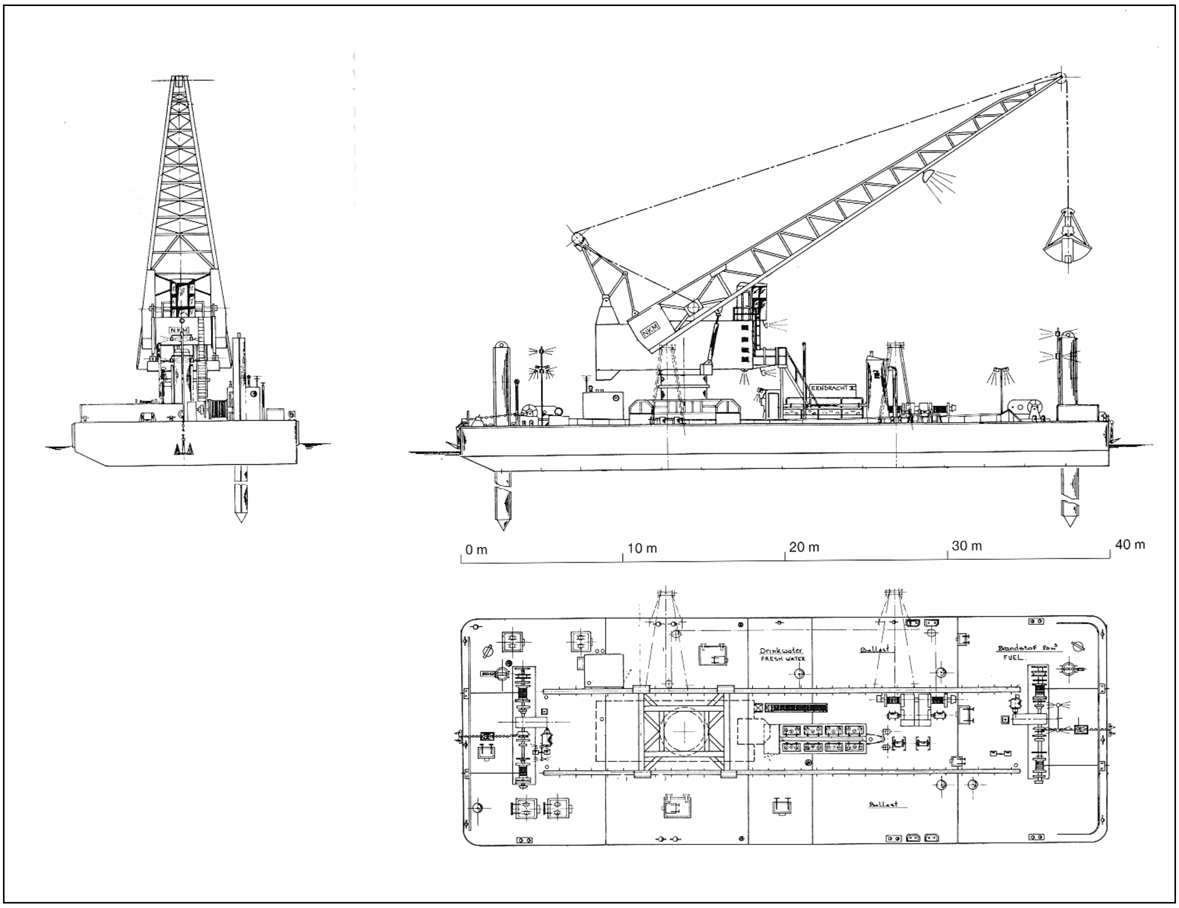

Figure 13: Plan view of Grab crane Eendracht, BOSKALIS.

An idea about the lightweight in relation to grab size is given in (Figure 14) and is in the order of 100 times the grab size.

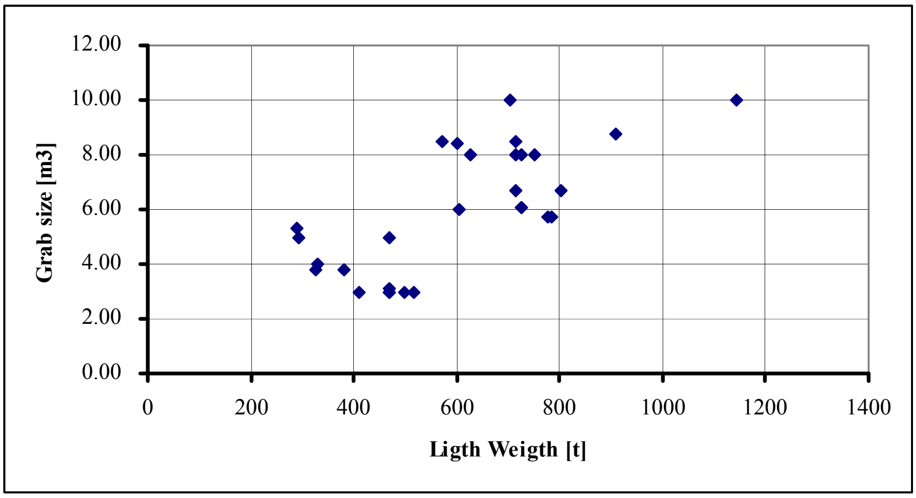

Figure 14: Light weight of grab dredge pontoons.

The lightweight of the pontoon is low compared to that of the other dredgers. The relation between light weight and pontoon volume is shown in Figure 15. The L/B and B/T ratios f the pontoons are respectively between 2 and 3 and 4 to 6 (Figure 16). Special attention needs the stability of the dredge because of the varying and eccentrics loads. Free fluid levels should be avoided.

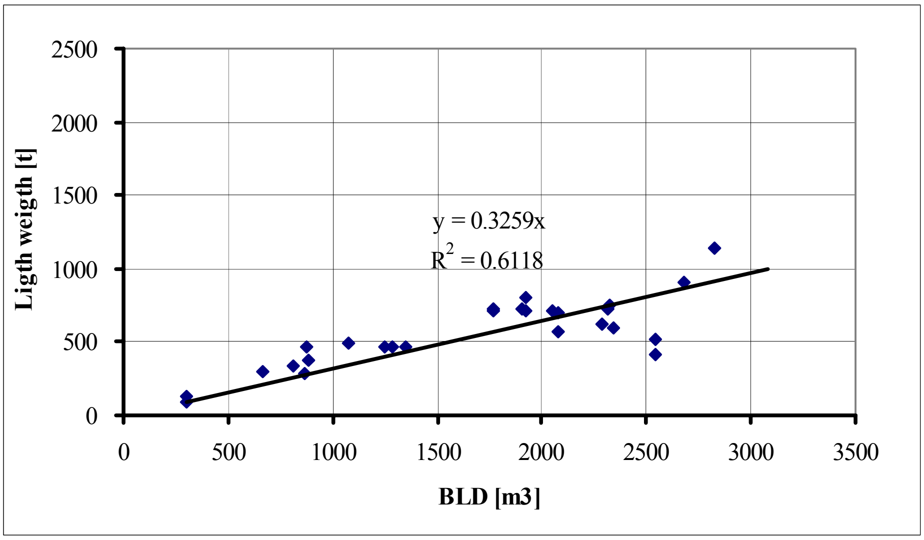

Figure 15: Pontoon volume.

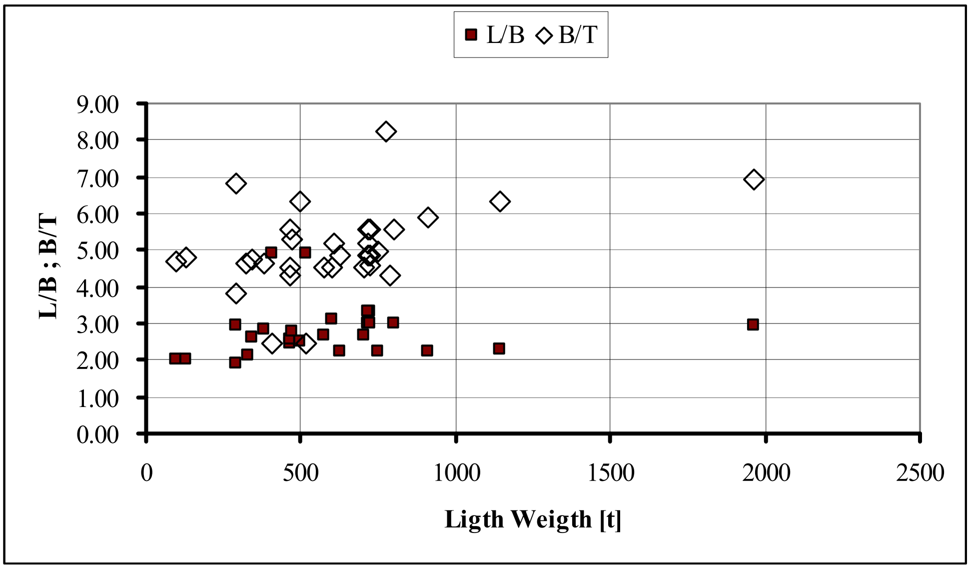

Figure 16: L/B and B/T ratios.

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. This was the reason for Great Lakes to start fundamental research into the processes involved in the digging of clamshell grabs in cooperation with dr.ir. S.A. Miedema. In 1989 this resulted in the computer program CLAMSHELL [9], which simulates the digging process of clamshell grabs in water saturated sand and clay. Although the results of the program were promising, there was a need for verification and validation of the program by means of measurements. Model research was carried out at the Dredging Engineering Research Laboratory of the Delft University of Technology in 1991, Wittekoek [21]. The results of the measurements correlate very well with the computer program. The program is used by Great Lakes for production estimates and as well for the design of new clamshell grabs. Figure 17 shows the largest clamshell grab used in dredging, the Chicago (not operational anymore), owned by Great Lakes Dredge & Dock Company. Figure 18 shows the 50 cubic yard clamshell of the Chicago. Figure 19 shows the clamshell against human size.

THE HISTORY OF CLAMSHELL RESEARCH.

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 [14] investigated the influence of the deadweight of a grab with respect to the payload for grabs of 1 m^3 to 2.25 m^3. He concluded that the payload has a linear relation with the deadweight. Ninnelt 1927 [12] carried out research similar to Pfahl [14] and confirmed Pfahl's conclusions. Niemann 1935 [13] 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 [14] and Ninnelt [12]. Tauber 1959 [17] conducted research on prototype and model grabs. Contrary to Nieman [13] 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 [18] studied the closing cycle of a clamshell in sand for three different 39.5 kg model grabs.

Figure 17: The largest clamshell grab used in dredging, the Chicago, in full operation.

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 [18] 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 [19] performed research on different types of grabs and concluded that wide span grabs are more efficient then clamshell grabs. He also concluded that no model laws for grabs exist and that existing grabs are proportioned in about the best way possible. The best grab is a grab that exerts a torque on the soil that is as high as possible especially towards the end of the closing cycle. Hupe and Schuszter 1965 [6] 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 [3] tested a 0.6 m^3 grab and measured the payload for different values of the deadweight, the grab area, the cutting angle and the grain size. He concluded that in hard material 80% of the closing force is used for penetrating the soil, while in soft material this takess only 30% of the force. The width/span ratio should be between 0.6 and 0.7 matching Tauber's [17] conclusions, while the cutting angle should be about 11 to 12 degrees with the horizontal in a closed situation matching Torke's [18] conclusions. Gebhardt 1972 [4] derived an emperical 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 [15] 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 [3]. Scheffler, Pajer and Kurth 1976 [16] 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 [19] as having derived the best conclusions about grab model testing, but regret that prototype results are not available. Bauerslag 1979 [1] investigated the process of grabbing ores of 55 mm with a motor grab. As with Torke [18] he first measured the closing curve (digging path) and then reconstructed the closing process.

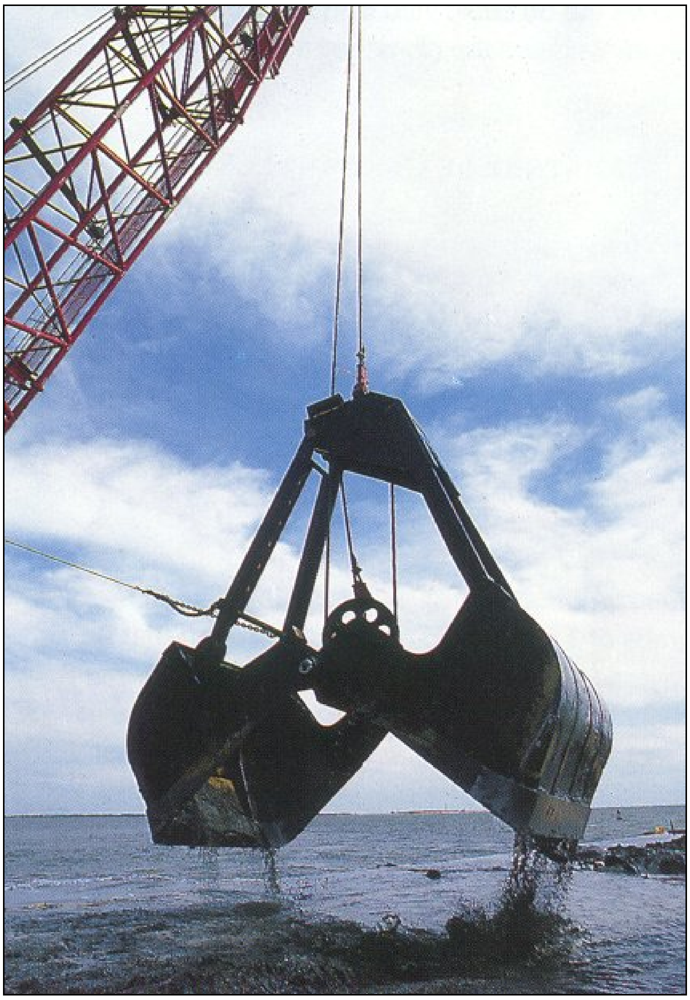

Figure 18: The 50 cubic yard clamshell buckets.

From the literature survey it can be concluded, that much research has been carried out in order to find the optimum geometry of clamshells with respect to the payload. The influence of the nature of the bulk material, however, has been underestimated, while no research has been carried out with respect to the use of clamshells under water. Several researchers manage to reconstruct the filling process of a clamshell, once the closing curve is known, but not one of them is able to predict the closing curve. One of the main problems is that grabs are designed by mechanical engineers, while the bulk material taken by the grab often behaves according to the rules of soil mechanics, the field of the civil engineer. This results in a communications problem. To be able to simulate and thus predict the closing process of clamshells, one needs to study the clamshell operation, kinematics, dynamics (equations of motion) and the soil mechanical behavior of the material taken. This will lead to a better understanding of the processes involved.

Figure 19: The clamshell buckets versus human size.

THE OPERATION AND KINEMATICS OF A CLAMSHELL.

Clamshell grabs as used in dredging industry, consist of six main bodies that can be distinguished as is shown in Figure 20. These six bodies are the upper sheave block, the lower sheave block, the two arms and the two buckets. In between the two sheave blocks the closing wire (rope) is reefed with a certain number of parts of line. The hoisting (and lowering) wire is mounted on top of the upper sheave block. A cycle of the grabbing process in a soil which is hard to dig consists of first lowering the clamshell fully opened and placing it on the soil to be excavated. When the clamshell is resting on the soil the hoisting wire is kept slack, so the clamshell will penetrate vertically into the soil by its own weight. This is called the initial penetration. The distance between the two sheave blocks is at a maximum during the initial penetration. Secondly the closing wire is hauled in, resulting in the two sheave blocks being pulled towards each other and thus causing the closing of the buckets. During this second stage, the hoisting wire is kept slack, so the buckets are allowed to penetrate into the soil. In soft soils it may be necessary to keep the hoisting wire tight, because otherwise the clamshell might penetrate too deeply into the soil, resulting in a lot of spillage. In this paper, only hard to dig sands will be considered. At the end of the second stage the clamshell is closed and will be raised with the hoisting (and the closing) wire. Figure 21 shows the stages of the closing cycle of the clamshell. The amount of soil taken by the clamshell depends on the kinematics and the weight distribution of the clamshell and on the mechanical properties of the soil to be dredged.

THE EQUATIONS OF MOTION OF A CLAMSHELL.

In order to calculate the closing curve of a clamshell, the equations of motion of the moving parts of the clamshell have to be solved. The type of clamshell considered has six main bodies that are subject to motions. These bodies are the upper sheave block, the lower sheave block, the two arms and the two buckets. Because the arms have a small rotational amplitude and translate vertically with the upper sheave block, they are considered as part of the upper sheave block. The error made by this simplification is negligible. If a clamshell is considered to be symmetrical with respect to its vertical axis, only the equations of motion of one halve of the clamshell have to be solved. The other half is subject to exactly the same motions, but mirrored with respect to the vertical axis. Since there are three main bodies left, three equations of motion have to be derived. In these equations weights are considered to be submerged weights and masses are considered to be the sum of the steel masses and the hydro-mechanical added masses. The weights and the masses as used in the equations of motion are also valid for one half of the clamshell. The positive directions of motions, forces and moments are as depicted in Figure 22.

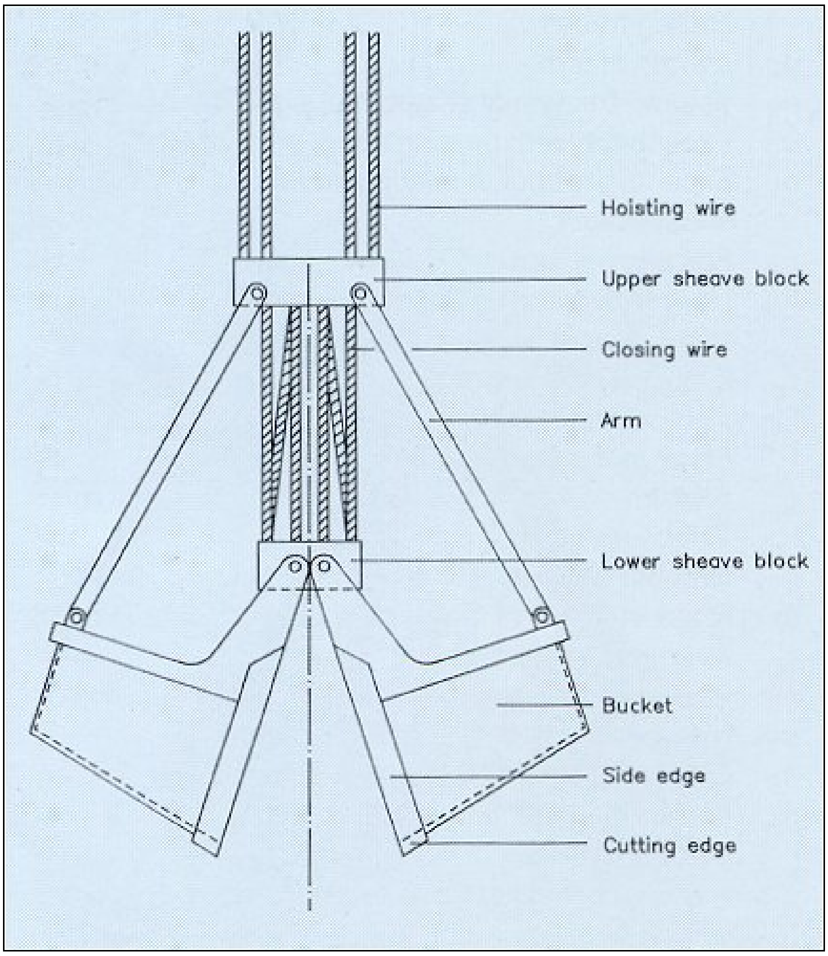

Figure 20: The nomenclature of the clamshell buckets.

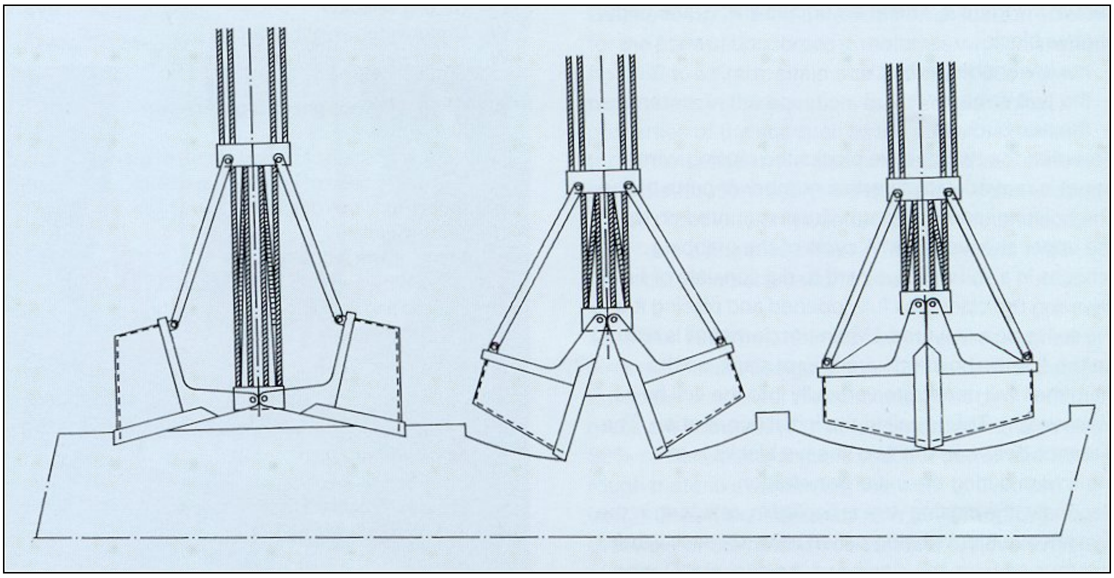

Figure 21: Three stages of the closing process.

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

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

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

$$\begin{aligned} m_i \cdot \ddot{y}_i = & -F_r \cdot i + W_l + W_b - m_b \cdot \ddot{y}_b + m_b \cdot bg \cdot \cos(\varphi+\beta) \cdot \varphi^2 \\ & + F_a \cdot \cos(\alpha) + F_{cv} + F_{ev} \end{aligned} \tag{2}$$

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

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

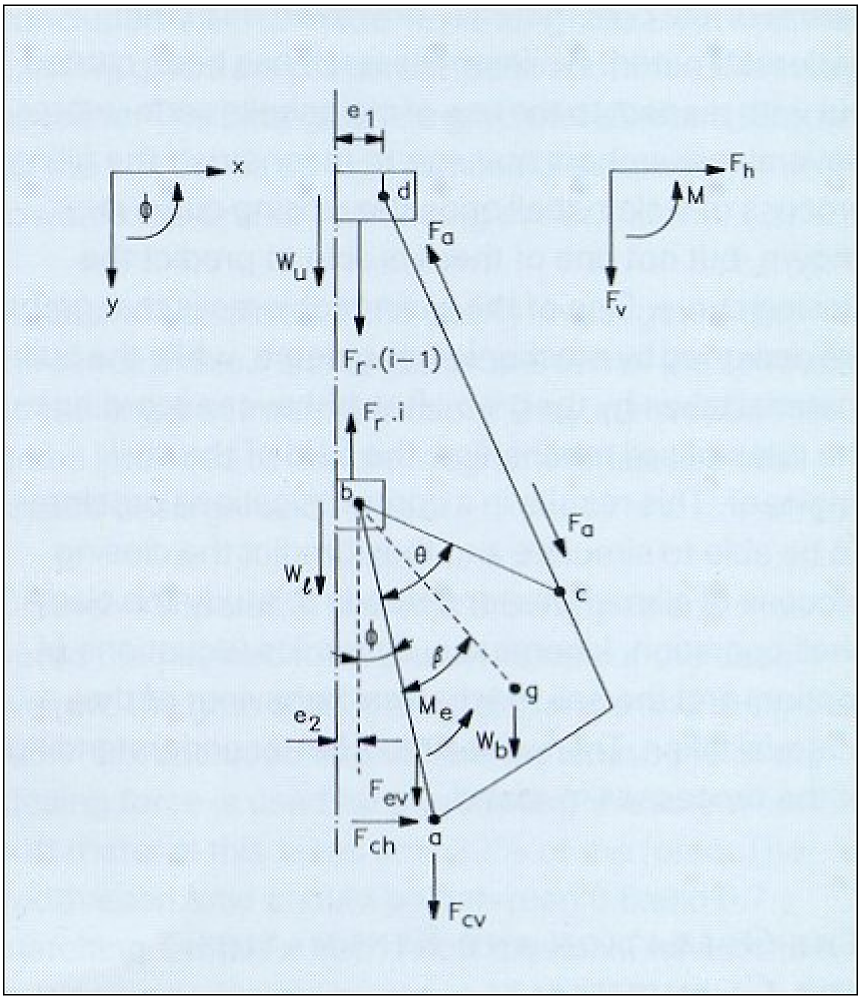

Figure 22: The parameters involved (forces and moments distinguished in the clamshell model).

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:

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

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

$$\ddot{y}_b, \ddot{y}_l, \ddot{y}_u, \ddot{\varphi} \tag{5}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

and for the lower sheave block:

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

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

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

The three vertical accelerations can now be expressed as a function of the rotational bucket acceleration. Velocities and motions can be derived by means of integrating the accelerations if boundary conditions are given. The force in the clamshell arm can be calculated from equation (1) if the rope force F_r and the vertical acceleration of the upper sheave block are known.

The vertical cutting force F_{cv}, the vertical force on the side edges F_{ev} and the torque on the side edges M_e will be discussed in the next paragraph. Since the equations of motion are non-linear, the equations have to be solved numerically. The solution of this problem is a time domain solution, in this case using the Newton Raphson iteration method and the teta integration method to prevent numerical oscillations.

THE FORCES EXERTED ON THE BUCKETS BY SAND.

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

Figure 6 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 [7,8] 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:

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

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

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

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

For the vertical cutting force:

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

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

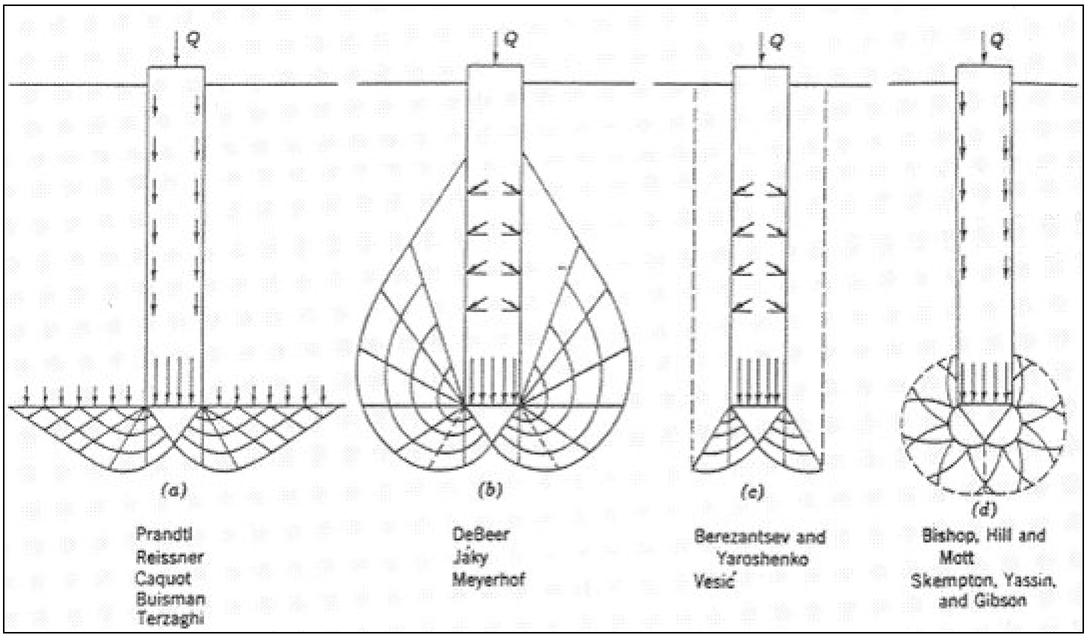

Figure 23: Typical failure patterns that might occur under deep foundations (ref. 23).

The forces and moments on the side edges were unknown when the research started. At first it was assumed that the forces were negligible when cutting sand. From the model experiments Wittekoek 1991 [21] carried out, it appeared that the computer program CLAMSHELL resulted productions that were too high. Changing the mechanical properties of the soil within the accuracy range could not solve this problem. Implementing pressure and friction forces on the side edges improved the calculated results drastically. The forces on the side edges are modeled as the forces on strip footings, Lambe & Whitman 1979 [23]. Figure 23 shows some typical failure patterns that might occur under foundations. The general equation for the pressure force on a strip footing is:

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

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

The coefficients N_c, N_γ and N_q can be calculated according to different theories. The best known theory is the theory of Terzaghi for shallow foundations. Theories for shallow and deep foundations have been developed by De Beer, Meyerhof, Brinch Hansen, Caquot-Kerisel, Skempton-Yassin-Gibson, Berantzef, Vesic and Terzaghi. Lambe & Whitman 1979 [23] give an overview of these theories.

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

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

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

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

The pore under pressure Δp in equation (21) follows from the sand cutting theory of Miedema 1987 [7]. The parts of equation (20) containing N_c and N_γ appeared to be negligible and thus cannot be found in equation (21). To calculate this penetration the empirical formula of Gebhart [4] can also be used, but does not consider the pore pressures:

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

THE RESEARCH CARRIED OUT.

For the verification and validation of the calculation method as described in the previous paragraphs, a test rig was built in the Dredging Engineering Research Laboratory of the Delft University of Technology. The test rig consisted of a model clamshell grab, a container filled with 100 μm sand, a vibration device, a cone penetrometer and a data-acquisition system. Figure 24 gives an impression of the test stand. Figure 25 shows the model clamshell used. On the model clamshell two displacement transducers were mounted, to measure the vertical position and the closing angle. In the closing wire a force transducer was mounted to measure the closing force. The vibration device was used to compact the sand and thus make it possible to get sand with different soil mechanical properties. The cone penetrometer was used to determine the cone resistance of the sand.

By means of calibration diagrams (Miedema 1987 [7]), when the cone resistance is known, the density, the angle of internal friction, the soil interface friction angle and the permeability of the sand could be determined. All transducers were connected with the data-acquisition system, so the data could be processed by a computer. The aim of the research was to do tests in dry and saturated sand, compare the results with simulations of the CLAMSHELL program, and adjust the calculation method if necessary. Since the calculation method is fundamental, it should not matter on which scale the tests are carried out. As explained in the previous paragraph, the forces exerted on the buckets by the sand include a part determined by the mechanical properties of the dry sand and a part determined by the mechanical properties of the saturated sand. Also the forces consist of a part acting on the cutting edges of the buckets and a part acting on the side edges of the buckets.

From Miedema 1987 [7] and 1989 [8] the cutting forces on the cutting edges can be calculated in dry and in saturated sand. What would occur on the side edges was not known when this research started.

To quantify the side edge forces, first 8 tests were carried out in dry sand. Since the force of the closing wire was measured and the real cutting forces could be calculated, the forces on the side edges remained. Repeating this with 14 tests in saturated sand gave a good impression of the influence of saturation on the side edge forces. As a result of these tests, an equation was derived for the side edge forces in dry and in saturated sand as described in the previous paragraph.

Figure 27, Figure 28, Figure 29 and Figure 30 give an example of the test results and the simulations. Figure 27 is the result of a test in dry sand with 10 minutes vibration time. Figure 28 is the result of a simulation with the same mechanical properties of the soil. As can be seen, the digging curves correlate well. The closing force calculated is very smooth, while the closing force measured shows irregularities as a result of the occurrence of discrete shear surfaces in the sand (chipping). The correlation is reasonable however. Figure 29 is the result of a test in saturated sand with 15 minutes vibration time. Figure 30 is the result of a simulation with the same mechanical properties of the soil. Again the digging curves correlate well. The shape of the simulated closing force as a function of the span differs slightly from the measured shape, but the magnitude of the measured and the calculated closing force correlate well. The angular velocity was derived from the signals of the displacement transducers. The shape of this signal from test and simulation correlates well, although irregularities occur in the measured angular velocity.

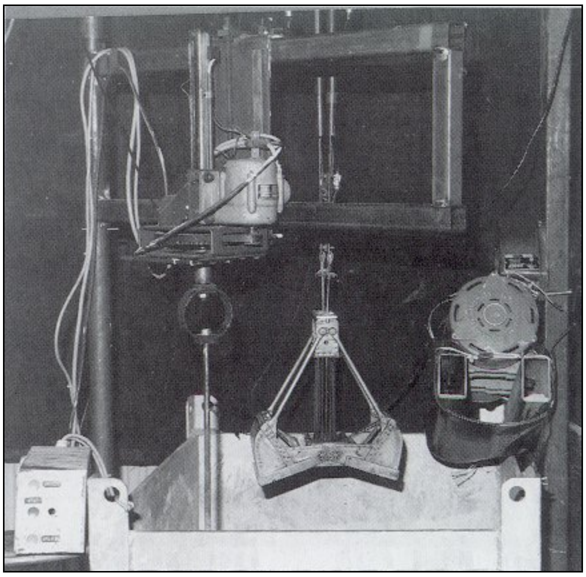

Figure 24: The test rig with the model clamshell grab, a vibration device and a cone penetrometer.

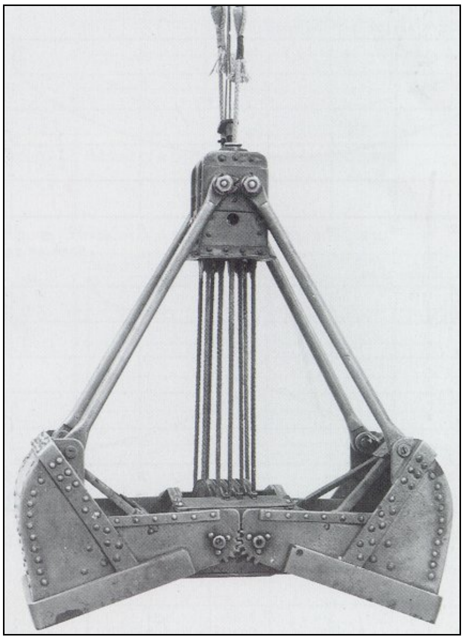

Figure 25: Close up of the clamshell model.

In the 90's a separate version of the CLAMSHELL program has been developed in cooperation with Boskalis called HYCLAM. This program is capable of simulating and prediction the closing behavior of hydraulic clamshell's.

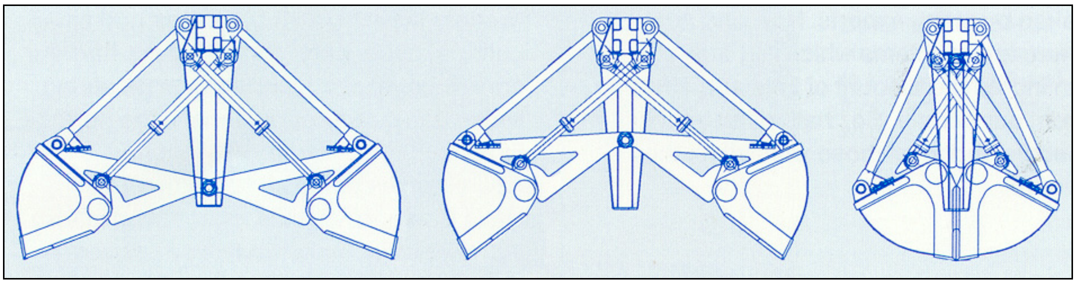

Figure 26: Horizontal closing hydraulic grab (Boskalis).

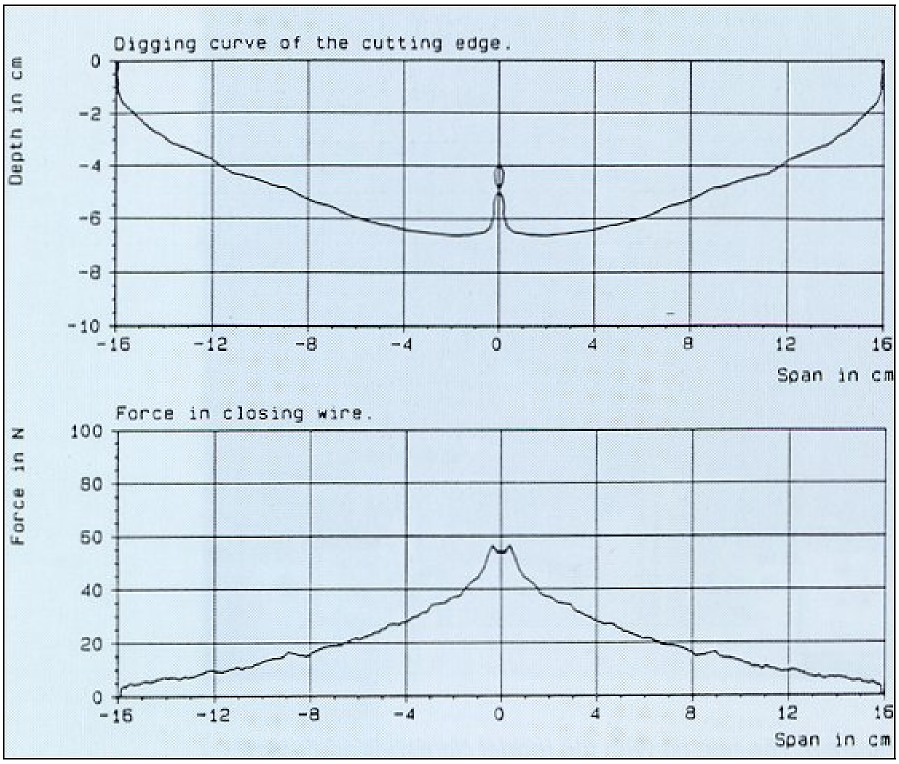

Figure 27: Result of a cutting test in dry sand.

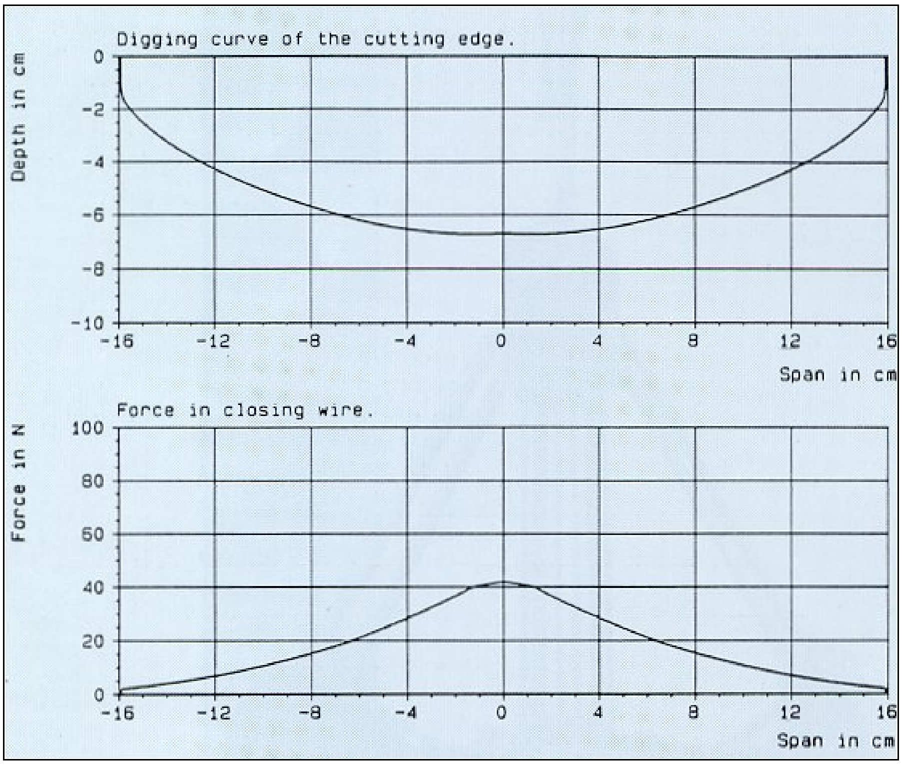

Figure 28: Result of a simulation in dry sand.

CONCLUSIONS.

As a result of analyzing the closing process of a clamshell from the point of view of a mechanical engineer and of a civil engineer, a numerical method of calculation has been developed that simulates the closing process very well. The laboratory research carried out has been a great help in adjusting and tuning the computer program CLAMSHELL. The correlation between the test results and the results of the simulations was good. With respect to the mathematical modeling it appears that the forces on the side edges of the buckets are of the same magnitude as the real cutting forces and can certainly not be neglected. With respect to the use of the CLAMSHELL program it can be stated that the program has already been very useful for the prediction of the production of a clamshell used in dredging operations, moreover the program can also be of great help in designing improved clamshells as well. Studies have already been carried out by Great Lakes, to find optimum clamshell kinematics and mass distribution. A next step in this research will be, the verification and validation of clay cutting with clamshell grabs.

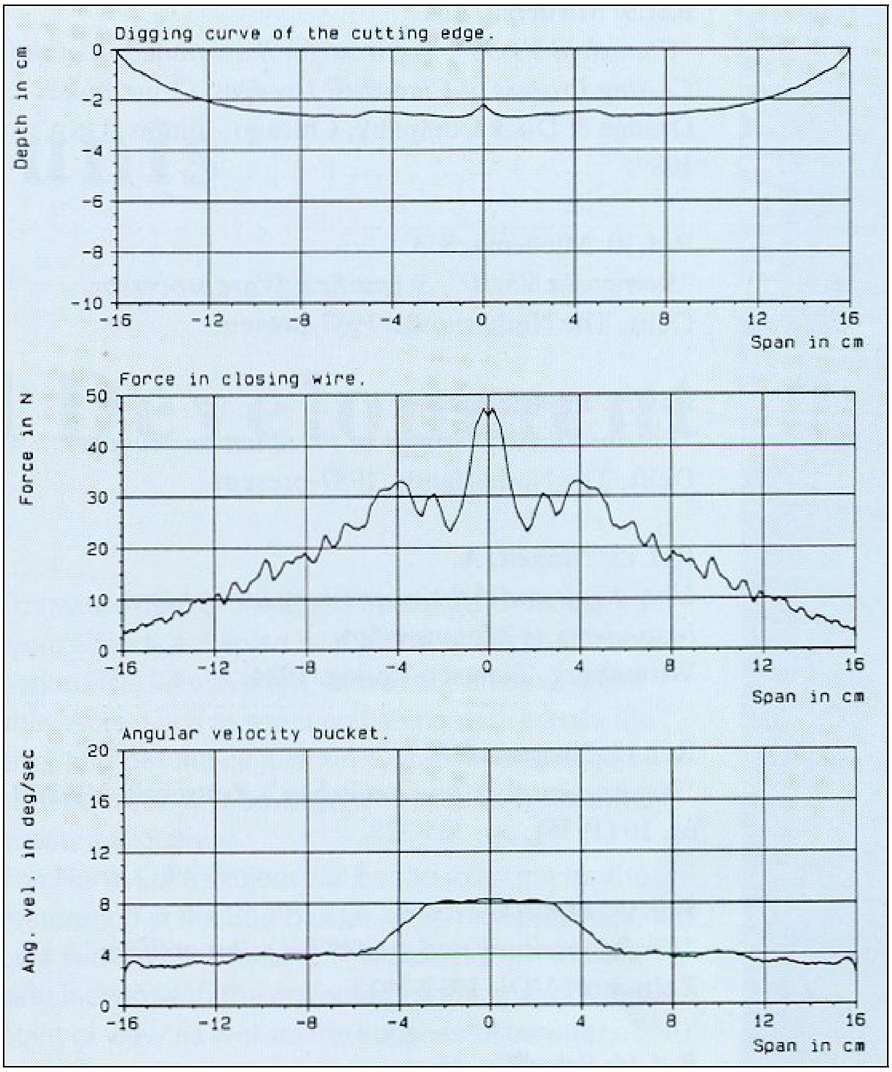

Figure 29: Result of a cutting test in saturated sand.

DEVELOPMENTS.

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

Hettiaratchi and Reece, (1975 [26]) 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 [27]), proved experimentally that also in water saturated sand at large cutting angles a wedge will occur.

The wedge occurs at blade angles larger then 70º and thus has a significant effect on the initial part of the closing process of clamshell's. In following publications the effect of this wedge on the closing process of clamshell's will be described (Miedema 2005 [25]).

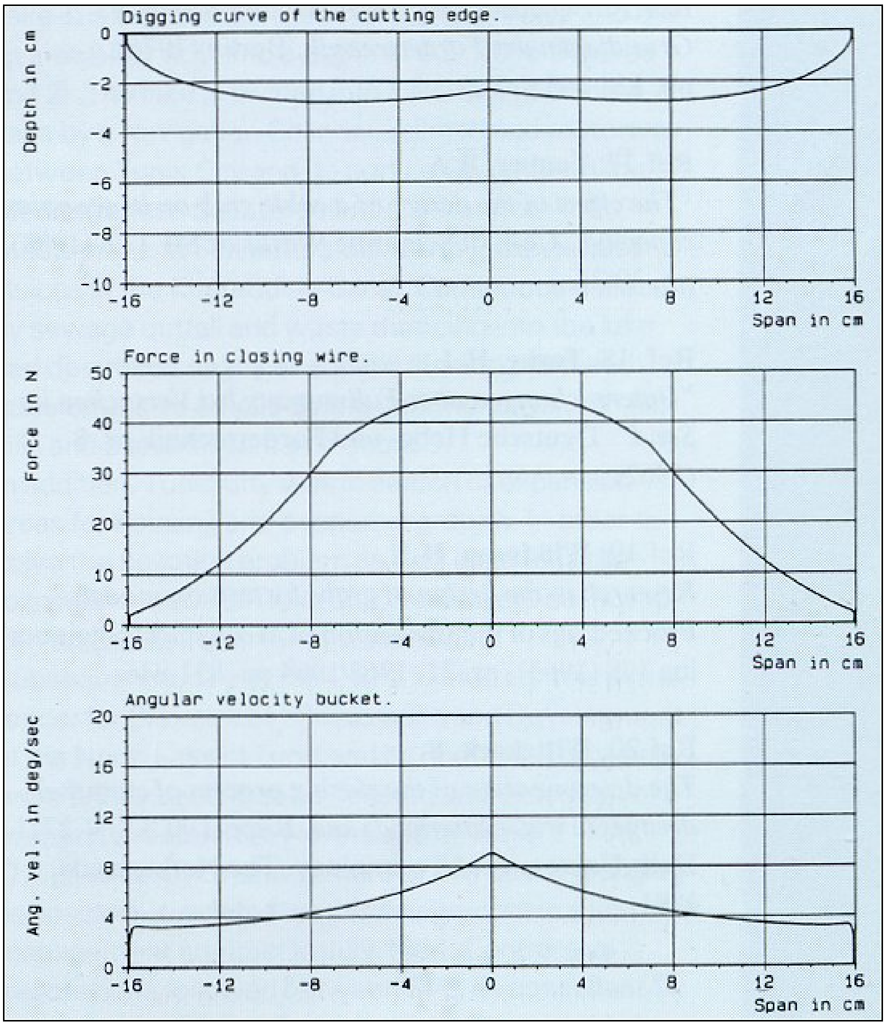

Figure 30: Result of a simulation in saturated sand.

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LIST OF SYMBOLS USED.

ab	Distance between cutting edge and bucket bearing	m
A_e	Surface of side edges (thickness*length)	m^2
b	Width of the buckets	m
bc	Distance between bucket bearing and arm bearing	m
bg	Distance between bucket bearing and centre of gravity	m
B	Width of grab	m
c	Cohesion	Pa
c_1	Proportionality coefficient non-cavitating cutting forces	-
c_2	Proportionality coefficient non-cavitating cutting forces	-
d_1	Proportionality coefficient cavitating cutting forces	-
d_2	Proportionality coefficient cavitating cutting forces	-

dc	Length of arm	m
d_m	Average grain diameter	µm
e	Volume fraction of dilatational expansion	-
e_1	Eccentricity arm bearing upper sheave block	m
e_2	Eccentricity bucket bearing lower sheave block	m
F_a	Force in one arm	N
F_{ch}	Horizontal force on the cutting edge	N
F_{cv}	Vertical force on the cutting edge	N
F_e	Force on side edges	N
F_{ev}	Vertical force on the side edges	N
F_r	Force in the closing rope (wire)	N
g	Gravitational constant (9.81)	m/s^2
h_i	Thickness of layer cut	m
h	The initial penetration	m
i	Number of parts of line	-
I_b	Mass moment of inertia of bucket	$kg \cdot m^2$
k_m	Average permeability	m/s
K_f	The grain shape factor	-
l	Rope length	m
L	Length of fully opened grab	m
m_b	Mass + added mass of bucket	N
m_l	Mass + added mass of lower sheave block	kg
m_u	Mass + added mass of upper sheave block and arms	kg
M_{bucket}	Mass of grab	kg
M_f	Mass of grab fill	kg
M_e	Moment of side edge forces around bucket bearing	Nm
N_c	Terzaghi coefficient	-
$N_\square$	Terzaghi coefficient	-
N_q	Terzaghi coefficient	-
p	Pressure	Pa
v_c	Cutting velocity	m/s
W_b	Underwater weight of bucket	N
W_l	Underwater weight of lower sheave block	N
W_u	Underwater weight of upper sheave block and arms	N
y_b	Vertical position of bucket centre of gravity	m
y_l	Vertical position of lower sheave block	m
y_u	Vertical position of upper sheave block	m
z	Water depth	m
α	Angle of arm with vertical	rad
β	Angle between cutting edge, bucket bearing and bucket centre of gravity	rad
φ	Closing (opening) angle of bucket with vertical	rad
θ	Angle between cutting edge, bucket and arm bearings	rad
$\eta(\varphi)$	Function	m
ρ_w	Density water	kg/m^3
γ_w	Specific weight of water	N/m^3
ρ_s	The situ density of material to be dredged	kg/m^3
γ_s	Specific weight of sand under water	N/m^3
δ	Thickness of side edges	m

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