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Design Aspects for Cutter Heads Related to the Mixture Forming Process When Cutting Coarse Materials


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After receiving his degree in Mechanical Engineering in 1995 from the Delft University of Technology, Marco den Burger joined the chair of Dredging Technology to work on PhD research. This research, initiated by the Dutch dredging contractors, dealt with the mixture forming processes in a dredge cutter head. He obtained his doctoral degree in 2003 and currently works as a freelancer.


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Abstract

Spillage, defined as the soil that is cut during the dredging process but not sucked up by the suction pipe, reduces the productivity of the cutter suction dredger and therefore needs to be minimised. Because insight into the phenomenon of spillage enables more accurate production estimates and makes it possible to design better cutter heads, a test model was set up.

Tests were performed that were representative for the cutting of rock or hard clay, whereby inertial forces play an important role. The tests have been carried out at the Laboratory of Dredging Technology of the Delft University of Technology. As shown from the test models, both cutter head speed and pump capacity have a major influence on the spillage of the cutter. Suggestions are made for improvements to both of these.

Introduction

In the PhD thesis "Mixture Forming in Cutter Heads" (den Burger, 2003), the processes associated with spillage for cutting relatively hard formations are identified and described. This research that was initiated by the dredging industry gives a better understanding of the occurrence of spillage when using a cutter suction dredger. Spillage, defined as the soil that is cut during the dredging process but not sucked up by the suction pipe, reduces the productivity of the cutter suction dredger and therefore needs to be minimised. Spillage rates can be up to 50% when relatively hard formations are cut, resulting in only half of the material that is cut actually is sucked up. Insight in this phenomenon enables more accurate production estimates and makes it possible to design better cutter heads. This article will describe briefly the research done in this field and particular the translation of the results to prototype values.

Cutting Tests in Cemented Banks of Gravel

The research was focussed on the mixture forming processes rather than the cutting process. Furthermore, the tests had to be representative for the cutting of rock or hard clay, whereby inertial forces play an important role. Therefore, an artificial bank was made of weakly cemented gravel. That way, the cutting forces would never become dominant and the available torque on the cutter head drive shaft was not the limiting factor. Moreover, the density of gravel was 2650 kg/m^3 and thus representative for cutting of rock or hard clay. By weakly cementing the gravel particles it was expected that single particles would enter the cutter head.

The tests have been performed on a 1:8 scale in relation to the large cutter suction dredgers. This scale was not chosen freely but results from the available test facilities and cutter heads at the Dredging Laboratory at Delft University of Technology.

Mainly the under-cut situation is investigated. In order to compare the simulated particle trajectories with the particle trajectories resulting from the cutting tests, a transparent back plate was used (see Figure 2, right, for the position and dimensions of the back plate). This made it possible to film inside the cutter head and visualizes the processes taking place inside the cutter head.

Test Facilities and Equipment

The tests have been carried out at the Laboratory of Dredging Technology of the Delft University of Technology. Figure 1 shows the cross section of the cutting tank. The numbers in the figure indicate:

1. radioactive density meter
2. suction pipe
3. cutter head
4. cemented gravel bank
5. main cutting tank
6. collecting tank (used for collecting the production during tests)

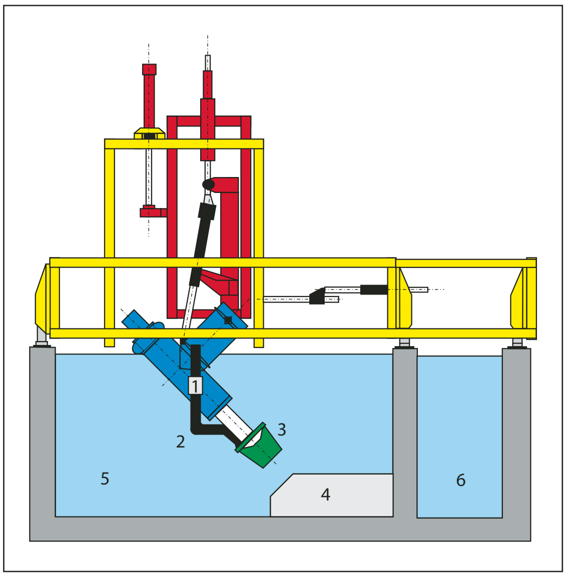
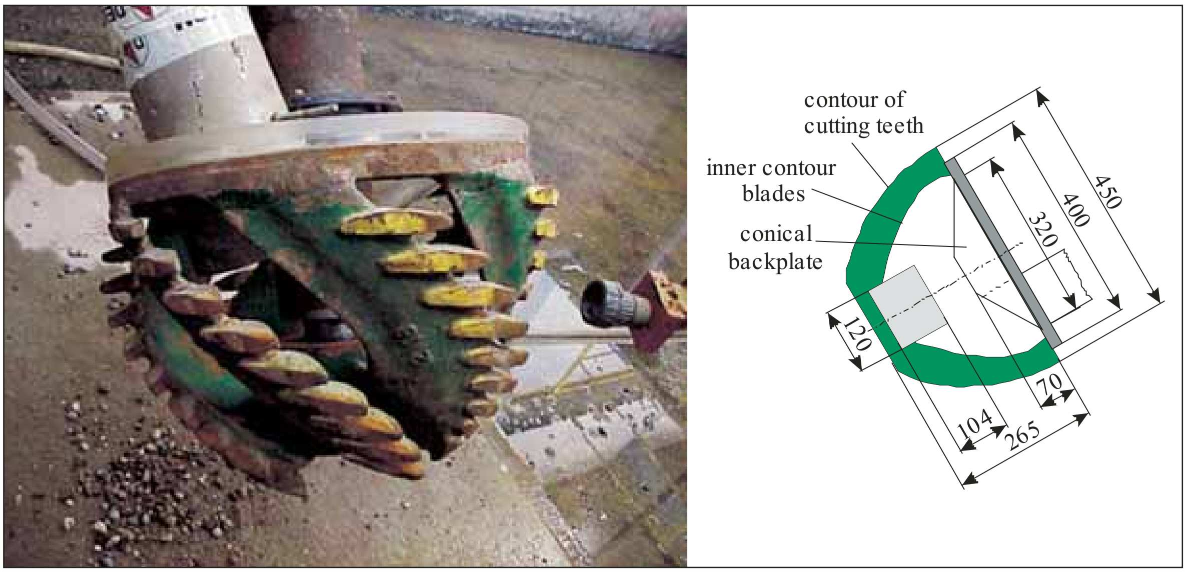


Figure 1. Cross section cutting tank.

All tests have been carried out with the same cutter head. Figure 2 gives the geometry and the most important measures of the cutter head (dimensions in mm).

The angle of the cutter shaft was 45˚ in the majority of the experiments.

Figure 2. Geometry and dimensions of the model cutter head.



Scaling the Rotational Velocity of the Cutter Head and Suction Flow

In order to determine the values of the operational parameters on a model scale their values on prototype scale need to be defined. For the prototype cutter head the parameters based on the cutter suction dredger *Ursa* have been used. The model cutter head is not exactly scaled geometrically as the diameter of the cutter head is scaled with a different factor than the diameter of the suction pipe. The diameter of the suction pipe on a model scale is 9.5 times smaller than on a prototype scale while the diameter of the ring of the model cutter head is 7.8 times smaller.

Furthermore, the densities of the cut material on model and prototype scale are not alike. For the density of rock a value of 2200 kg/m^3 is taken while the gravel particles have a density of 2650 kg/m^3.

On a model scale there is the additional issue that the density of the bank differs from the density of a single gravel grain. This has some consequences for the filling degree of the cutter head and thus on the scaling of the haul velocity.

Directly applying the Froude scale for determining the values of the operational parameters on model scale will give a certain abnormality owing to the fact that the cutter head is not exactly scaled geometrically. This can be avoided by realising that scaling according to the Froude number is a way of realising dynamic similarity on prototype and model scale. This means that all the relevant force ratios should be equal on both scales.

To realise these two dimensionless groups can be formed by the ratio of forces (den Burger 1999).

First of all:

Condition 1

$$\frac{F_{cf}}{F_g} \sim \frac{m_p R_c \omega_c^2}{(\rho_p - \rho_w) V_p g} \sim \frac{\rho_p}{(\rho_p - \rho_w)} \frac{R_c \omega_c^2}{g}$$

in which mp is the mass of the particle, R_c the radius and ω_c is the angular velocity of the cutter head. ρ_p and ρ_w are respectively the density of particle and water. V_p is the volume of the particle and g is the acceleration of gravity. Note that the buoyancy effect is included in the gravitational force. In the latter fraction the Froude number can be recognised.

The second dimensionless group is formed by the ratio of the centrifugal force at the blades and the suction force. The magnitude of the suction force acting on the particle equals the pressure gradient multiplied by the volume of the particle. The ratio then becomes:

Condition 2

$$\frac{F_{cf}}{F_s} \sim \frac{\rho_p}{\rho_w} \left(\frac{\omega_c R_c^3}{v_m R_{sp}^2} \right)^2$$

in which v_m is the mixture velocity and R_{sp} is the radius of the suction pipe.
The term between brackets represents the flow number.

In these two equations, the dissimilarity in geometrical scale factors is taken into account as the dimensions for the cutter head and suction pipe appear in the equations. Furthermore, the difference in densities of the cut particles on both scales is taken into account.

Scaling the Haul Velocity

The haul velocity and the cut-off area determine the amount of material that is cut per unit of time and if the fluid flow is not affected the amount, or rather concentration, of particles inside the cutter head. Hereby the cut-off area is the area perpendicular to the haul velocity, determined by the contour of the cutting teeth and the positioning of the cutter head in the bank. The concentration of particles inside the cutter head is important for the processes taking place inside the cutter head. It will determine the proportion of the following generalised forces:

– Forces resulting from fluid-particle interaction;
– Inter particle forces (such as friction or inter-particle collision).

Furthermore, the interaction between particles and the blades (friction, collisions) depends on the concentration of particles inside the cutter head. These forces are of the same category as the inter-particle forces. An important additional effect of large concentration of particles is the fact that the flow will be disturbed. This may have a significant influence on the production.

In order to have the same effects on model scale as on prototype scale, the filling degree of the cutter head (concentration) needs to be equal on model and prototype scale. Consequently the ratio of the mass flow of particles into the cutter head and the mass flow of particles through the suction pipe (discharge) needs to be equal on model and prototype scale. Thus

Condition 3

$$\frac{\rho_b v_h A_{cut}}{c_{vd} \rho_p Q_s} = \text{constant}$$

in which A_{cut} is the cutoff area and c_{vd} is the delivered

Table I. Values for Prototypes and Models.

Parameter	Prototype	Model	dimension
Diameter suction pipe	0.95	0.10	[m]
Diameter ring cutter head	3.12	0.40	[m]
Mean particle diameter	0.078	0.01	[m]
Suction flow Qs	3.00	0.021	[m^3/s]
Mixture velocity	4.20	2.64	[m/s]
Density rock particles	2200	2650	[kg/m^3]
Density cutting face	2200	1700	[kg/m^3]
Rotational speed	30	90	[RPM]
Haul velocity	0.2	0.1	[m/s]
Cut off area	1.4	0.023	[m^2]

or transport concentration of particles in the suction pipe. ρ_p and ρ_b are respectively the density of particle and the density of the bank. v_h the hauling speed and Q_s the pump capacity.

Using the above equations leads to the values for prototype and model as given in Table I.

Test Results for the Under-Cut Situation

The results of the model tests in under-cut situation with a cutter shaft inclination angle of 45˚ are shown in Figure 3 and Figure 4. In Figure 3 the production percentage is plotted against the rotational velocity. The different markers correspond with different mixture velocities and indicate the measured points. The dashed lines connect the measured points at similar mixture velocities (second order polynomial fit). These lines are merely used for representation purpose and hold no physical background.

The plot shows that the production curves at constant mixture velocity do have optimum values. An initial increase in rotational velocity of the cutter head results in an increase in production. After a certain optimum has been reached, further increasing the rotational velocity causes a decrease in production. Increasing the mixture velocity (at constant rotational velocity) always results in an increase in production.

In the second plot (Figure 4), the production percentage is plotted against the mixture velocity for the different rotational velocities. The plot shows that the maximum production percentage varies almost linearly with the mixture velocity between mixture velocities of 2 m/s and 3.5 m/s (indicated by the dashed line). Beyond a mixture velocity of about 3.5 m/s, the maximum attainable production starts to deviate from the dashed line.

The reason that the production percentage decreases when the rotational velocity becomes too high is, first of all, because of the larger centrifugal forces acting on the particles. Because of the large centrifugal forces the particles are thrown out of the cutter head (segregation). The higher the rotational velocity of the cutter head the higher the centrifugal forces and the lower the production percentage. Secondly, further increasing rotational velocities cause for an increasing pump effect of the cutter head and thus an increasing outgoing flow when the suction flow remains constant. Therefore, more particles will escape from the cutter head as they are dragged along with this outgoing flow.

Figure 3. Production vs. RPM at different mixture velocity.

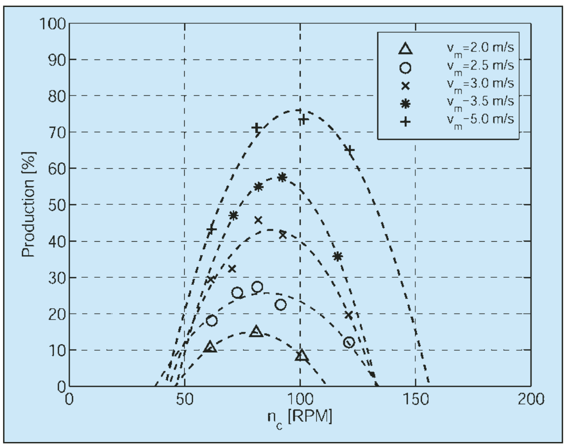


Figure 4. Production vs. mixture velocity at different RPM.

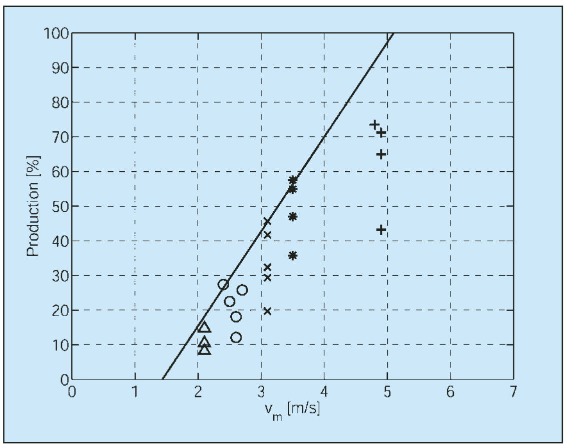


Figure 5. Filling model cutter head at 1 RPM.

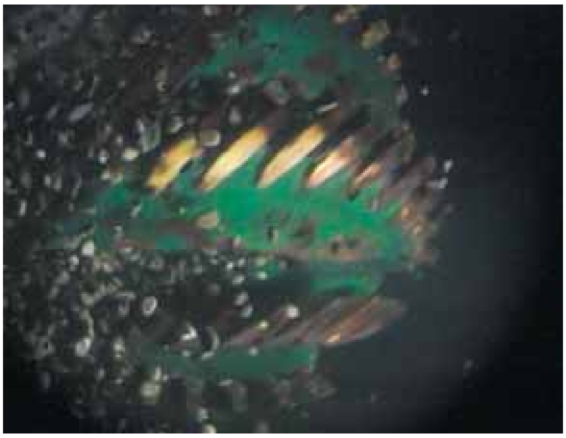


Figure 6. Particles thrown out of the cutter head at 90 RPM.

The increase in production with increasing rotational velocity is more difficult to explain. At low rotational velocities the gravitational forces are clearly dominant and most particles will gather at the lowest point in the cutter head and can be considered as spillage. The most likely reasons for the increase in production percentage with increasing rotational velocity were thought to be:

– better mixing of the particles because of collisions of particles with the blades;
– positive change of flow inside the cutter head.

Additional tests have been performed to investigate these phenomena. In these tests gravel particles have been injected into the cutter head through the back plate by means of a silo and tube system (den Burger, 2001). Therefore the cutter head was not placed in the bank but rotating freely. A camera was placed on the right hand side of the cutter head to film the processes inside the cutter head through the gaps between the blades. The video recordings did not show the evidence of particles colliding with the cutter blades. In fact, the particles showed a sliding motion along the cutter blades towards the cutter ring, which increased with increasing rotational velocity. Figure 5 and Figure 6 emphasise this. Figure 5 shows the filling of the crown cutter head for a rotational velocity of 1 RPM and a mixture velocity of 2.5 m/s. Increasing the rotational velocity to 90 RPM (Figure 6) showed a clear axial motion towards the cutter ring.

Most particles were thrown out of the cutter head near the cutter ring and hardly any particle left the cutter near the hub. As the particle move closer towards the cutter ring they get closer to the suction mouth and are sucked up more easily. This is the reason for the increase in production with increasing rotational speed. The reason for sliding motion of the particles along the cutter blades is supposed to be the centrifugal forces acting on the particles in combination with the bladeís geometry. As this centrifugal force has a component along the bladeís inner surface directed towards the cutter ring, it can force particles towards this cutter ring if it is large enough.

To what extent the axial motion of the particles is caused by the component of the centrifugal force was not directly clear. Therefore a dynamic model was set up that describes the trajectory of a particle along the inner surface of a cutter blade for a cutter head rotating in a fluid (den Burger, 2001). The main purpose of the model was to verify that the component of the centrifugal force acting along the surface of a cutter blade could be responsible for the motion of particles towards the cutter ring. The model set up it is not restricted to one-blade geometry but can be used for any reasonable blade geometry. The particle is represented by a point mass with finite size.

The model was set up for single particles that slide (not roll) along the blade’s surface. Considering the elliptical shape of the gravel particles it is fair to assume that the particles do not roll over the blades. The absence of multiple particles in the model can be justified by the fact that attention was focused on the influence of the centrifugal force acting on a particle plus the bladeís geometry on the axial motion of a particle towards the cutter ring. For both single and multiple particles this effect should be present, although to different extents.

Simulations describing the trajectory of a particle along the cutter blade show that the bladeís geometry in combination with the centrifugal force can be responsible for the axial motion of particles towards the cutter ring. This could explain the increase in production with increasing rotational velocity as resulted from the cutting tests. The axial motion is certainly visible for rotational velocities of the cutter head beyond 80 RPM on model scale (which corresponds with 28 RPM on prototype scale). The axial transport of particles along the blade is generally higher near the hub due to the larger blade angle and the strong curvature of the blades near the hub. Therefore, in this region, the component of the centrifugal force along the bladeís surface is larger.

Translating the Results to Prototype

As shown from the model tests (Figure 3) both cutter head speed and pump capacity have a major influence on the spillage of the cutter, while the optimal cutter head speed varies slightly with the pump capacity. Translation of the results to nominal prototype values shows relative production values in the order of 30%, which are very low. It should be noted, however, that the ladder angle was 45˚, which represents an unfavourable situation in practice. For more custom ladder angles of 30˚ the production percentage are much higher (den Burger, 1999).

In addition, the results of the model tests show that in order to get a relative production of 75% (25% spillage), the mixture velocity v_m should be in the order of 5 m/s and the rotational velocity nc 100†RPM for prototype particles with a density of 2200 kg/m^3.
It should be noticed that for the proto type cutter head with a diameter of 3.12 m the pump capacity should be 5.7 m^3/s (mixture speed 8 m/s in the suction line) to get a relative production of a little more than 75% (25% spillage). This pump capacity is so large compared to the original prototype pump capacity 3 m^3/s that it is not acceptable in practice.

The physical explanation for the large amount of spillage in the laboratory tests is the fact that the cutter head diameter is too large in relation to the suction flow, resulting in a high ratio of the centrifugal force over the suction force which means that the particles are easily thrown out of the cutter head. It would therefore be interesting to see what the effect is of reducing the cutter head diameter of the prototype while keeping the suction flow at 3 m^3/s.

In Figure 7 the values for the operational parameters at optimum productions (as resulting from the model tests) are translated to an arbitrary scale using the scale laws of condition 1 and 2, mentioned above. This is done for the following three points of the model tests;
v_m = 2.6 m/s, n_c = 90 RPM, P = 27.5%;
v_m = 3.5 m/s, n_c = 93 RPM, P = 57%;
v_m = 5 m/s, n_c = 100 RPM, P = 75%.

In Figure 7 the green line corresponds with a relative production P = 75%, the red one with P = 57% and the blue one with P = 25%. The arbitrary prototype scale ranges for cutter head diameters of 0.4 to 4 m.

The figure shows that it is possible to achieve a production percentage of 75% with a suction flow of m^3/s when the cutter diameter is 2.4 m. The matching optimum rotational speed was 38 RPM. The diameter of the prototype cutter head was 3.1 m at the same capacity (see Table I). Its production percentage, however, was just 27.5% at a corresponding rotational speed of 30 RPM.

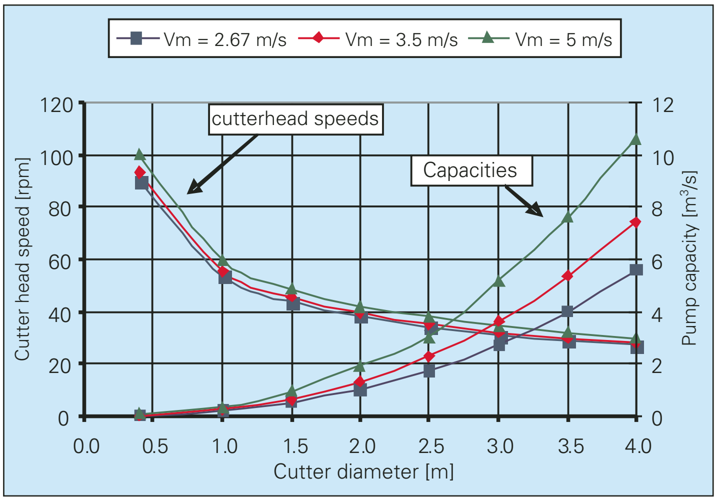


Figure 7. Optimal pump and cutter head speed for different cutterhead dimensions.

In conclusion, by decreasing the cutter head diameter from 3.1 to 2.4 m the relative production percentage increases with a factor 2.7.

In practice, the absolute production is of more interest than the production percentage.
In the case that the smaller cutter head is positioned relative to the bank in the same way (on scale) as the original proto type head, the cut off area will decrease with the square of the diameters to:

$$\frac{\{A_{cut}\}\ D_c = 2.41}{\{A_{cut}\}\ D_c = 3.12} = \left[\frac{2.41}{3.12}\right]^2 = 0.59.$$

However, to fulfil condition 3, the corresponding hauling velocity decreases from 0.2 to 0.175 m/s, which is a factor of 0.875. On the other hand, because of the increase in flow number, the production percentage will increase from 27.5% to 75%, a factor 2.7.

In other words the absolute production will increase with a factor 2.7 x 0.59 x 0.875 = 1.39.

It should be noted that the mean particle size decreases from 78 mm to 63 mm to fulfil the scale laws, when the cutter head diameter is reduced from 3.1 to 2.4 m. In this situation both the cut off area (Figure 8) and the haul velocity are reduced, which means that the required cutting power reduces accordingly by a factor 0.59 x 0.875 = 0.52 under the assumption that the specific energy of the soil does not change.

So, in conclusion, an amazing absolute production gain is achieved of 39% in absolute sense with 48% less cutting power.

Even higher productions are possible when the installed cutter power is fully used. In general,

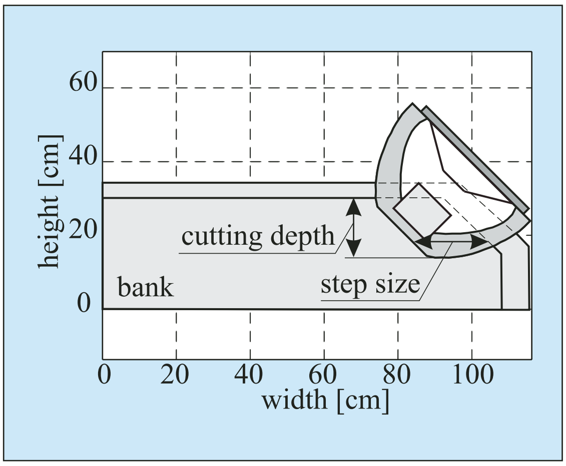


Figure 8. Position of the 2.4 m and 3.1 m diameter cutter head.

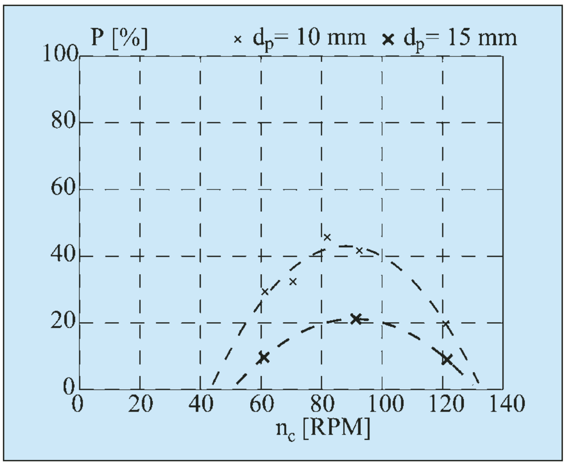


Figure 9. Influence of particle size.

this either needs a larger cut off area or a higher haul velocity. Step size and cutting depth can increase as long as the maximum cut off area is not exceeded. When that is not the case the absolute production will lay between 1/0.59 x 1.39 = 2.36 and 1.39 depending on the influence of the concentration in the cutter head on the mixture forming. If there is no influence the production percentage will increase even further than the 75%, because the cutter head is on the hauling side more surrounded by the bank, causing a more efficient flow towards the suction mouth.

Higher haul velocities may increase the particle size and result in less production efficiency as shown in Figure 9. An increase of the particle diameter from 10 mm to 15 mm on model scale decreases the production percentage with at least a factor 2 and can destroy the production gain completely. This phenomenon is well known in rock dredging practice. A higher cut off area is preferable above a higher hauling speed.

Conclusions

When dredging coarse materials two phenomena play an important role in the mixture forming process:

- An increase in production with increasing rotational velocity caused by the component of the centrifugal force acting along the blade and directed towards the cutter ring.
- Beyond the optimum rotational velocity the production percentage decreases with increasing rotational velocity as a result of the increasing magnitude of the centrifugal forces acting on the particles.

It looks if the existing rock cutter heads are over sized or do have too low pump capacities.

Large improvements can be expected when pump capacities and cutter head sizes are better tuned.

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