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THE RELATION BETWEEN DREDGE PUMP BALL PASSAGE, SLURRY PROPERTIES AND THE PROBABILITY OF CLOGGING

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The total efficiency of a pump and pipeline system is not only determined by its instantaneous production, but also by its uptime. This uptime is influenced by the number of times the pumping process is interrupted. For a dredging system, such an interruption can be the clogging of the pump due to large particles in the system. Important parameters of a dredge pump are its efficiency and its spherical passage. The first one affects the total efficiency in a direct way, the second one shows its influence in the uptime. There is a negative relationship between both parameters: a larger spherical passage leads to a lower hydraulic efficiency of the dredge pump. In order to optimize the total efficiency of the dredging system, an optimum value for the spherical passage has to be determined, which requires knowledge about the probability a pump will clog related to the properties of the slurry which is pumped. Nowadays this knowledge is based on experience. In this paper, we propose a theoretical model for this clogging probability. An analysis of the slurry parameters which influences the pump clogging is presented. The probability model is based on equivalent theories from granular media literature sources and adapted for analysis of pump clogging. With this model, the total uptime of the dredging system can be included in the pumping system efficiency optimization.

KEY WORDS: Dredging, optimization of dredge installations, pump clogging.

NOTATION

Symbol	Units	Definition
C_v	–	Volume concentration
D_{ball}	m	Spherical passage, diameter of the largest ball which can pass the pump
F	–	Shape parameter
$\dot{P}$	m^3/hr	Solids production
Q	m^3/hr	Discharge
R	m^3/kW	Yield
S_g	–	Specific weight relative to carrier fluid
c_t	–	Transport concentration factor
c_{u}	–	Coefficient of uniformity

Symbol	Units	Definition
d_i	m	Particle diameter break, i% (by mass) of the soil particles has a diameter smaller than the given value
d_{mf}	m	Normative particle diameter
v_{critical}	m/s	Critical velocity, below this velocity sedimentation in the pipeline can occur
Δp	Pa	Pressure difference
η	–	Efficiency
ρ_m	kg/m^3	Mixture density
ρ_s	kg/m^3	Density of solid particles
ρ_w	kg/m^3	Density of carrier fluid

1. INTRODUCTION

In the process of optimizing the production of a dredging vessel, it is important to investigate which time scales are involved in the dredging process. On the shortest timescale, the efficiency η of the dredgepump is important. A higher efficiency implies a higher momentary yield R. However, a dredging system is in general a non-stationary process. On larger time scales the yield is influenced by other factors like changing working position or working direction of the dredge vessel. Also system downtime influences the yield on larger timescales. This downtime can be caused e.g. by a blockage of the pump due to large particles. See Fig. 13 for an example of a pump impeller blocked by some large stones.

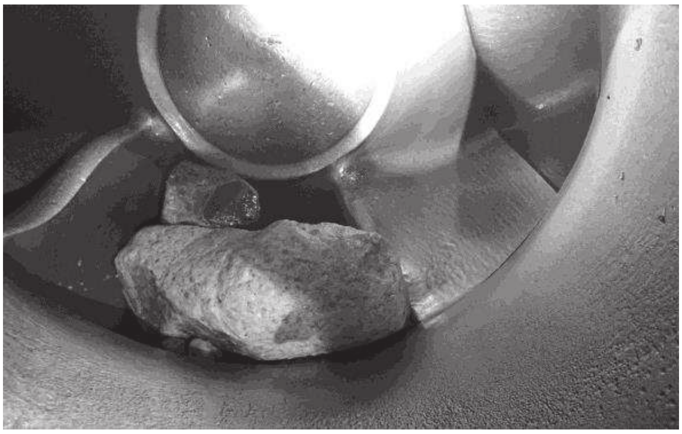

Fig. 13. Dredge pump impeller blocked by stones

In previous work it was shown that in order to optimize the total efficiency of a dredging system on the larger time scale, it is important to find the right balance between the efficiency η and the spherical passage D_{ball} of the dredge pump. See Slager and Winkelman, (2016) for details. In the mentioned work, the probability that a dredge pump will block, given the properties of the pumped mixture, was needed. Data originating from experience was used in this research because a theoretical model was not available. In this paper, we present a new model which tries to fill the knowledge gap.

1.1. PUMP PRODUCTION AND PUMP BLOCKING

The solids production $\dot{P}$ of a pump and pipeline system in a certain timespan $t_0 ... t_1$ is given by the equation:

$$\dot{P}(t) = \int_{t_0}^{t_1} Q(t) \cdot \frac{\rho_m(t) - \rho_w}{\rho_s - \rho_w} \cdot c_t \, \mathrm{d}t \qquad (20)$$

From Eq. (20) it can be seen that maximisation of the production is a matter of increasing both discharge Q and mixture density ρ_m. The transport concentration factor c_t mainly depends on the properties of the solid particles and cannot be influenced directly.

The production of a dredging vessel is limited by a number of constraints. The constraints which are of paramount importance for solids production are (for given values of discharge Q and mixture density ρ_m):

1. The pump must be able to deliver the required pressure loss Δp from the pipeline.
2. The pressure drop before the pump must be low enough to prevent cavitation

The first constraint calls for a high efficiency of the pump, the second constraint for good suction behavior. At the same time, it is important to operate without interruptions, which requires a large enough ball passage. From Eq. (20) it is clear that interruptions have a large influence on the production at large timescales. This can be illustrated by a simple calculation. Suppose that production is constant during the time between two blockings. Let t_p be the average time between blockings and t_b the downtime due to blockings. Now the average production can be calculated to be

$$\left\langle \dot{P} \right\rangle = \frac{Q(t) \cdot \frac{\rho_m(t) - \rho_w}{\rho_s - \rho_w} \cdot c_t}{t_p + t_b} \qquad (21)$$

Nonzero values of the downtime t_b lead to a lower average production. So in optimizing the production, it is important to choose the ball passage of the pump in such way that blocking of the pump is prevented. However, a large ball passage leads to a lower efficiency and also detoriates the suction performance of the pump and therefore it is important to choose the ball passage of the pump just high enough to prevent blocking.

1.2. OUTLINE OF THE PAPER

In this paper, first the parameters which influence the probability of blocking the pump will be discussed, leading to a selection of parameters to be included in the model. An overview of relevant literature sources is presented and discussed. A theoretical model is derived using the selected parameters and comparable models from literature. The paper ends with an outlook to further development.

2. GOVERNING PARAMETERS

The characteristics of soil can be described by a number of parameters which try to capture the important properties of the soil. The parameters which are considered to be important with respect to pump blocking are discussed here.

2.1. PARTICLE SIZE DISTRIBUTION

The first parameter is the particle size. Because natural soils always consists of particles of various sizes, a particle size distribution is the proper way to describe this characteristic. In modelling the physics of dredging, mostly the mass median diameter d_{50} is used to incorporate the effects of particle size. For pump blocking however, this might not be the best choice because the process will be dominated by the largest particles. So the d_{90} or the d_{mf} might be a better choice. The d_{mf} is given by Eq. (3),

$$d_{\mathrm{mf}} = \frac{1}{9}\sum_{i=1}^{9} d_i \qquad (22)$$

Another factor which can have its influence on the pump blocking is the steepness of the particle size distribution curve. This property can be described by the coefficient of uniformity c_{u} and is given by the ratio of the particle sizes d_{60} and d_{10}:

$$c_{\mathrm{u}} = \frac{d_{60}}{d_{10}} \qquad (23)$$

A larger value of c_{u} indicates a broader particle size distribution.

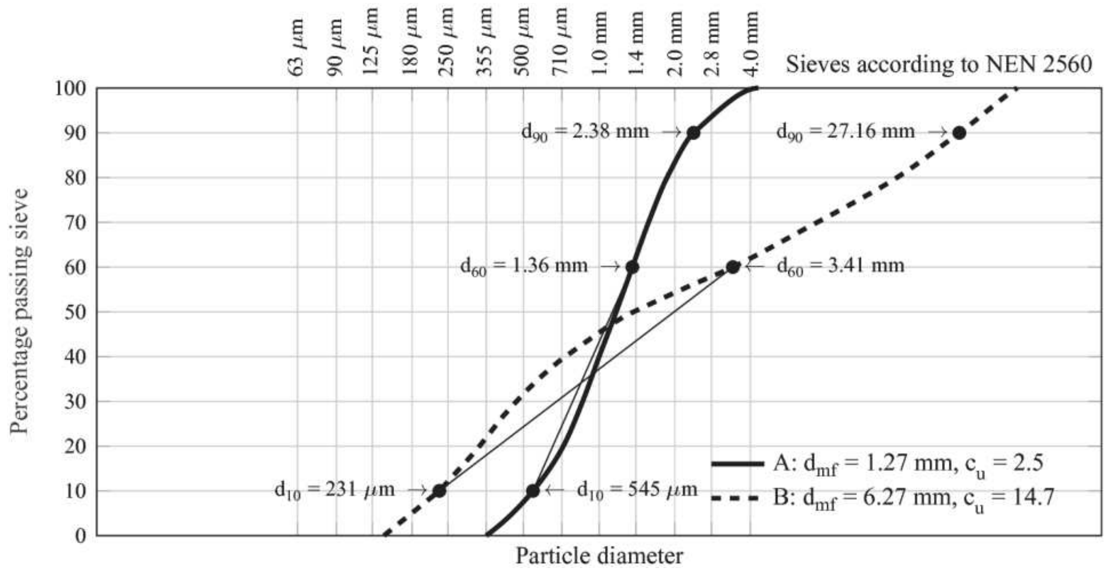

Figure 14: Particle size distribution diagram

The effects of the various parameters is illustrated with the particle size diagram in Figure 14. Here two soil types are presented, for which the values of the d_{50} are about the same. The values of both d_{90} and c_{u} are quite different, and it is clear that the soil designated with B has a much higher blocking probability than soil A. So in order to capture the soil properties which influence the blocking probability, the d_{90} is a good choice for the characteristic length scale. Information about the steepness of the distribution is needed too, this can be provided by c_{u}.

2.2. MIXTURE PROPERTIES

The number of particles in a dredged mixture is given by the volume concentration C_v, which is defined by

$$C_v = \frac{\rho_m - \rho_w}{\rho_s - \rho_w} \quad (24)$$

In dredging operations, the volume concentration of the dredged mixture varies. Common values are in the range from 10% to 25% and values up to 40% are possible. Higher concentration implies more particles in the same volume of mixture and this increases the probability of pump blocking.

2.3. PARTICLE PROPERTIES

A particle property which was discussed before is the diameter. This property is determined by sieving of a soil sample. There are a number of other properties which influence blocking probability. Important properties are the angularity and the sphericity of the particles. These properties are illustrated in Fig. 15. For the current study it is assumed that these shape properties can be captured by a single parameter F.

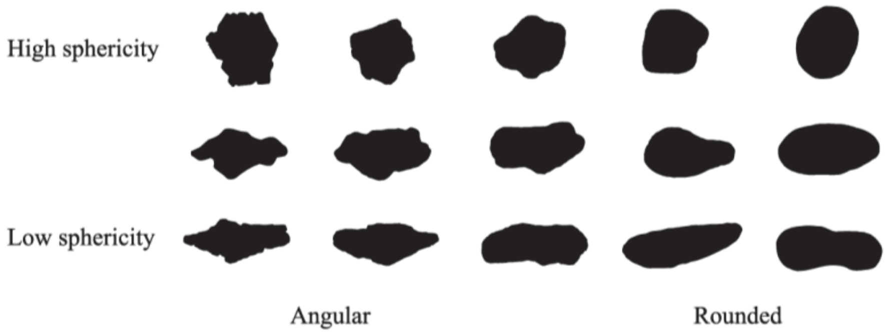

Fig. 15: Angularity and sphericity

Furthermore the solid density ρ_s is mentioned, which also influences the pump blocking probability. A particle with a lower specific weight S_g will follow the carrier fluid better.

2.4. PUMP PROPERTIES

A dredge pump is designed in such a way that the risk of blocking the pump is minimized, the width of the impeller is kept constant over the whole radius of the impeller to prevent blockings due to a narrowing channel. See e.g. Gülich, 2008 for more details on dredge pump particulars. For the current study, it is assumed that good care is taken to have the best pump design and that the influence of the pump geometry on the clogging probability is constant. The only relevant parameter considered here is D_{ball}.

3. LITERATURE REVIEW

From literature comparable studies from other subject areas were selected. Special attention was given to the subject of granular matter, as a lot of research is available in this area. A number of literature sources are presented and discussed here. *Note that symbols used in this section represent the symbols of the original paper and are not necessary included in the notation section.*

3.1. LITERATURE SOURCES

The first source to mention here is Valdes and CarlosSantamarina, 2008, which deals with bridge formation and vibration-based destabilization. Experimental work is shown for a variety of particle properties and minimum and maximum orifice sizes for clogging are determined.

The subject of the work of A. Janda et al., 2008 is the jamming and critical outlet size in the discharge of a two-dimensional silo. Experimental work was performed with spherical particles. A relation for the jamming probability J was derived as a function of the outlet diameter D for a given avalanche size N, which takes the form

$$J_N(D) = 1 - e^{-x} \tag{25}$$

where x is a rescaled parameter which incorporates the properties of the geometry and the granular matter. Also a mean avalanche size $\langle s \rangle_D$ is defined, which can be translated to a mean time between jamming.

The work found in Zuriguel et al., 2014 includes, but is not limited to granular matter. This work gives an overview of clogging transition of many-particle systems flowing through bottlenecks. Non-granular matter subjects include flow of sheep through a bottleneck and pedestrian simulation. A general modelling involves a flowing parameter Φ, which defines the state of the particle system. It is influenced by three factors: a compatible load C_L, which is responsible for development of clogging structures, an incompatible load I_L, which can destabilize the clogging structures and a characteristic length scale Λ, which relates particle sizes to opening size. A general clogging phase diagram is proposed.

An extensive overview of the clogging of granular material in bottlenecks can be found in Zuriguel, 2014. For granular matter in hoppers, important properties like avalanche size distribution, critical outlet size, orifice geometry and particle shape are discussed. A modelling of the mean avalanche size distribution related to outlet and particle diameters is given by

$$\langle s \rangle = A \cdot (R_C - R)^{-\gamma} \tag{26}$$

The work of Thomas and Durian, 2015 covers the subject of a critical bottleneck size. It proposes an approach based on possible configurations of the flow. Using this theory, a critical bottleneck size does not exist and clogging is possible for every configuration. However, there are configurations which are very unlikely to clogg.

The subject of the work presented in Alvaro Janda et al., 2015 is not on flow through bottlenecks, but on flow in narrow pipes. It is shown that a flow of particles in a narrow pipe shows clogging behaviour. Furthermore, the mean avalance size can be modelled by

$$\langle s \rangle = \frac{A}{(\phi_c - \phi)^{\gamma}} \tag{27}$$

which is equal to the modelling found for granular matter in hoppers with a restricted outlet.

3.2. DISCUSSION

From the results of the literature review a number of things can be learned. The first thing to mention is that clogging of general particle systems from different areas show remarkable similarity. This motivates to search for a model for dredge pump blocking based on results from other areas. Furthermore there are models available where a pump blocking model can be based on. Especially we mention the modelling of the mean time between avalanches, where production calculations can be based upon. The modelling will be the subject of the next section.

4. MODEL

In the previous sections the important parameters were presented and an overview of comparable models from other areas was given. Now this information is combined and a model for the pump blocking is formulated.

An important question is if there exists a critical ball passage (or ball passage vs. particle size ratio) for which no blocking will occur. E.g. in the work of Valdes and CarlosSantamarina, 2008 a critical outlet size exists. For a dredging system, it can be argued that the pipeline diameter is a critical value for the ball passage of the pump. So for our model, it is assumed that a critical value exists.

4.1. PARAMETERS

In section 2 the relevant parameters were presented and discussed. The parameters selected to be included in the model are: particle diameter d_{90}, coefficient of uniformity c_{u}, mixture concentration C_v, shape parameter F and pump ball passage D_{ball}.

4.2. FORMULATION

The outcome of the model is defined to be an average time $\langle\tau\rangle$ between pump blockings. This is comparable with the mean avalanche size of clogging problems in granular matter. The general form of the model is

$$\langle\tau\rangle = \frac{\alpha}{(\phi_c - \phi)^{\gamma}} \qquad 2.\ (28)$$

From literature it can be learned that this general formulation is broadly distributed among the different areas, so it is assumed that this formulation also covers the basic behavior of the pump clogging process.

The characteristic length scales are represented in the parameters denoted by ϕ. We define ϕ to be the ratio between ball passage of the pump and particle size (represented by d_{90})

$$\phi = \frac{D_{\mathrm{ball}}}{d_{90}} \qquad 3.\ (29)$$

The critical ratio ϕ_c is the ratio for which no clogging of the pump occurs.

Effects of the parameters c_{u}, F and C_v are included via the coefficients α and γ. Here c_{u} and F are involved in the structure of the blocking process and will therefore be included in both γ and α. The parameter C_v does not influence the blocking structure but has its effect on the probability and is therefore included in α. So we end up with the general formulations

$$\alpha = \alpha\left(c_{\mathrm{u}}, F\right) \quad \text{and} \quad \gamma = \gamma\left(c_{\mathrm{u}}, F, C_v\right) \qquad 4.\ (30)$$

The values for ϕ_c, α and γ have to be determined for a given set of pump and soil characteristics.

4.3. VALIDATION

The model presented here is based on theoretical work only. Validation is needed in order to construct a model with can predict pump blocking probability with good accuracy. The problem with validation of the model is that large scale experimental data is not available.

A simple calculation for two different ball passages, D_{ball}=40% or D_{ball}=50%, with Φ_c=5.0 and γ=6.0 shows that the blocking probability with the smaller ball passage is 13 times higher than with the larger ball passage. This agrees with the trend known from experience and shows that the model is able to capture this trend in a qualitative way.

To proceed towards a predictive method, more data are needed. This data can origin from experiments, although this will quite labourous. Another possibility is performing simulations with e.g. a discrete particle model. Further research on this subject is ongoing.

5. CONCLUSION

A theoretical model for the probability of the clogging of a dredge pump is presented in this paper. It is based on equivalent modelling from other areas. It provides a measure of the mean time between blockings, which can be used in an overall optimization of a dredging system.

As it is based on theoretical modelling only, the model is mainly suited for the qualitative effects of the particle properties on the probability of clogging of a pump. Further experimental data or additional simulation techniques are needed to build a clogging prediction model with reliable quantitative results. This will be the subject of ongoing research.

The first application of this model is in the pump performance software package ProDredge of Damen Dredging Equipment. In the next release, a pump clogging warning will be generated based on the model presented in this paper.

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