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THE INFLUENCE OF NODULE DEGRADATION ON THE VERTICAL HYDRAULIC TRANSPORT OF MANGANESE NODULES

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Prospective manganese nodule mining requires vertical transport of the nodules over a few kilometers distance. During hydraulic transport through a riser with centrifugal pump booster stations, the nodules suffer from degradation mainly caused by the pumps. Particle degradation influences the key parameters of the transport process and it directly determines the quality of the produced mixture. The mixture particle size distribution and the associated flowrates of the different fractions is important for the design and operation of the post-processing equipment. In this paper the influence of degradation on the quality of the mixture leaving the vertical transport system is investigated by numerical simulation. Results are presented for the case of mining manganese nodules in the Clarion Clipperton Zone.

KEY WORDS: vertical hydraulic transport, deep sea mining, nodule degradation

NOTATION

Symbol	Description	Unit
c_v	Volume fraction of solids	-
d	Particle diameter	m
D	Riser diameter	m
k	Fraction specific constant related to particle degradation	
K	Number of fractions in particle size distribution	-
L	Length	m
n	Richardson and Zaki exponent	-
N	Number of passages through a centrifugal pump	
q_s	Solids production	kg/s
Stk	Stokes Number	-

t	time	s
v_f, v_m, v_s	Fluid, mixture and solids velocity	m/s
w_t, w_h	Terminal settling velocity, hindered settling velocity	m/s
z	vertical coordinate	m
$\varepsilon_z, \varepsilon_{Taylor}$	Axial dispersion coefficient	m^2/s
ρ_f, ρ_m, ρ_s	Fluid density, mixture density, solids density	kg/m^3
τ_f, τ_m, τ_s	Fluid, mixture and solids wall shear stress	Pa
CCZ	Clarion Clipperton Zone	
PSD	Particle Size Distribution	
VTS	Vertical Transport System	
sc	Size Class	

1. INTRODUCTION

Particle degradation during hydraulic transport is inevitable. With respect to vertical transport for deep sea mining purposes, it affects the main transport parameters, e.g. transport velocities, axial dispersion and wall friction. The most important however is that degradation heavily determines the quality of the produced mixture. The more fines, the more costly the processing of the slurry. In this paper it is explored how the exact quantities of material leaving the VTS are related to particle degradation itself and to its effect on the transport parameters.

2. PARTICLE DEGRADATION DURING HYDRAULIC TRANSPORT

The degradation process is complex, involving both impact fracturing as well as abrasion due to friction. Impact fracturing mainly occurs in centrifugal pumps, while abrasion mainly occurs in the pipeline (Worster and Denny, 1955). Van den Berg and Alvarez Grima (2006) report on degradation experiments with limestone and coarse gravel in the IHC MTI test circuit and on the degradation of quartz sand and rock salt during dredging. These four material types showed both impact fracturing by the centrifugal pump and abrasion due to the horizontal hydraulic transport, but the relative contribution of one mechanism above the other differs between the cases. Especially rock salt and coarse gravel were influenced by impact fracturing occurring in the centrifugal pump.

Particle degradation during vertical transport is expected to be dominated by impact fracturing due to the centrifugal pumps. The volume fraction of solids, especially of the larger particles, is small or nearly zero near the pipe wall, thus minimizing abrasion for the bulk of the material. Furthermore, nodules are porous and often more of them are agglomerated into a single particle. Degradation by fracturing can be expected and they show brittle behavior already under saturated and atmospheric conditions. When the permeability of the nodules is small, the internal pressure in the nodules originating from their condition at the seafloor might not dissipate fast enough resulting in increasing internal stresses in the nodule during transport. This might even propagate degradation by fracturing. In the case of nodules the centrifugal pump impellers and all the bends in the booster stations are therefor expected to dominate the degradation process.

Yamazaki and Sharma (2001) experimentally studied the degradation of subsea sediments from the CCZ zone. They used a small scale circulating flowloop (one pump and a few meters of pipeline, in operation for 30 minutes). The PSD's point at the production of significant amounts of fines. The maximum sediment diameter in their test reduced from about 200 μm to 50 μm. This indicates that the already fine seabed sediment will become even finer upon transport, a trend that is also expected to be present for manganese nodules. This case was studied earlier by Yamazaki et al. (1991). They show the PSD of abraded nodules after pump and riser passage. Unfortunately no initial PSD is shown so no conclusions about degradation rates can be drawn.

Recent research work by Zenhorst (2016) focused on degradation of real, water saturated manganese nodules under atmospheric conditions. He used a test circuit with a D = 300 mm centrifugal pump, comparable to the one used by Van den Berg and Alvarez Grima (2006), but now with only ten meters of steel pipeline with two 90° bends (pumping nodules from one basin to another). The setup was operated at 450 RPM resulting in a flow velocity of 4 m/s in the suction and discharge lines. Initially and after ten passages, the PSD of the batch was determined, see Fig.1. The setup is representative for real transport conditions, but the degradation of particles under atmospheric conditions could be different from degradation under deep sea conditions.

The degradation mechanism is depending on the material type and size of the particles. The ratio UCS/BTS of rock (unconfined compressive strength over Brazilian tensile strength) is a good indication whether rock will fail ductile, brittle or with an intermediate mechanism (Verhoef, 1997). Manganese nodules have a different geological origin than rock, i.e. the nodules grow around a nucleus which is not the case for rock, and there could be internal paths of preference for breaking. UCS and BTS values of nodules could give an indication of the failure mechanism of these deposits, but given the geological differences between rock and nodules care should be taken. Dreiseitl and Kondratenko (2012) report on UCS values of manganese nodules from the Clarion Clipperton Zone, ranging from average values of 0.68 MPa for particles with d > 100 mm to 3.26 MPa for particles in the range 0 < d < 20 mm. No BTS data is known to the author, but the observations of Zenhorst (2016) point at an intermediate to brittle failure mode of the nodules.

The main transport parameters influenced by particle degradation are the particle transport velocity, the axial dispersion process and the solids contribution to wall friction. In the 1D model described by Van Wijk (2016), the particle slip velocity is modelled as $w_h = w_t \cdot 10^{-\frac{d}{D}} \cdot (1 - c_v)^{n-1}$. It proves that, irrespective of the volume fraction of solids, for $d > 40\ mm$ the particle slip velocities are nearly constant. This implies that particle degradation might actually increase the *relative* slip velocities, i.e. the velocity of one fraction compared with another, when particle diameters enter the region $d < 40\ mm$.

The axial dispersion process shows a large dependency on particle inertia. Highly inert particles *(Stk >> 1)* hardly show axial dispersion, while for *Stk << 1* the model of Taylor (1954) is a good approximation. The overall axial dispersion will increase upon degradation of particles, thus damping out disturbances in the volume fraction of solids more rapidly which is favourable for stable slurry flow.

The solids contribution to wall friction depends on the particle diameter. In the model of Ferre and Shook (1998) it holds $\tau_s \propto d^{2.75}$, so a decrease in particle size has impact on the amount of wall friction.

The 1D model of Van Wijk (2016) will be extended with a particle degradation model to investigate the influence of degradation on the mixture output of the VTS..

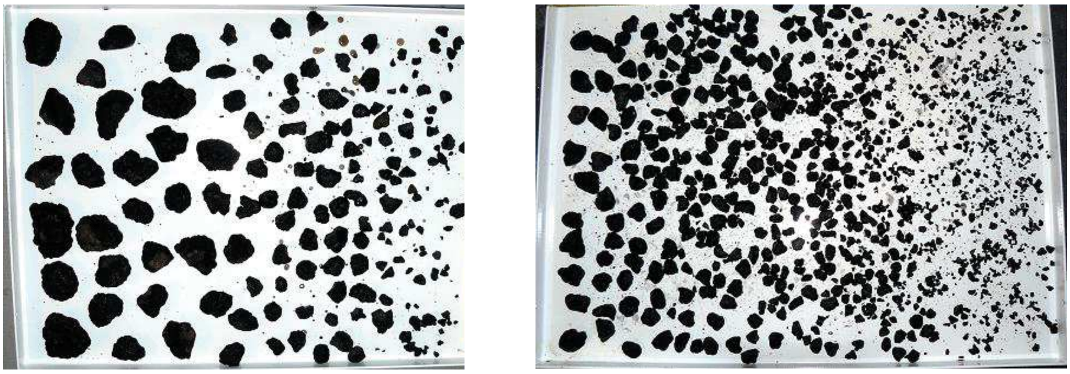


Fig. 1. Manganese nodule sample from the CCZ. Initial distribution (left) and after 10 passages through a 300 mm centrifugal pump (right). Photographs by Zenhorst (2016).

3. IMPLEMENTATION OF A PARTICLE DEGRADATION MODEL

In Section 2 it was pointed out that impact fracturing by the pumps is the most likely degradation mechanism, and abrasion is not expected to play a significant role. After degradation, a particle is fractured into new particles with sizes all smaller than the original particle size. Under the assumption that the particle shape does not change due to degradation, Wilson and Addie (1997) (based on a.o. Gillies et al. (1982)) put forward that degradation due to a centrifugal pump could be approximated by $\frac{d}{d_0} \propto e^{-k \cdot N}$ with N the number of passages through the pump and k a constant. Their approach implicitly assumes that a centrifugal pump can be treated as a black box that simply reduces nodule size. It is expected that the rate of degradation strongly relates to the nodule velocity inside the pump and the speed of the impeller since this combination determines the impact with the nodule. The black box approach has the benefit that it allows for implementation in a 1D transport model, but this is only valid when the particle degradation rates are matched with actual pump conditions. This can be done experimentally. Wilson and Addie's (1997) approach is the basis of the degradation model implemented in the 1D flow model:

$$\frac{d_{i,N}}{d_{i,0}} = x_i \cdot e^{-k_i \cdot N} \quad (1)$$

With i the index of the particle fraction in the PSD, $d_{i,N}$ the fraction diameter after N passages and k_i a fraction specific constant. For $N = 0$ it follows $x_i \cdot e^{-k_i \cdot 0} = 1$ so $x_i = 1 \forall i$. By measuring the PSD of the solids in a mixture before and after a certain amount of passages through a centrifugal pump at different pump conditions, the degradation coefficient k_i could be experimentally determined by rewriting Eq. 1 to $k_i = -\frac{1}{\mathrm{N}} \cdot \ln d_{i,N}/d_i$.

In this article we assume that the rate of degradation is independent of particle size, we do not have the data in support of a more detailed approach, so $k_i = cst \; \forall i$. As soon as more data is available the model can be further improved by making the rate of degradation size-specific, as already noted by Shook et al. (1979) for bituminous coal.

Degradation alters the size of a particle, but the total amount of material needs to remain constant. Conservation of mass (under assumption of a constant solids density) is enforced by redistributing the volume fraction of solids after degradation so it holds $\sum_{i=1}^{K} c_{v,i} = cst$. The initial PSD in the model determines the size classes, which read $sc = [\min\{d\}, \max\{d\}]$ with ten intervals. In this article it is assumed that the material remaining after degradation of a particle is distributed evenly over all fractions smaller than the degraded particle. One can think of more sophisticated distribution algorithms that do exist f.i. from milling and grinding theory, but the basic physics are covered by the even distribution.

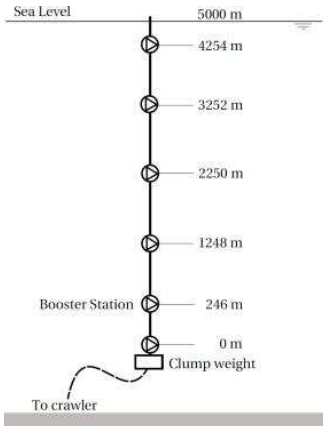
The model of Van Wijk (2016) is extended with Eq.1, using $k_i = 0.07 \; \forall i$ (based on a visually estimated size reduction of 50% of the largest particles in Fig.1). The next paragraph shows simulation results of vertical transport of manganese nodules from the CCZ.

4. SIMULATION OF TRANSPORT WITH PARTICLE DEGRADATION

In Van Wijk and Smit (2015) the transport of manganese nodules from the CCZ over 5 km vertical distance is discussed, where the slurry ($\overline{c_v} = 0.12$, $\rho_s = 2500 \; kg/m^3$) passes 12 centrifugal pumps (in 6 booster stations). This case will again be used in this paper, see Fig. 2a. The PSD of the mixture after each booster station as obtained by Eq. 1 and conservation of mass is shown in Fig. 2b.

The maximum particle size encountered at the outlet can be read directly from the PSD, which is d_{max} = 54 mm. According to the PSD, the cumulative mass passing for d < 8 mm is 10% initially and 61% after passing twelve pumps. This results in a factor 6.1 more material. After twelve pumps, 20% of the material has d < 3.45 mm.

It is interesting to take a closer look at the mass flowrates. At the inlet of the riser, the 500 s time averaged mass flowrate is 108.3 kg/s while the same averaged flowrate at the outlet is 117.1 kg/s. During this period the average system density thus drops. Next we zoom in on the individual fractions. Fig. 3 shows q_s summed for all fractions with d < 8 mm, which is the smallest size class in the initial PSD for the current simulation containing also the fines. The average inflow during 500 s is 11.49 kg/s, the average outflow is 59.35 kg/s. This is a factor 5.17 more fines at the outlet, which is less than the factor 6.1 derived from the PSD's directly. The nature of this disparity is not clear at the moment. There proves to be a minor fluctuation in this number due to the averaging itself, and there is a minor fluctuation due to the slip velocities of the solids. These add up to a variation of a few percent on this ratio, which does not fully explain the disparity. The material entering the first booster station still shows large fluctuations in c_v, these are more smoothened after leaving the last booster station due to the effect of axial dispersion.



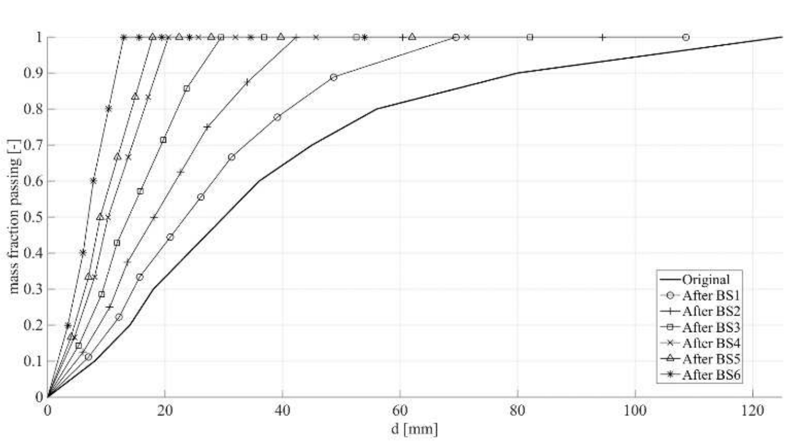


Fig. 2a. Schematic layout of the vertical transport system (VTS) using the VTS coordinate system as presented in Van Wijk and Smit (2015).

Fig. 2b. PSD according to Eq. 1 as used in the simulation. The PSD develops over the length of the VTS due to degradation of particles by the booster stations.

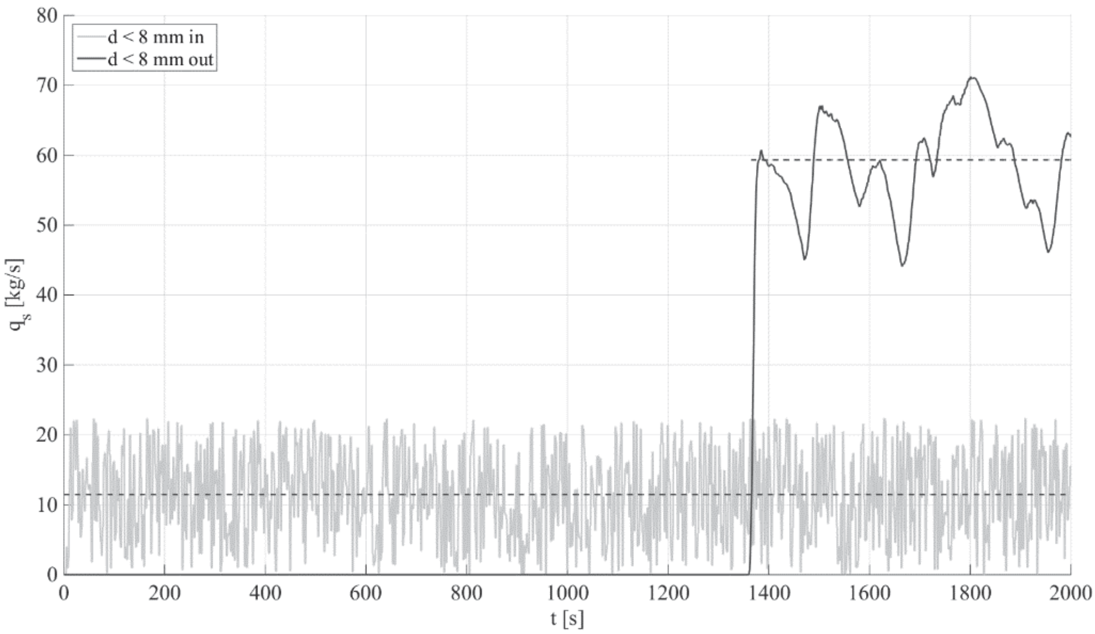


Fig. 3. Mass flowrates of the fraction d < 8 mm at the inlet of the first booster VTS and at the outlet of the last booster. The material leaves the last booster after 1359 s. The amount of material smaller than 8 mm leaving the VTS is a factor 5.17 larger than at the inlet. The average total mass flowrate is 112.7 kg/s.

5. CONCLUSIONS AND RECOMMENDATIONS

The main assumption in this paper is that particle fracturing due to centrifugal pumps prevails over abrasion due to particle-riser interaction. This is based on experience with the vertical transport process and particle behavior, but it is recommended to have the assumption experimentally verified. There are near-future plans to do so within the Blue Nodules research program.

The degradation model presented in this paper models particle fracturing due to impact. It gives the PSD's of particles after passage of a centrifugal pump. Conservation of mass is enforced by redistribution of the volume fraction of solids to smaller size fractions under the assumption of constant particle density.

The model requires experimental closure on the degradation rates, taking into account both nodule properties and centrifugal pump operational setpoints. In this paper the degradation rate is based on the degradation of real manganese nodules under atmospheric conditions. Rates are expected to be particle-size dependent, but the data currently available did not allow for size-dependent rates. Improvement of the model closure can be realized by actually measuring the PSD's in dedicated experiments, which is foreseen in the Blue Nodules research program.

The smallest fraction ($d < 8$ mm) in the PSD used in this article is still very large. Since for design of processing equipment a more detailed view on the fines is required (i.e. sub-millimeter scale), the PSD's used in engineering practice should have sufficient detail in the smaller size range.

The degradation model is implemented in a one dimensional model for vertical hydraulic transport of manganese nodules, and applied to a real case study in the CCZ area. It proves that the dependency of particle transport velocities, axial dispersion and wall friction on particle size and volume fraction of solids is only of secondary importance to the actual mass flow rates of finer material. For engineering purposes therefor the PSD's can be used directly.

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