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AN EXPERIMENTAL STUDY INTO FLOW ASSURANCE OF COARSE INCLINED SLURRIES

Edwin de Hoog[1], Maarten in ’t Veld [2], Jort van Wijk[3] and Arno Talmon[4]

[1]*IHC MTI / Royal IHC, Delftechpark 13, 2628 XJ, Delft, The Netherlands, e.dehoog@ihcmti.com*

[2]*IHC MTI / Royal IHC, Delftechpark 13, 2628 XJ, Delft, The Netherlands, jm.intveld@ihcmti.com*

[3]*IHC MTI / Royal IHC, Delftechpark 13, 2628 XJ, Delft, The Netherlands, jm.vanwijk@ihcmti.com*

[4]*Delft University of Technology, Mekelweg 2, Delft, 2628 CD, & Deltares, P.O. Box177, 2600 MH, Delft, The Netherlands, a.m.talmon@tudelft.nl*

During hydraulic transport for deep sea mining, polymetallic nodules are transported in various ascending inclined pipes located at the sea floor. These inclined pipes can constantly change their angle of inclination due to moving excavation equipment attached to these pipes. Flow assurance during transport requires a safe transport velocity which takes into account all inclination angles. A study was conducted into safe transport velocities of slurries composed of gravel sized material in ascending inclined pipes.
Experimental research was conducted with 4.6, 6.3 and 12 mm diameter gravel in a 100 mm experimental flow loop up to an inclination angle of 52 degrees. Measured parameters include pressure losses, mixture velocity, delivered concentration, deposit limit velocity and velocity profiles from high speed camera footage.
During this research, various literature sources have been studied for definitions and models of transition velocities between safe and unsafe transport. These definitions and models are discussed in terms of their relevance for coarse slurries. With these definitions in mind and with the experimental data a recommendation is given for a transportation velocity of coarse slurries in inclined pipes.

KEY WORDS: hydraulic transport, deep sea mining, flow assurance, deposition limit velocity, experimental research

1. INTRODUCTION

Deep sea mining entails the excavation of polymetallic nodules from the sea floor and transporting the nodules hydraulically to the sea surface through a long vertical riser. Manganese nodules vary in size from 10 mm to 100 mm and the riser pipe diameter between 250 and 400 mm. To compensate for movement in the riser a flexible vertical S-shaped jumper hose is required at the bottom of the riser. This S-bend is connected to either a mobile mining tool or a stationary separator with an inclined pipe. The inclination angle of this inclined pipe will constantly vary due to the riser and excavation equipment movement. To avoid blockages the flow of nodules must be ensured for all positive inclination angles in the inclined pipe.

2. COARSE PARTICLE SLURRIES

A mixture of polymetallic nodules and water can be considered as a coarse mixture, which implies that the mixture is strongly-stratified with particles sliding over the pipe wall (Wilson et al., 2006). For fully stratified mixtures the additional pressure drop, from the presence of particles, is caused by mechanical friction of the particle bed sliding against the pipe wall, which is theoretically independent of the mixture velocity and particle diameter (Newitt et al., 1955). This is shown with following relationship found by Newitt et al. (1955):

$$\frac{I_m - I_f}{C_{vi}(S_s - 1)} = constant$$

Where I_m and I_f are the hydraulic gradient of a mixture and fluid respectively, C_{vi} is the spatial volumetric concentration in the pipe and S_s is the specific density of the solids. The hydraulic gradient is defined as:

$$I = \frac{\Delta P}{\rho_f g L} \quad [-]$$

In which ΔP is the pressure drop, ρ_f is the fluid density, g the gravitational constant and L the length of the pipe. The relationship by Newitt et al. (1955) tells us that the resistance curve for coarse mixtures is parallel to the water resistance curve for constant spatial concentration.

In hydraulic transport a threshold velocity between flow with stationary solids and all solids in motion is called the deposition limit velocity, V_{dl}. Classic models for the deposition limit velocities like Durand & Condolios (1952) are made for sand water mixtures and are unsuitable for coarse mixtures.

Another threshold velocity is the critical velocity (van den Berg, 1998), which is the threshold velocity between heterogeneous flow and sliding bed flow for sand water mixtures. As per definition a critical velocity for coarse mixtures does not exist, because coarse particles are not transported in the heterogeneous regime, rather in a stratified regime.

Wilson et al. (2006) made a physical model for stratified flows and the deposit limit velocity can be estimated with the so called demi-McDonald nomograph. However for large particle diameters and small pipe diameters the nomograph has no solution.

Wilson & Tse (1984) conducted research into the deposition limit of gravel with a diameter up to 6 mm and an inclination angle of 40°. This showed that the deposition limit has a maximum for inclination angles of around 30° (figure 4). In deep sea mining steeper inclination angles are expected, therefore more research is desired.

3. EXPERIMENTAL RESEARCH

Experiments were conducted in a 100 mm PVC flow loop which can be inclined up to 52 degrees. The flow loop contains an inclinable five meter long transparent section where a differential pressure transmitter measures the manometric pressure gradient over the last two meters. In the measured hydraulic gradient the water column is eliminated due to the presence of water in the polyflow tubes connected to the pressure sensors. A Krohne Optiflux 4000 is used to measure the mixture flow velocity V_m. An inverted U-loop is used to measure the delivered concentration C_{vd} according to Clift and Clift (1981) with both pressure sensors and conductance concentration sensors. Visual observations and a high speed camera are used to identify the deposition limit. The high speed camera is also used to calculate velocity profiles with a normalized image cross correlation technique (Lewis, 1995).

Tests were conducted with three gravel sizes, 3.15-5.6 mm gravel with a d_{50} of 4.6 mm, 5-8 mm gravel with a d_{50} of 6.3 mm and 8-16 mm gravel with a d_{50} of 12 mm. The average volumetric concentration of solids in the flow loop was chosen to be 20%. The deposit limit velocity and pressure difference has been measured while varying the particle diameter and the inclination angle. Three gravel types and five inclination angles $(0°, 15°, 30°, 45°, 52°)$ result in 15 measurements. Each measurement has between 12 and 25 data points and each data point is created by measuring and averaging over a five minute period.

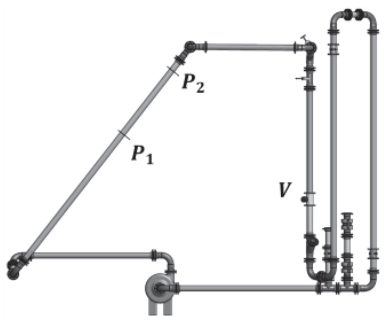

Figure 1 - Drawing of the experimental flow loop.

4. EXPERIMENTAL RESULTS

Figure 2 shows the measured hydraulic mixture gradient I_m as function of the mixture velocity V_m and particle diameter for horizontal flow. The experiments start at low flow velocities where a stationary bed is present and some particles are transported by saltation over the bed top. As the mixture velocity increases so does the hydraulic gradient, until a peak is reached. This peak is around deposition limit and for higher mixture velocities the stationary bed starts sliding.

The experimental flow loop is a closed loop system. This means that for low flow velocities the spatial concentration in the pipe is higher than 20% which increases I_m. In figure 2 the mixture velocity is increased past V_{dl} (the peak) causing the concentration to decrease and therefore the hydraulic gradient as well, until a minimum is reached. This minimum is caused by the closed loop system as explained above. In this region the 4.6 mm and 6.3 mm gravel showed unstable shocking behavior with noticeable density waves which did not decay over time. The 4.6 mm gravel is thought to be subject to stationary pressure waves reported by Matoušek and Krupička (2013) and Talmon (2015).

Increasing the mixture velocity beyond the minimum causes an increasing I_m and the hydraulic gradient becomes similar for the three particle sizes when the delivered concentration reaches a maximum.

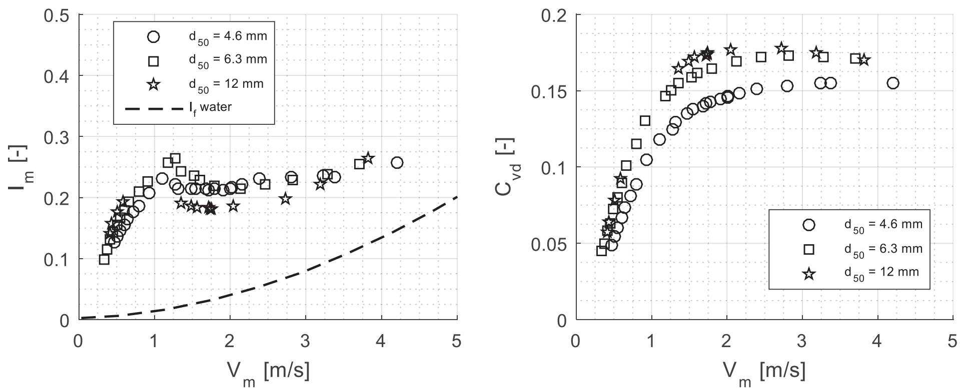

Figure 2 – Left: Hydraulic gradient against mixture velocity for horizontal transport of 4.6 mm, 6.3 mm and 12 mm gravel. Right: The measured delivered concentration matching the data points of the left figure.

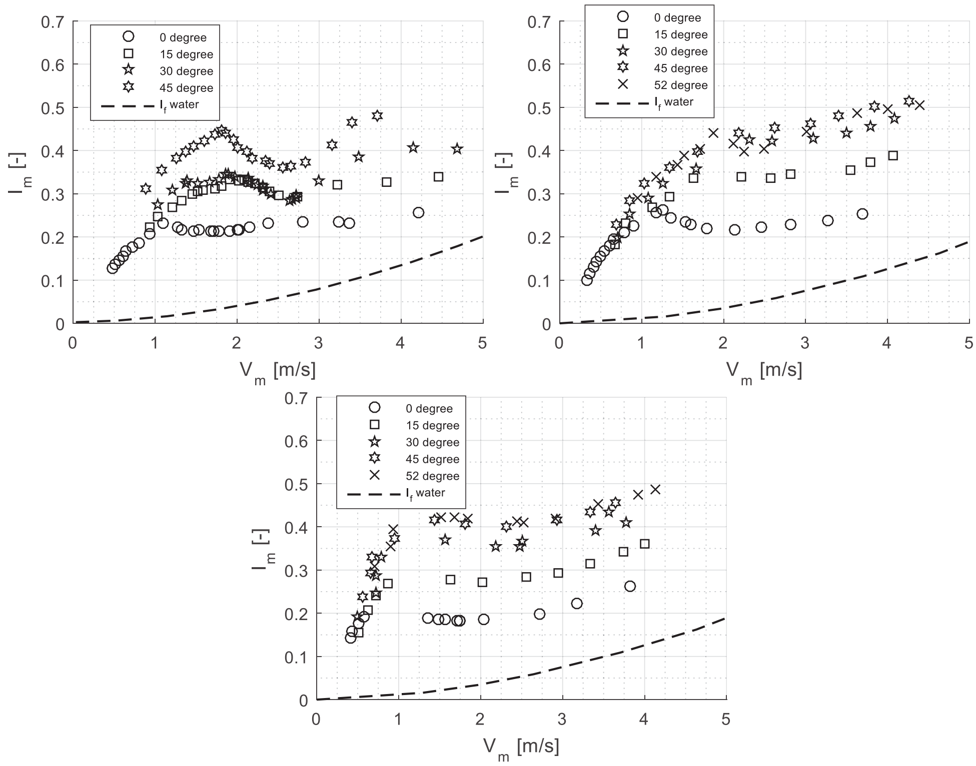

Figure 3 - Influence of the inclination angle on the hydraulic gradient. Top left: 4.6 mm gravel, top right: 6.3 mm gravel and bottom: 12 mm gravel.

The effect of the inclination angle on the mixture gradient can be seen in figure 3. In general I_m is increased with the inclination angle mainly due to the additional hydrostatic mixture column. The 4.6 mm gravel shows strong inclination angle induced minima, while the 6.3 mm and 12mm gravel do not and the resistance curves remain parallel to each other. The deposition limit velocity can still be found around the peak.

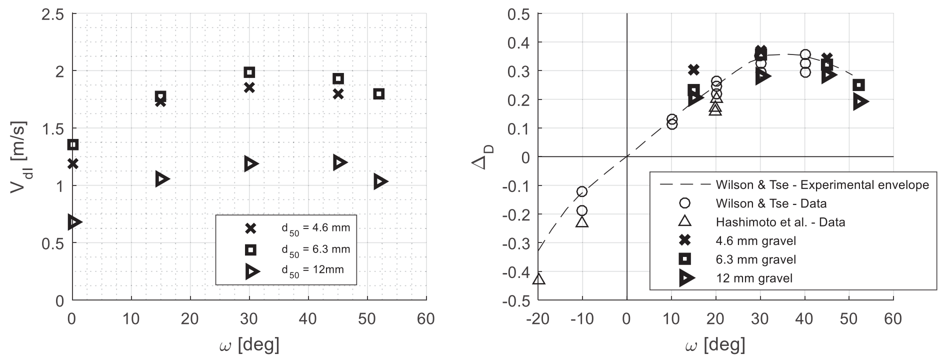

Figure 4 – Left, the measured deposition limit velocity as function of the angle of inclination and particle diameter. Right, the results plotted in Wilson & Tse (1984) coordinates.

Figure 4 (left) shows the resulting deposition limit velocities for all particles and inclination angles. The results are also plotted in the Wilson & Tse (1984) coordinates. This shows that the experimental envelope is still valid for larger particles and inclination angles up to 52 degrees. Do note that the spatial concentration is not the same for each data point, because of the closed loop. Therefore the effect of concentration is not clear from these results.

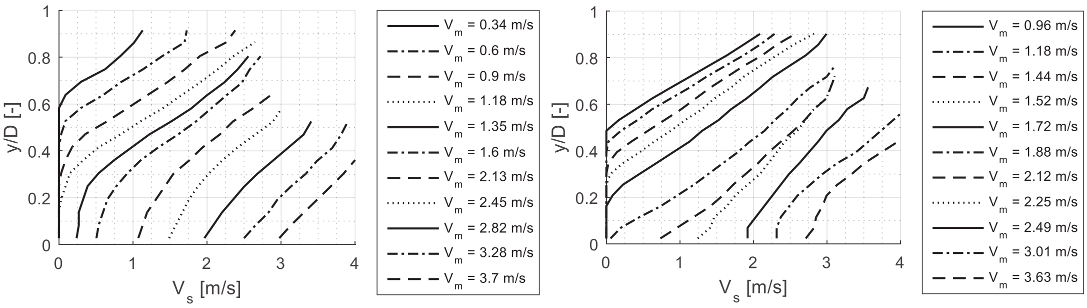

Figure 5 – Left: velocity profile of 6.3 mm gravel at an inclination of 0 degrees. Right: 6.3 mm gravel at 52 degrees. The relative height of grains in the pipe (y/D) is plotted against the grain velocity V_s. The effect of inclination and average mixture velocity is visible.

Figure 5 shows velocity profiles (grain velocity against the relative height in the pipe) calculated from high speed camera footage. Figure 5 shows the velocity profile development of 6.3 mm gravel with increasing mixture velocity. In essence the bottom of the velocity profile dictates the deposition limit velocity, thus the profiles give insight in the changing deposit limit caused by inclination. What can be seen in that the stratified profile in horizontal flow disappears and changes into a shear profile for steep inclination angles. This effect was similar for the 4.6 mm and 12mm gravel. For high mixture velocities the top of the profile is undefined, because of degraded fines clouding the water at the end of an experiment.

5. DISCUSSION

The experiments gave insight on the development of the deposition limit velocity with increasing angle of inclination. Velocities lower than the deposition limit velocity will cause stationary deposition, which significantly increases the risk of blockages. Therefore the deposition limit velocity should be the bare minimum velocity of the mixture in practice during deep sea mining. However, the delivered concentration is low at deposition limit which makes this a unsuitable velocity for high productions. So at what velocity should the mixture be transported?

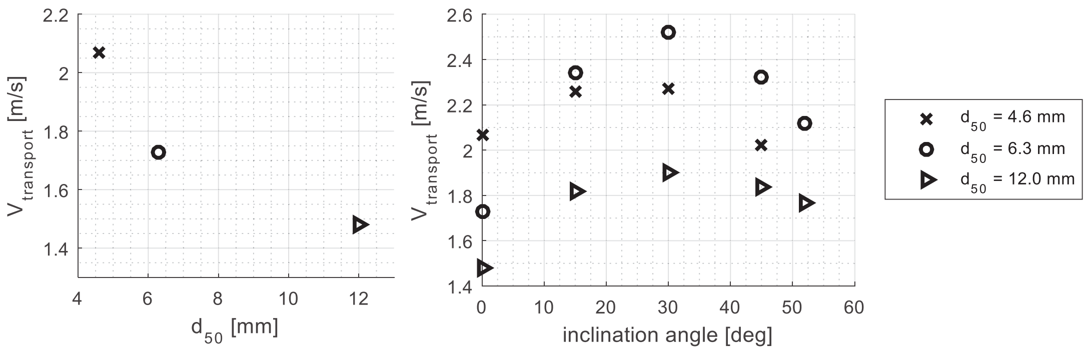

Figure 6 – Left: particle diameter against the transport velocity for horizontal transport. Right: the inclination angle against the transport velocity.

The specific energy is defined as the energy required to transport a specific mass of solids over a length of pipe.

$$E_{sp} = \frac{I_m \cdot g}{S_s \cdot C_{vd}} \qquad \left[\frac{J}{kg \cdot m}\right]$$

For constant spatial concentration the addition particle induced gradient is constant (Newitt et al., 1955), which means that the specific energy reaches a maximum when the delivered concentration reaches a maximum. Therefore a good velocity for transportation of coarse particles is when the delivered concentration reaches a maximum. However the delivered concentration has a asymptotic like maximum (figure 2), which means the maximum delivered concentration is very sensitive to small changes in velocity. To get around the problem the 'transport velocity' for coarse particles is defined as the velocity at which 95% of the maximum delivered concentration is reached. Figure 6 shows the particle and inclination dependency of the 'transport velocity' measured during the experiments. It must be stated that the concentration measurement of the 6.3 mm and 12.0 mm gravel was measured with conductance concentration sensors, which had a measuring error of about 20% due to the presences of degraded fines in the carrier liquid. Therefore the results in figure 6 (right) for 6.3 and 12.0 mm gravel is slightly inaccurate. Despite this inaccuracy the same trend as the 4.6 mm gravel is still visible.

6. CONCLUSION

The experiments showed that the deposit limit velocity is the bare minimum velocity to avoid stationary deposits of coarse particles and is maximum for an inclination angle around 30 degrees. However the production at deposit limit is very low, therefore it make sense to transport at higher velocities. A better velocity is the 'transport velocity' at which the delivered concentration is at 95% of its maximum value. The transport velocity also shows a peak at an inclination of 30 degrees.

When designing a practical deep sea mining system the transport velocity at 30 degrees should be used as the design velocity to account for all inclination angles. A full sized deep sea mining system will have a pipe diameter between 250 and 400 mm, therefore the pipe diameter dependency on the deposition limit velocity at the delivered concentration requires more research.

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