DREDGED MATERIAL PLACEMENT UNDER NON-SEGREGATING CONDITIONS

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ABSTRACT

With traditional methods of placing dredged material slurry submerged into a Confined Disposal Facility (CDF) by means of hydraulic fill, a sand delta often builds up around the discharge point, with fines settling farther out in the pond. This segregation process has an adverse effect on the constitution of the fill and the storage space, because this segregation of the coarse fraction in deposits reduces the consolidation of the fines slurry and will increase the final volume of the deposit. Furthermore the sand concentrations can be very sensitive to liquefaction resulting in unexpected slides, especially when the deposit will be re-used for industrial areas.

By purposeful managing the slurry flow and the shear rate during discharge, the dredged material can be deposited without segregating by particles size, allowing permanent storage of the fine particles within the voids of the larger grains.

A new approach was developed to place dredged sediments while keeping sands from segregating from the fine-grained sediment.

The benefits of this operating procedure include:

- Reduced use of water
- Elimination or reduction of the need for settling capacity in the CDF
- No flocculants needed
- High efficiency packing of coarse and fine sediment, increasing the storage capacity of the CDF or shrinking its footprint
- Reduced operating costs by eliminating or reducing the need to move the discharge point
- Improved reuse potential for the entire CDF
- Substantial reduction in contaminant and particulate loading at the supernatant treatment plant
- Virtual elimination of volatile emissions from the CDF water surface

This paper goes into the mechanisms and physics of the segregation. Although an excess entrainment of ambient water allows a start of segregation, still the reduction of water entrainment leaves open a shear induced segregation. Based on the combined knowledge of these phenomena the conditions are derives that must be met to achieve the benefits of non-segregating deposition. Next to that the kinds of tests used in the evaluation are presented in order to apply this technology.

Keywords: Slurry transport, waste management, contaminated sediment, sand segregation, transition clay to sand dominated deposit.

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INTRODUCTION

With traditional methods of placing dredged material slurry submerged into a Confined Disposal Facility (CDF), a sand delta often builds up by the discharge point, with fines settling farther out in the pond. This segregation of the coarse fraction in deposits reduces the consolidation of the fines slurry and will increase the final volume of the deposit. The creation of sand piles requires the movement of deposition equipment. Furthermore these sand piles can be very sensitive to liquefaction resulting in unexpected slides, especially when the deposit will be re-used for industrial areas. An example of segregation is shown in Figure 1, where deposition with a traditional tremie was forming sand piles in a deposition pond (Tremblay, 2003). In order to prevent segregation during deposition the mechanisms that cause segregation must be understood. In this paper these mechanisms and involved physics are discussed. An experimental set-up (shear cell) is presented to determine non-segregating conditions as function of operational parameters and rheological properties of the slurry. With these test results it is possible to the design a multiple tremie/diffuser mounting, which is preventing segregation within a certain operational window.

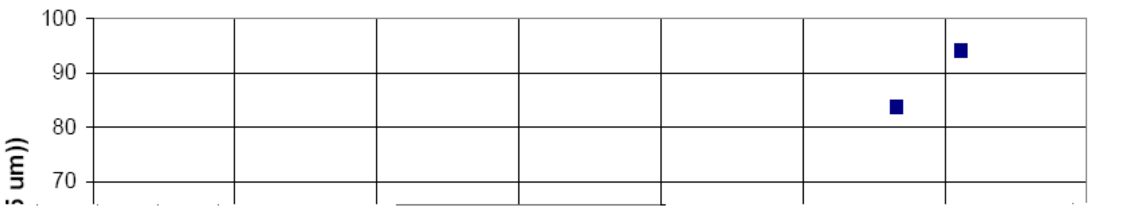

Figure 1. Field data segregation in deposition pond (Tremblay, 2003)

EFFECT SEGREGATION IN DEPOSIT

The effect of segregation on the final volume of the deposit is important for the solids capacity of the storage facility. Given certain storage space the maximum amount of solids that can be stored after consolidation can be expressed as function of the sand content of the total solids. In Figure 2 the relative volume of solids in the deposit after self weight consolidation is shown for non-segregated deposit (red solids line) and a deposit where all sand segregated (dashed solids line). The fines solids are indicated in blue. It is assumed that the segregated sand is building up a sand skeleton with an averaged porosity of 50%, and that the fluid in these pores contains unconsolidated fines, i.e. the same fines water content at the moment of deposition. Also the relative volume of the segregated sand body, including pore space is shown (orange line). Figure 2 shows that with increasing sand content more solids can be stored when segregation is prevented. The maximum additional storage is around 70% sand content, where the increase in solids for both fines and sand is about 26%. For higher sand contents the sand skeleton starts dominating the consolidation in the non-segregated slurry and the additional storage reduces to zero when the porosity of the sand skeleton in the non-segregated slurry equals the porosity of the segregated sand skeleton. In this example with 50% porosity of the sand skeleton and an initial fines water content of 180% at deposition the maximum sand content is 85%.

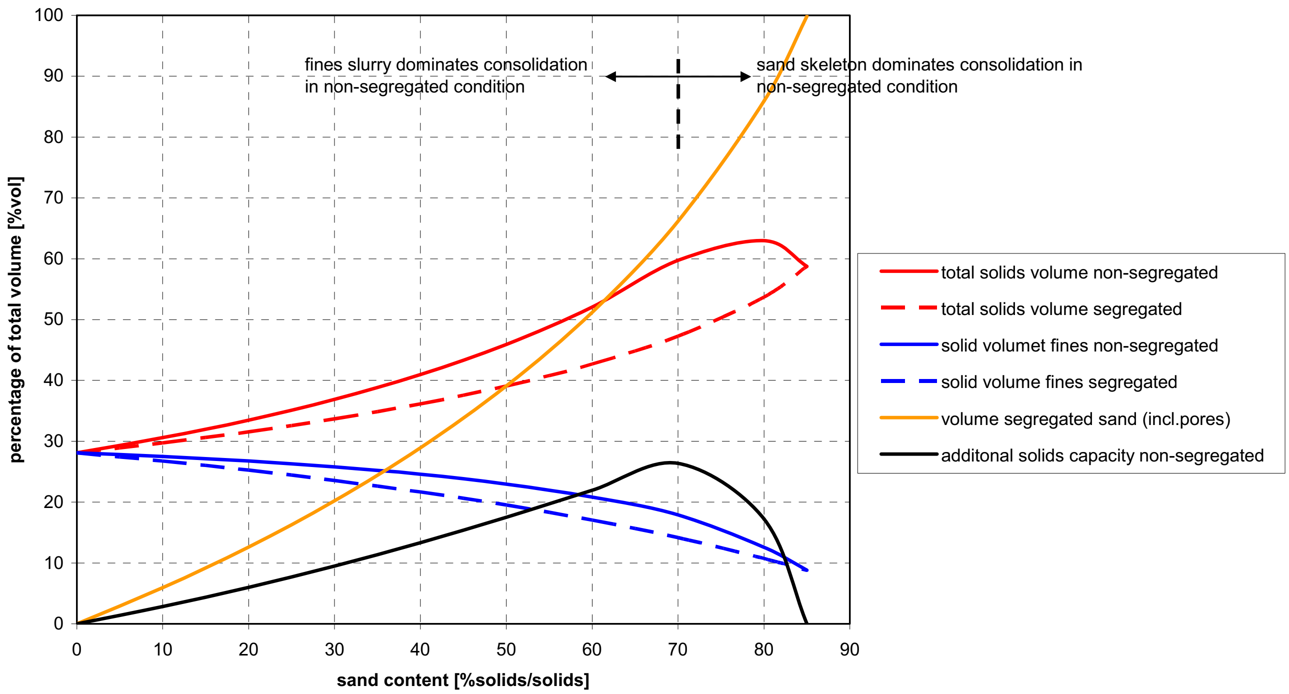

Figure 2. Effect of segregation on solids storage capacity.

THEORY OF SHEAR INDUCED SEGREGATION

Segregation of the coarse fraction is determined by the rheological properties of the fines slurry (<63 μm), which are controlled by the water content with respect to the clay fraction. When the slurry is not flowing, i.e. static condition, the particles will settle if the yield stress satisfies the following criterion:

$$Y \equiv \frac{\tau_y}{(\rho_s - \rho_f)gD} < Y_{\max} \tag{1}$$

in which: Y is dimensionless number of the ratio between yield stress and "hydrostatic" pressure, Y_{max} is the particle stability criterion, D = particle diameter, g = gravity, ρ_f = fluid density, ρ_s = particle density, τ_y = yield stress.

Empirically determined values of Y_{max} are in the range 0.02 to 0.20 (Chhabra (1993)). Based on plasticity theory a critical value of Y_{max} = 0.065 is found (Ansley and Smith (1967)). If a fluid mechanical approach is followed, the critical value for Y_{max} is 0.048 (Beris et al., 1985). In Figure 3 measured Y_{max} values are shown as function of shape and orientation of particles in a non-Newtonian Bingham fluid (Jossic et al., 2001).

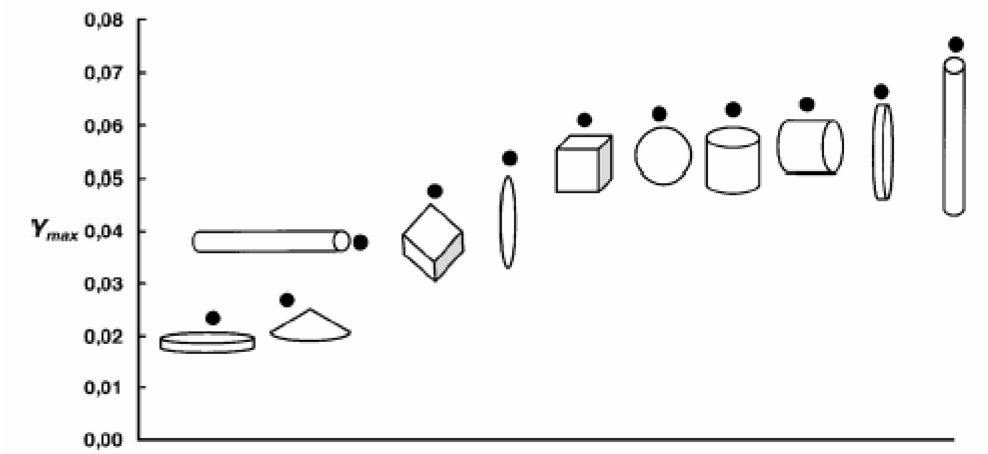

Figure 3. Variation of particle stability criterion for different shapes and orientation (Jossic and Magnin, 2001).

Applied to sand with a maximum grain size of 2 mm and Y_{max} = 0.065, the required yield strength for non-segregation in quiescent fluid is about 2 Pa. For lower values a reasonable value for the settling velocity in viscous non-Newtonian fluids can be obtained from the Stokes settling formula given by:

$$w_{s,0} = \frac{(\rho_s - \rho_f) g D^2}{18\eta_a} \tag{2}$$

in which η_a is the apparent viscosity of fluid surrounding the particle.

As an example the Herschel-Bulkley model is used for the rheological behavior of fines slurry:

$$\tau = \tau_y + K\dot{\gamma}^n \quad \text{with apparent viscosity} \quad \eta_a \equiv \frac{\tau}{\dot{\gamma}} = \frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \tag{3}$$

in which: K = viscosity parameter, $\dot{\gamma}$ = shear rate, τ_y = yield stress.

The shear rate around the settling particle in a pseudo-plastic fluid can be scaled with (Hannah and Harrington 1981, Chien 1994):

$$\dot{\gamma} = \frac{w_{s,0}}{D} \tag{4}$$

(for a Newtonian fluid, the theoretical value is $\dot{\gamma} = 2w_{s,0} / D$, Roodhart 1985)

Combining this with Stokes settling formula yields the settling velocity of a single particle in quiescent non-Newtonian fluid with a yield strength:

$$w_{s,0} = D\left(\frac{(\rho_s - \rho_f) g D}{K}\left(Y_{\max} - Y\right)\right)^{1/n} \tag{5}$$

In a shear flow particles have a tendency to settle Thomas 1979, Wilson & Horsley 2004 and Talmon & Huisman 2005. For single particles it was concluded in Talmon & Huisman (2005) that co-rotation of the particles with the flow and vertical equilibrium of forces determine the fall velocity in viscoplastic fluids. It was further concluded that the use of a Stokes type formula for fall velocity is justified in these fluids. No differences were found between horizontally sheared flow and vertically sheared flow.

For a particle in quiescent fluid, the fluid stresses are directed upwards, along the surface of the particle as indicated in Figure 4a. The magnitude of these fluid stresses is at maximum equal to the yield- or gel-strength. In shear flow, the fluid stresses redistribute around the circumference of the particle as indicated in Figure 4b, and the particle commences to settle.

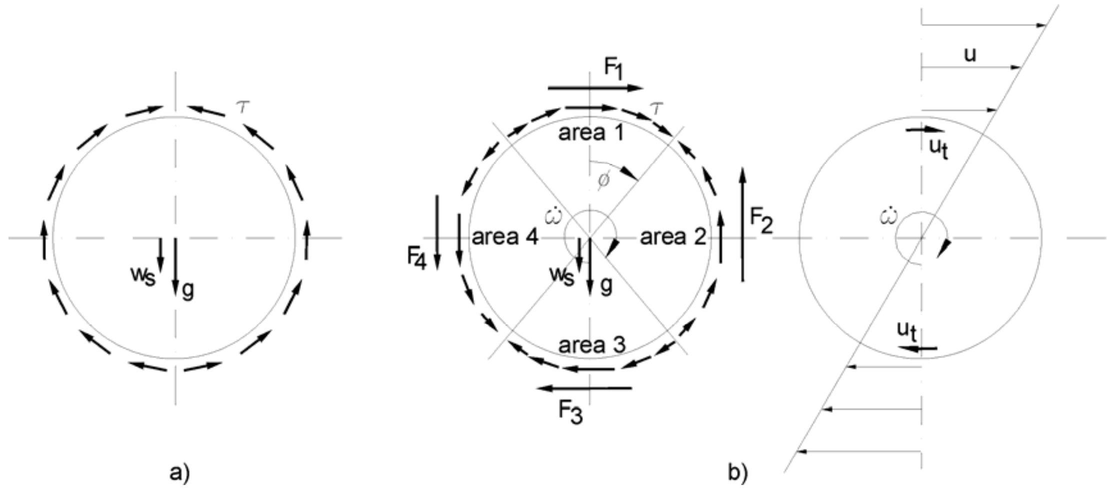

Figure 4. Shear stress distribution around particle in quiescent fluid (a) and in shear flow (b), (after Talmon & Huisman, 2005).

The Stokes type formula for the settling velocity of a single particle in a shear flow of a non-Newtonian fluid is given by:

$$w_{s,0} = \alpha \frac{(\rho_s - \rho_f) g D^2}{18 \eta_a} \tag{6}$$

in which η_a is the apparent viscosity and α is an empirical coefficient.

Theoretically the coefficient α equals π/2, but from experiment a value of 0.5 is found by Talmon & Huisman (2005). A similar settling velocity formula as Equation(5) can be derived by introducing a relative shear rate $\dot{\zeta}$ defined by:

$$\begin{aligned} &\frac{\dot{\gamma}}{w_{s,0} / D} > \frac{18 Y_{\max,s}}{\alpha} \Rightarrow \dot{\zeta} = \frac{\alpha}{18 Y_{\max,s}} \frac{\dot{\gamma}}{w_{s,0} / D} \\ &\frac{\dot{\gamma}}{w_{s,0} / D} < \frac{18 Y_{\max,s}}{\alpha} \Rightarrow \dot{\zeta} = 1 \end{aligned} \tag{7}$$

Substitution in the Stokes formula Equation (7) yields for the Herschel-Bulkley model:

$$w_{s,0} = D \left(\frac{(\rho_s - \rho_f) g D}{K} \left(Y_{\max,s} \dot{\zeta} - Y \right) \right)^{1/n} \frac{\alpha}{18 Y_{\max,s} \dot{\zeta}} \tag{8}$$

in which $Y_{max,s}$ is the stability criterion for settling in shear and can be expressed as function of the ratio Y/ Y_{max} assuming that for $\dot{\zeta}$ <1 the settling velocity should be equal to the settling velocity without shear:

$$\frac{Y_{\max,s}}{Y_{\max}} = \alpha + \left(\alpha^{\frac{n}{n-1}} - \alpha \right) \exp\left(-c \frac{Y}{Y_{\max}} \right) \quad c \approx\sim 1.9 \tag{9}$$

For multiple grains hindered settling formulas (Winterwerp and Van Kesteren 2004) can be applied. It must be noted that for non-Newtonian fluids a correction is necessary for the increased local shear around the particles due to the hindered settling. Therefore the apparent viscosity will be lower than for a single grain.

The dependence of the shear rate on settling velocity of a single grain according to Equation(8) is depicted in Figure 5 and compared with the measurements by Talmon & Huisman (2005) (α=0.5, τ_y=0.7 Pa, K=0.41, n=0.62, Y_{max}=0.02). It shows that when the condition in Equation (7a) is fulfilled, settling of the coarse fraction will increase with shear rate. For Y<Ymax the settling velocity at zero shear rate is given by Equation(5). It can be concluded that when a shear rate is present settling will always occur. By controlling the upper limit for the shear rate and a lower limit for the rheological properties of the fines slurry, the settling velocity of the coarse fraction can be limited to a level that corresponds to local drainage of the fines slurry around the particle. This local drainage will increase the apparent viscosity around the particle and will finally arrest the particle in a shear flow. These conditions can be determined in an annular flume or a shear cell (Talmon & Huisman, 2005).

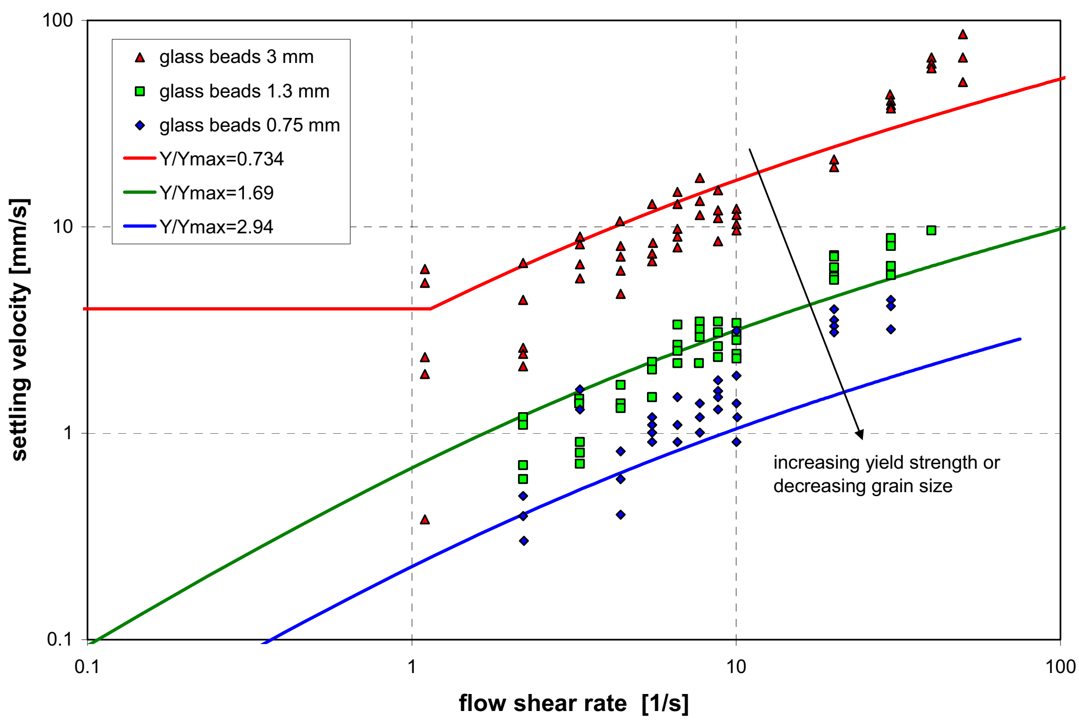

Figure 5. Settling velocity coarse fraction as function of shear rate fines slurry.

SHEAR INDUCED SEGREGATION IN SHEAR CELL

The shear cell (see Figure 6) is a settling column with a rotating bob, which creates a horizontal shear flow. By means of electrical conductivity probes the porosity of the slurry is measured from which the sand concentration is determined. A typical test result is shown in Figure 7 for a medium sand in bentonite slurry, with a yield strength sufficient to keep the sand in suspension in quiescent fluid. The volumetric sand concentration is 16%. Median particle size is d_{50}=0.34 mm and non-uniformity is d_{90}/d_{10}=2. The Herschel-Bulkley parameters of the bentonite slurry are τ_y=7.8 Pa, K=0.57, n=0.5 In Figure 7 the relative sand concentration at three levels (see Figure 6) is given as function of time. The S-curved shape is determined by the grain size distribution: a wider distribution result in lower gradient. The shift of the S-curve at different heights yields the front velocity of the sand and is a measure for averaged settling rate. By applying the shear cell test at different share rates the amount of non-segregated sand can be determined as function of shear rate as indicated in Figure 8. The gradient in Figure 8 will decrease with decreasing water content of the carrying fluid, i.e. increasing apparent viscosity. In order to determine non-segregating conditions the shear cell tests must be performed at different water contents of the carrying fluid. These yield for a certain shear rate a segregation flux (kg sand/m^2/s) as function of water content of the carrying fluid.

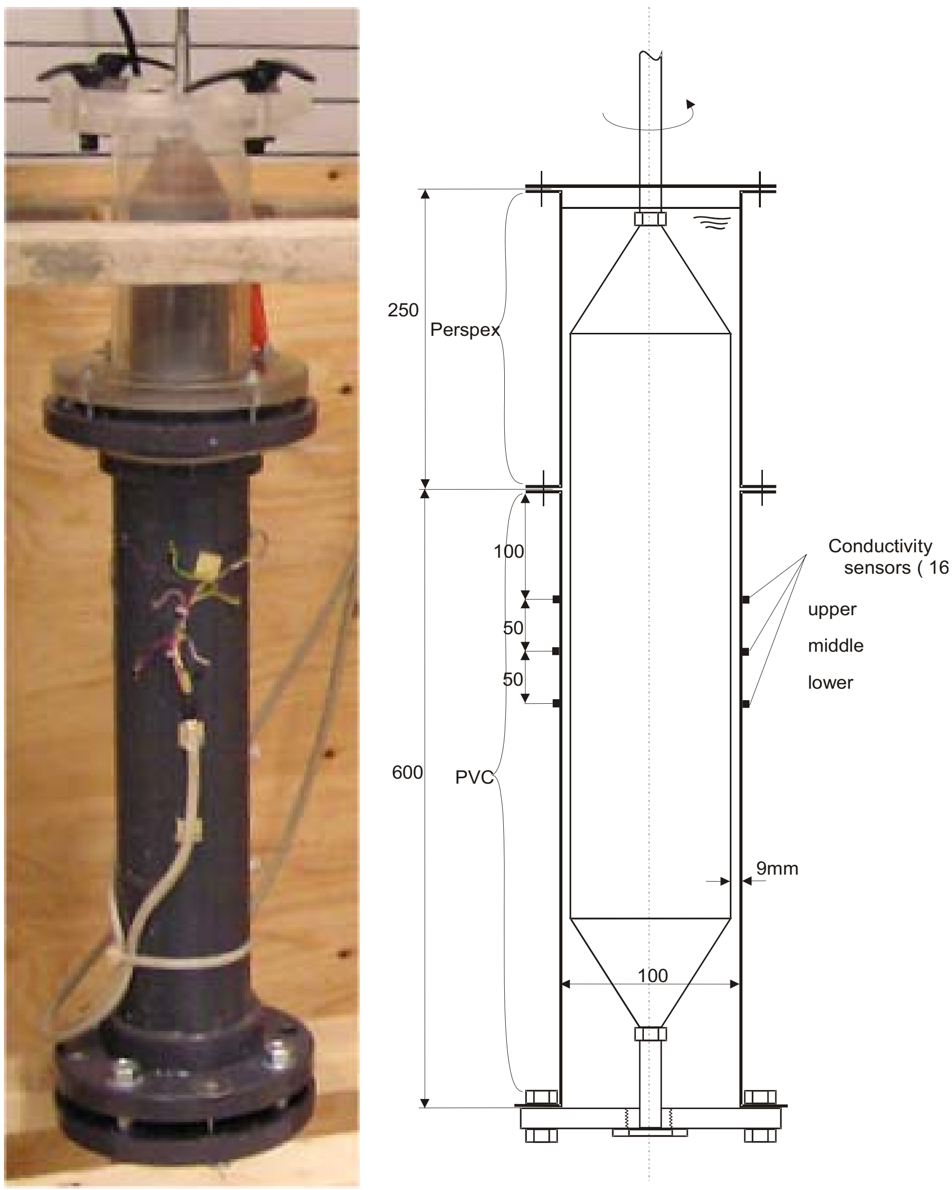

Figure 6. Shear cell for shear induced segregation tests.

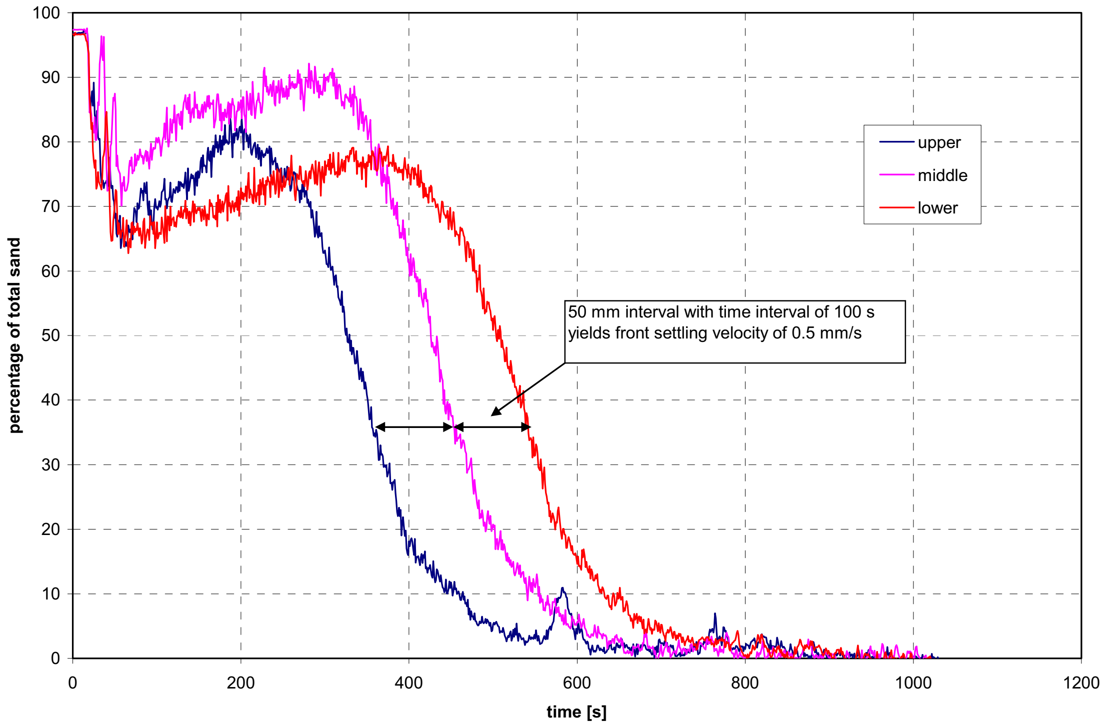

Figure 7. Measurement result sand segregation in shear cell at 150 rpm.

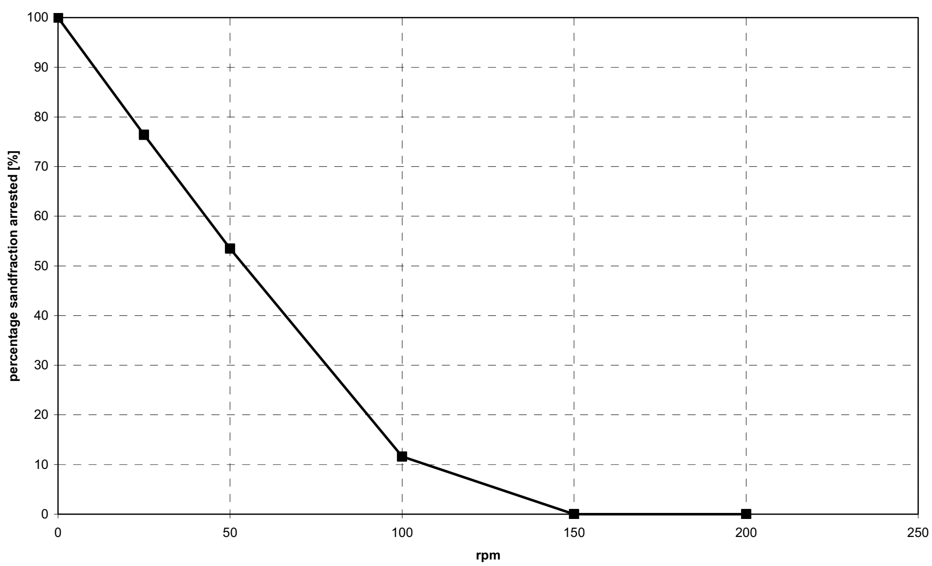

Figure 8. Percentage sand in suspension.

NON-SEGREGATION CONDITION WITH MULTIPLE TREMIE / DIFFUSER MOUNTING

During the deposition of slurries containing cohesive fines and sand, three main processes are important for its controlled placement:

1. Acceleration in the vertical section of the deposition system
2. Super critical density current outside deposition system
3. Segregation of the coarse fraction (>63 μm)

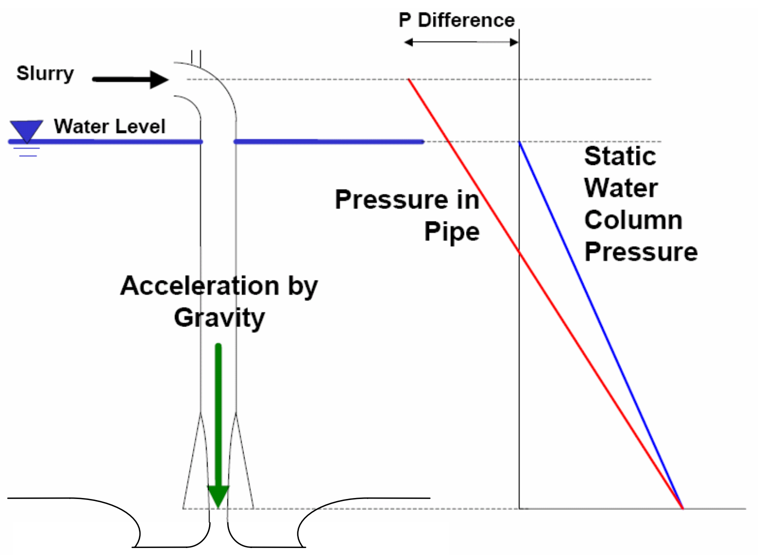

Figure 9. Traditional slurry deposition with a single tremie. Acceleration is due to density difference in the pipe section and the ambient hydrostatic pressure at the outlet.

The slurry accelerates during vertical flow due to the density difference between the slurry and ambient water. The slurry velocity increases, entraining water that dilutes the slurry thus increasing the amount of contaminated water (see Figure 1). When the slurry hits the bed, the horizontal flow can be sub- or super-critical, which is defined by the internal Froude number:

$$Fr_i = \frac{u}{\sqrt{\varepsilon g\, h}} \quad , \quad \varepsilon = \frac{\rho - \rho_w}{\rho} \tag{10}$$

in which u is horizontal velocity, h is mud depth, ρ is slurry density, ρ_w is water density .

In the super-critical case (Fr_i>1), the horizontal radial flow velocity will decrease and an internal jump to sub-critical flow will occur at some distance outside of the tremie (Figure 10). A lot of energy is dissipated in the jump. The jump (or currents it creates) will be turbulent, which increases mixing between the slurry and ambient water. Furthermore the shear rate in the super-critical horizontal radial flow will be high (>>1 s^{-1}), which may result in shear induced segregation of the coarse fraction.

In order to control the deposition of slurry it is important not to dilute the slurry and to prevent segregation of the coarse fractions. Dilution of the slurry will increase the amount of effluent water that has to be treated and will enhance segregation. When segregation occurs the coarse fraction builds up a skeleton and the weight of the coarse solids will not contribute anymore to self-weight consolidation of the fines slurry. The consolidation of the fines slurry within the skeleton of the coarse fraction is limited by the higher stiffness of the coarse skeleton. Therefore segregation will always result in a larger volume of the deposited slurry after consolidation.

The slurry deposition can be controlled by a multiple tremie/diffuser system (see Figure 10, Mastbergen et al., 2004). By increasing the friction in the vertical pipe section of the multiple tremie acceleration is prevented. Still the velocities in the vertical pipe section must be high in order to create sufficient friction or energy losses to counter balance the density difference. These velocities result in general in super-critical flow near the bottom. Therefore the diffuser must be designed in a way that the flow velocity is reduced to a sub-critical level. This can be achieved by generating a controlled internal hydraulic jump within the diffuser. The diameter and outlet height of the diffuser is designed such that outlet velocities are sub-critical and the shear rate at the outlet is sufficiently low to prevent segregation of the coarse fractions. In order to minimize mixing with the ambient water, the outlet of the diffuser should be kept submerged in the disposed slurry (Figure 10).

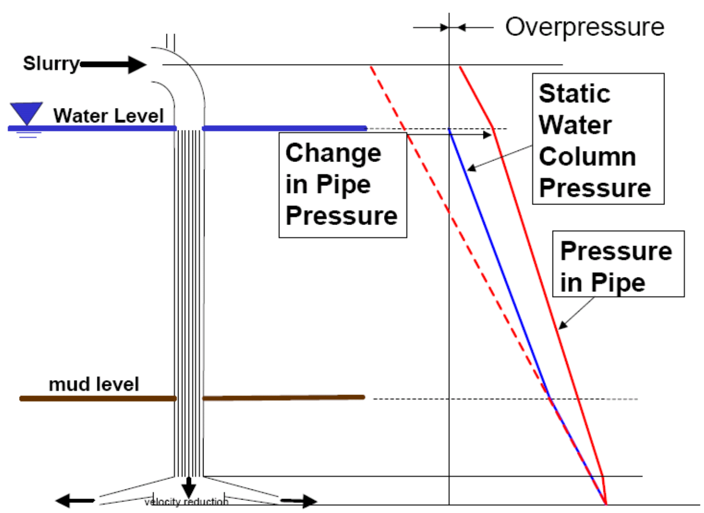

Figure 10. Multiple tremie / Diffuser - system, minimizing dilution with ambient water and minimizing segregation.

A consequence of using the clay-water-mixture for controlled placement, is that slurries are thickened, and flow rates will be low. This will put pipe-line transport in the laminar regime. In absence of a dispersion mechanism, solids concentrations will not remain uniform in laminar flow. Although such flows are difficult to probe, in-line segregations have been found by means of a magnetic resonance imaging technique, Pullum and Graham 2000. Such segregations can be dangerous. It was demonstrated by Talmon and Mastbergen 2004 however, with reference to the horizontal directional drilling method, that in-line segregations are admissible provided no grain skeleton is formed. Clay-matrix properties have to be checked for grain skeleton formation.

CONCLUSIONS

Multiple tremie/ Diffuser mountings are capable of delivering slurries that are denser than water in a way that they are placed underneath the water, with minimal mixing. The slurried fluid (e.g., dredged material or mine tailings) remains separate from the overlying water, yielding the following benefits:

- Especially useful in deep placement. As the water gets deeper, the heavier slurry has more distance over which it can accelerate. Acceleration causes mixing, cavitation, and turbulence – defeating the project goals. The multiple tremie / diffuser provides the backpressure to cancel the acceleration.
- Useful when placing low weight solids. As shown in the Netherlands project (Mastbergen et. al. 2005), underwater placement of low specific gravity solids is difficult. The multiple tremie / diffuser places this material beneath the overlying water without mixing, allowing placement in desired locations without having to move the discharge point during placement.
- Prevents mixing. Therefore the dissolution of soluble volatile compounds or odor-causing chemicals is also prevented. When the chemicals do not dissolve, they won't emit to the air.
- Reduced effluent wastewater treatment costs. Eliminates need for flocculation and clarifiers, reduces load on carbon.
- Works with other conventional equipment.

Depending on the hydraulic conditions, the various grain sizes of material contained in the slurry can also remain together (non-segregated). The benefits of this feature include:

- Dense is better. A high solids material is especially important when seeking non-segregating conditions. The clay-water matrix can be used to suspend the sand without requiring high pipeline velocities. The reward is high efficiency placement, and usable ground conditions.
- Prevents sand buildup. Sand buildup is not inevitable. High efficiency packing of coarse and fine sediment, increasing the storage capacity of the CDF or shrinking its footprint
- Reduce the need for carry water in the slurry. Carry water can be left in the dredge area and the wastewater treatment plant can be smaller.
- Reduced operating costs by eliminating or reducing the accumulation of segregated sand and the need to move the discharge point. Moving discharge points around the disposal site is not necessary.
- Still Works with other conventional equipment. Pumps capable of transporting high solids are most attractive. (e.g., Positive displacement pumps, Eddy Pumps, etc.).

REFERENCES

Ansley, R.W. en T.N. Smith, 1967, Motion of spherical Particles in a Bingham plastic, AlChE Journal, Vol.3, No.6, pp.1193-1196.

Beris, A.N., Tsamopoulos, J.A. & R.C. Armstrong, 1985, Creeping motion of a sphere through a Bingham plastic, J. Fluid Mech.,Vol. 158, pp. 219-244.

Chhabra, R.P., 1993, Bubbles, drop and particles in Non-Newtonian Fluids, CRC Press.

Chien S.F., 1994, Critical velocity of sand-fluid mixtures in horizontal pipe flow, FED Fluids Engineering Division, ASME, vol.189, pp. 231-246.

Hannah, R.R. en Harrington L.J., 1981, Measurements of proppant fall velocities in fracturing gels using a concentric cylinder tester, J. Petroleum Technology, pp. 909-913.

Jossic, L. and A. Magnin, 2001, Drag and Stability of Objects in a Yield Stress Fluid, AIChE Journal, Vol. 47, No. 12, 2666-2672.

Mastbergen, Dick R., Van Kesteren, Walther G.M. and Loman, Gerard J.A. (2004), "Controlled Submerged deposition of fine grained dredged sediment with various diffuser types", *Proceedings XVIIth World Dredging Congress 2004*.

Mastbergen, Dick R., Van Kesteren, Walther G.M. and Loman, Gerard J.A. (2005), "Making Sediment Deposition Work", *2005*; Dredging and Port Construction, pp. 16-19.

Pullum, L. and L.J.W. Graham, 2000, The use of magnetic resonance imaging (MRI) to probe complex hybrid suspension flows, proc. 10th int. conf. Transport and Sedimentation of solid Particles, Wroclaw Poland, pp129-139.

Roodhart L.P., 1985, Proppant settling in non-Newtonian Fracturing Fluids, SPE/DOE 13905.

Talmon, A.M. and Huisman, M. (2005), "Fall velocity of particles in shear flow of drilling fluids", *Journal Tunneling and Underground Space Technology incorporating Trenchless Technology Research*, March, vol. 20, no. 2.

Talmon A.M. and D.R. Mastbergen, 2004, Solids transport by drilling fluids: Horizontal Directional Drilling. 12th Int. Conf. on Transport and Sedimentation of Solid Particles, Praque

Thomas, A.D, 1979, Settling of particles in a horizontally sheared Bingham plastic, 1st National conference on rheology, Melbourne, May 30-juni, pp89-92.

Tremblay, M.A.J. and Rowson, J., 2003, Tailings Management Best Practice: A Case Study of the MacClean Lake JEB Tailings Management Facility, COGEMA Resources Inc., Saskatoon, Saskatchewan, CANADA.

Wilson, K.C. and R.R.Horsley, 2004, Calculating fall velocities in non-Newtonian (and Newtonian) fluids: a new view, Proc. Hydrotransport 16, Santiago, Chile, pp37-46.

Winterwerp, J.C. and W.G.M. van Kesteren (2004), “Introduction to the Physics of Cohesive Sediment in the Marine Environment”, in *Development in Sedimentology 56*, Elsevier.