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A LARGE-SCALE EXPERIMENTAL STUDY OF HIGH DENSITY SLURRIES DEPOSITION ON BEACHES

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One of the biggest uncertainties affecting the operations of mine and land reclamation activities is the management of tailings/slurry, in which the processes of beach deposition play a critical role. Upon deposition, tailings exhibit channelized flow behaviour causing varying velocity profiles which influences the beach slope and deposition. These processes impact slurry management operations as well as the mine closure and/or reclamation planning. Even though critical, little is known about the physics involved in these processes. In order to improve this knowledge, Deltares initiated large scale flume experiments. In the experiments a mixture of clay, silt, sand and salty water is discharged over a 2% slope. The composition of the deposited mixture varies during the experiments. Our results show that the flow behaviour changes with decreasing strength from robust sheet flow to more dynamic channel formation. The change in flow behaviour corresponds to a change in observed surface shear-profile. Accompanying the change of strength, flow behaviour and shear mechanism, a shift from non-segregating to segregating slurry is observed. The observed decrease in strength corresponds to a decrease in equilibrium slope.

KEY WORDS: tailings, flume, non-Newtonian, laminar transport, segregation, deposition

1. INTRODUCTION

One of the biggest uncertainties affecting the operations of mine and land reclamation activities is related to tailings/slurry management, for which the processes of beach deposition play a critical role. During deposition of a high density slurry, exhibiting complex non-Newtonian properties, the resulting flow dynamics comprises sheet flow and migrating meandering channels. The varying velocity field that is produced within and outside the channels produce different shear rates which are responsible for differences in sand settling or segregation. The settling of sand along the slope or segregation ultimately impacts the particle size composition and the geometry of the beach. The resulting deposition pattern has significant impact on slurry management operation (e.g. fines capture, capacity of a tailings storage facility) as well on mine closure and reclamation planning (e.g. strength of the deposit, hence bearing capacity differential consolidation, hence total settlement or reclamation topography). Even though critical, little is known about the physics and dynamics of slurry flows over beaches, and predictive tools are mostly parametric. In this context, Deltares have started an important research program towards the understanding and prediction of the physics associated with the flow of dense non-Newtonian slurry flow over beaches.

This research program starts with the execution of a large scale pilot, in which slurry of different densities and sand content (typical of industry tailings) is discharged over a 2% slope, aiming to observe and understand flow dynamics of slurries when deposited over beaches. A vast amount of digital, electronic, visual and physical data is collected to quantify flow behavior and deposit characteristics (particle size distribution and strength). The data is designated to be used for validation of the new Delft3D-slurry module designed for the prediction of non-Newtonian flow behavior, sediment transport and deposition (Sittoni et al. 2015).

2. EXPERIMENTAL TEST SET-UP

So far experimental work on tailings deposition has been carried out in flumes of typically 1 m width. In contrast to previous studies this pilot is unique in terms of scale. The tests are conducted in an in-house flume at Deltares, which is 55 m long, 5.5 m wide and 2.5 m deep. The test setup includes the full length and width of the flume in which an artificial slope of 2% is constructed.

2.1 FLUME DESIGN

The test facility consists of two separate parallel flumes, one test flume of 5.5 m width and an adjacent storage flume of 3.5 m width. A wooden slope is constructed in the main test flume (5.5 m width), which simulates a previously deposited tailings beach. A schematic overview of the test setup is shown in Fig.1 and a side view of the beach in Fig.2. To assure mixture supply and homogeneity a mixing tank was installed between storage outflow and test inflow. The slurry is issued from an open-end pipe, underneath of which a plunge pool develops. At the end of the beach, at the outflow, a sump pump is placed after a downward step cavity, so that boundary condition effects upstream of the pump are minimized. To obtain a higher resemblance with the field situation, a uniform base layer of tailings is deposited over the wooden slope before every test, representing earlier deposited tailings.

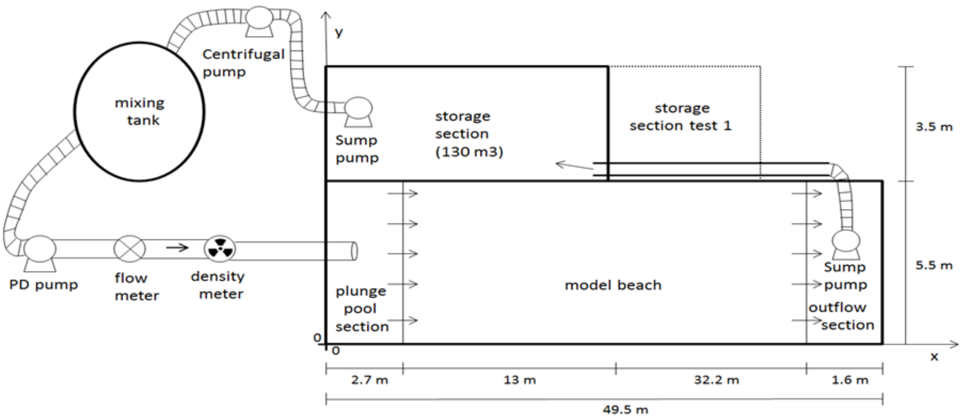


Fig.1 Top view of experimental test setup

During the test the mixture is pumped from the mixing tank into the flume where it gradually overflows the plunge pool and flows over the beach. The mixture is collected at the end of the beach in the outflow basin from where it is pumped to the storage section. On the other side of the storage section the mixture is then pumped to the mixing tank and the cycle is started again.

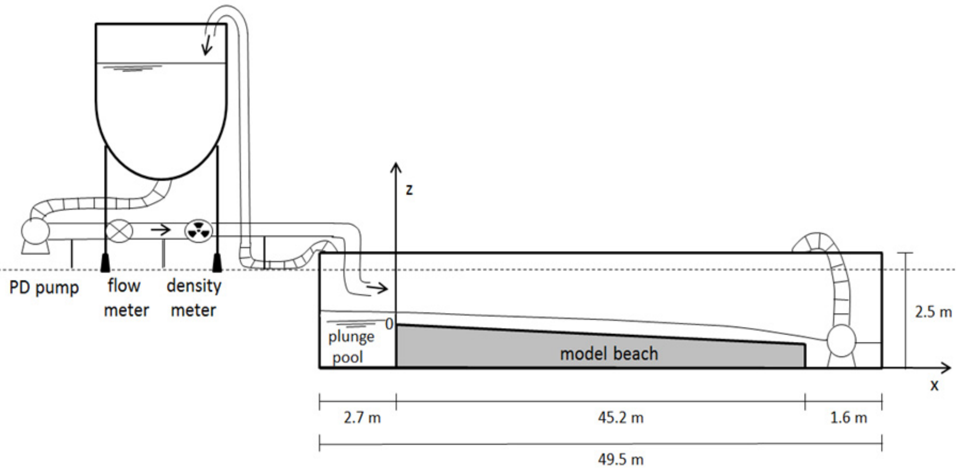


Fig.2 Side view of experimental test set-up.

1.1. MIXTURE CHARACTERISTICS

The engineered mixture is composed of two sands (d_{50}=133 µm, d_{50}=330 µm), kaolinite clay with silt and water similar to compositions in oil-sands. But a broader scope is pursued, conditions may apply also to dredge operations for creation of salty marshes. The composition is based on vane-measurements (strength) in the Physical Laboratory of

Deltares. The strength of the initial mixture was targeted at 40 Pa. The slurry used in the subsequent tests was obtained by diluting the initial mixture. The slurry is mixed with an industrial fly-ash mixer, producing alternating batches of fine and coarse sand. To monitor strength development each batch was carefully measured. The mixture is characterized by the water content and sand-to-fines ratio:

$$\boldsymbol{wf} = \frac{\boldsymbol{mass\ water}}{\boldsymbol{mass\ clay\ and\ silt}} \qquad \boldsymbol{SFR} = \frac{\boldsymbol{mass\ sand}}{\boldsymbol{mass\ clay\ and\ silt}} \qquad \text{Eq.1}$$

The experimental program is divided into a number of different tests that are characterized by a varying water content (hence strength), sand-to-fines ratio and duration of the test. The slurry is diluted to trigger segregation and consequent channel formation. During test 1 the mixture was not recirculated to ensure a continuous consistency, therefore the duration of the test was limited. To increase the test duration and capture all flow dynamics observed in practice the mixture was recirculated during the other tests. Before test 1, 2 and 3.1 the flume was cleaned and a homogeneous layer of tailings (~ 0.1 m) was deposited to mimic a partially consolidated base layer. After test 3.1 the experiment was restarted in the subsequent days and called test 3.2, 3.3 and 3.4. The characteristic parameters of each test are shown in Tab. 1.

Tab. 1 Characteristic parameters per test.

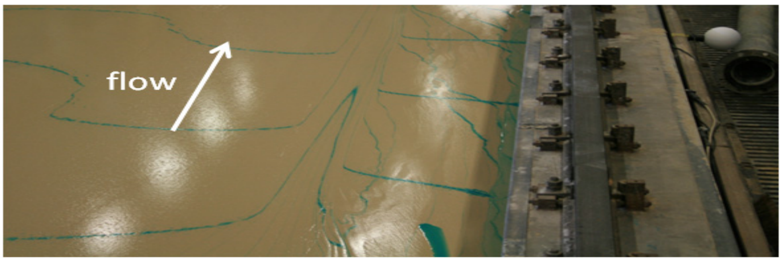
Test	**1**	**2**	**3.1**	**3.2**	**3.3**	**3.4**
Duration [min]	22	265	450	115	420	330
Wf [%]	223	223	273	314	314	314
SFR [-]	1.49	1.49	1.80	1.26	1.08	0.63

3. RESULTS

During the tests inflow properties, bathymetry scans and video data was collected, and after the test cores and vane (strength) measurements were taken on characteristic locations. This data is analyzed and discussed in this section.

3.1 GENERAL OBSERVATIONS

The water content was artificially increased over the experiments, this produced segregation, hence sand-to-fines ratio decreased. These two circumstances result in a decrease of the strength of the mixture. With a decreased strength, the flow behavior changes. Surface velocities are revealed by regularly spraying ink-lines over the width of the flume. At the start of the experiments ‘sheet-flow’ was observed. Sheet flow is referred to as slow, full-width shallow flow with uniform velocity. While the experiments evolved, the flow behavior changed to more dynamic flow with non-uniform velocity profiles, similar as observed during flume experiments described by Sisson et al. (2012). This led to channel-formation and becomes more pronounced towards the end of the experimental program. Both sheet flow and channels showed unsheared plug regions in the velocity profile, similar as observed by Pirouz et al. (2013). The velocity profile observed during slow flow of a stronger mixture is stepped. The flow-profile however differs from the profile observed when channels are formed. In stepped flow abrupt discontinuities in velocity profile are visible in the slow moving part, revealing longitudinal shear planes (Fig. 3, bottom), whereas during channel formation the velocity profiles have a smooth shape (Fig. 3 top) accompanied with a higher velocity.



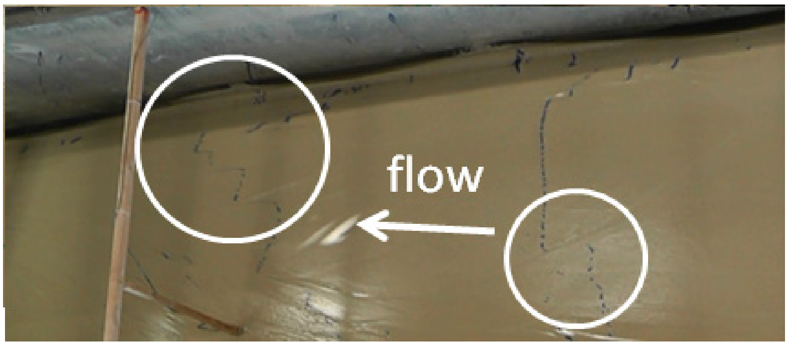


Fig. 3 Smooth channel profile (top) and trapped velocity profile (bottom)

Along with the change from stepped to continuous velocity profiles, the mud level increases, indicating that the mixture starts to segregate and sand is deposited. The mixture characteristics corresponding to the start of deposition are shown in Tab. 2.

Tab. 2 Mixture characteristics at the onset of deposition.

Test [-]	**Density** [kg/m^3]	**Water content** [%]	**SFR** [-]	**Peak strength** [Pa]
3.1	1454	314	1.62	6.8

3.2 SEDIMENTATION

As from test 3.1 the mud line is increasing with corresponding deposition of solids. The absolute development of the mud layer during test 3.1-3.4 is presented in Fig. 4. The rate of mud-level rise decreases in the subsequent experiments; this is related to the decrease in sand content of the mixture. It is observed that test 3.2 yields minor sedimentation, which is caused by the short duration of test 3.2 (2 hours). Sedimentation velocities measured from bathymetry scans are in the range 3-25 mm/hr. The decrease in strength of the slurry is also influencing the equilibrium slope of the mud-line as is shown in Fig. 5. The decrease in strength causes the mixture to adapt a flatter equilibrium slope, the measured slopes are in the same range as measured by Fitton et al. (2006).

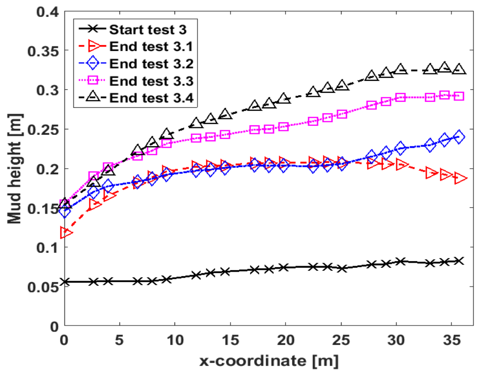


Fig.4 Mud level development during the subsequent experiments of test 3.

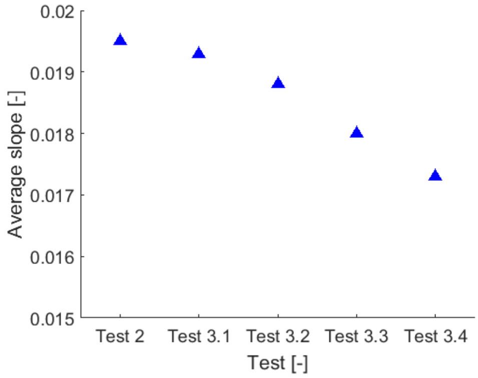


Fig.5 Average slope per test.

3.3 CHANNELIZATION

Both real time observations as video data show an ‘erosion-hole’ or slump at the head of the channel see Fig.6 and Fig. 7. This jump moved in upstream direction causing the channel to increase in length. Bathymetry laser scans show a relative decrease in mud height at the location of the flowing channel, indicating a steeper slope in the channel than at the adjacent parts.

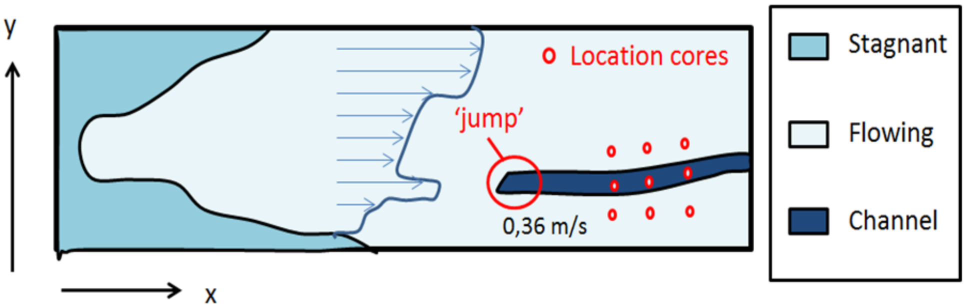


Fig. 6 Observed channel, slump/erosion hole and location of cores.

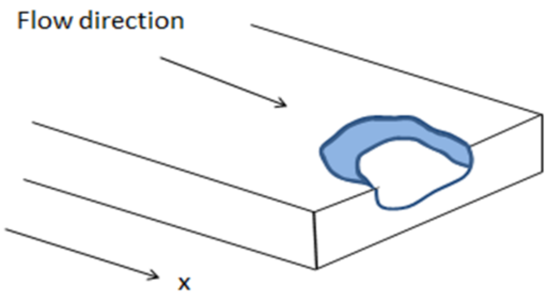


Fig.7 Erosion hole/slump observed at head of channel

3.3 CORE ANALYSIS

After formation of a channel the experiment was stopped and cores were taken at multiple locations both in flowing and stagnant parts, see Fig. 6. The cores were cut in ‘slices’ and analyzed on PSD and water content. Subsequently vane-measurements were conducted at similar locations at different depths of the bed. As shown in Fig.8 and Fig.9 it is found that the water content, sand content and strength do not differ significantly between flowing and stagnant parts (thus in y-direction). The properties however do vary over the vertical as a result of segregation and consolidation. Similar observations were found for the particle size distribution over the height of the bed.

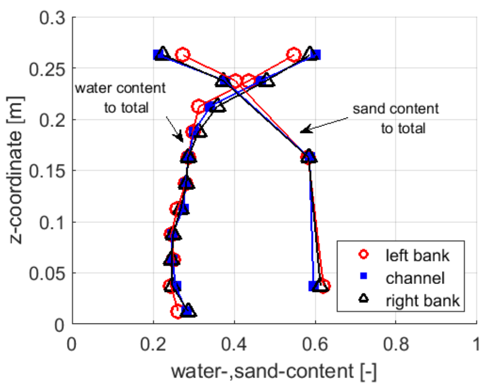


Fig.8 Water-, sand content over the height of the bed for stagnant and flowing part.

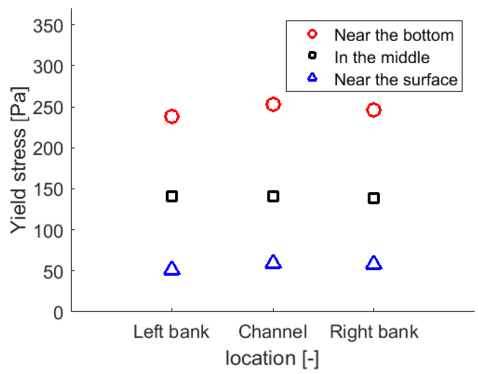


Fig.9 Strength measurements of the bed for stagnant and flowing part.

4. CONCLUSIONS

The following conclusions are drawn from observations and analysis of the large-scale flume experiments conducted at Deltares:

1. Sand particles can be conveyed in dense clay/sand slurries, without measurable/significant segregation, for at least 50 meters if the peak strength of the mixture exceeds 6.8 Pa.
2. The flow behavior changes with decreasing strength from slow and constant to a more dynamic flow with channel formation.
3. Accompanied with this change in flow behavior, the surface velocity profile was changing from a stepped profile with elongated shear planes to a smooth and parabolic profile.
4. The mixture changes from non-segregating to segregating corresponding to above mentioned changes.
5. Analysis of cores and strength measurements show that no significant difference exists in PSD, water content and strength between flowing and stagnant parts.
6. Bathymetry measurements show that the mud height of the flowing part in a channel is lower than the stagnant parts; this implies that the slope in the channel is steeper than at the adjacent stagnant parts.
7. The decrease of strength of the mixture causes the slope of the mud line to decrease during the experiments.

PRACTICAL APPLICATIONS

These preliminary observations appear to suggest that strength is determining the flow-characteristics (sheet, channel-flow), hence segregation of sand particles. This implies that segregation could be minimized by controlling the rheological properties (i.e. strength) of the mixture. Non-segregating (homogeneous) slurry is of interest for mining and land reclamation activities because of homogeneous bearing strength, consolidation and maximization of fluid fine capture in the deposit. Analysis of cores substantiates a homogeneous bed layer, since the sand and water content are reasonably constant in the bottom part. To quantify the capacity of containment basins, the beach slope of the stored slurry is essential. The described flume experiments provide full-scale data to develop a beach slope prediction tool. It is to be noted that these are preliminary conclusions that may change as the analysis of the data (and numerical modeling activities) continue.

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