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# LATEST NUMERICAL DEVELOPMENTS FOR THE PREDICTION OF BEACHING FLOW AND SEGREGATING BEHAVIOR OF THICK NON-NEWTONIAN MIXTURES

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Improving the understanding and predictability of tailings or slurry management reduces the risk, the liability and the cost of mining, dredging, and land reclamation activities. Some of the key questions related to tailings or slurry refer to deposition behavior; beach slopes; segregation of coarse and fine fractions; consolidation, strength development and stability of ultra-soft deposits. The knowledge of the basic processes is still limited and predictive tools are largely based on practical experience gained through "business as usual". With these challenges in mind we have recently developed a new numerical module, Delft3D-Slurry, which is designed to predict the deposition behavior and consequent particle size distribution or segregation of thick and diluted sand-mud slurries or tailings to aid to design, operation, management and reclamation of tailings or slurry deposits. Delft3D-Slurry is an extension of the open source Delft3D modeling suite. Delft3D-Slurry specifically includes the non-Newtonian and sand particles settling in viscous slurries physics. Here we present the results of preliminary tests of the Delft3D-Slurry model implemented to simulate beaching (subaereal deposition) of thick non-segregating tailings (NST) as well as diluted Whole Tails. The model well reproduced non-segregating non-Newtonian (plug) flow velocity profile for thick NST, while it reproduced strongly segregating near-turbulent flow for whole tailings. While the module still needs careful validation, these preliminary results reproduced well the theoretically expected behavior as well as experimental observations on oil sands tailings. Given these encouraging preliminary results, the authors invite the community to join the development of this module by sharing knowledge, experience, data or key practical challenges.

KEY WORDS: sand-mud-water mixtures deposition, numerical model, sand settling, sand segregation, non-Newtonian flow.

## NOTATION

$C_{mix,y}$= model parameter Bingham yield stress
$C_{visco}$= model parameter Bingham viscosity
$d$ = particle size
$g$ = gravitational acceleration
$k$ = model constant hindered settling
$n_f$= fractal dimension parameter
$R_{\mathrm{mix}}$= variable in rheology model mixture
$w_{sand}$ = settling velocity of a conc. of grains
$w_{sand,0}$ = settling velocity single grain

$\Phi_{fines}$ = volumetric concentration fines
$\Phi_{mix}$= volumetric conc. fines-sand mixture
$\Phi_{sand}$=volumetric concentration sand
$\mu_{\mathrm{a,cf}}$ = local apparent viscosity of carrier fluid
$\mu_{\mathrm{mix}}$= Bingham viscosity of mixture
$\rho_{cf}$ = density sand carrier fluid
$\rho_{sand}$= grain density sand
$\tau_{\mathrm{mix,y}}$= Bingham yield stress of mixture

# 1. INTRODUCTION

One of the biggest uncertainties affecting the operations in mining, land reclamation and dealing with contaminated sediments are related to tailings or slurry management. This is especially so when these activities move toward areas or applications comprising higher fines (mud) and less sand.

Improving the understanding and predictability of tailings or slurry management reduces the risk, the liability and the cost of these operations. Next to that, it opens the way for innovative approaches and engineering concepts. Some of the key questions related to tailings or slurry, hence sand-mud mixtures management refer to deposition behavior; beach slopes; segregation of coarse and fine fractions; consolidation, strength development and stability of ultra-soft deposits.

While the need for engineering solutions in these areas increases, the knowledge of the basic processes is still limited and predictive tools are largely based on practical experience gained through “business as usual”.

With these challenges in mind we have recently developed a new numerical module, Delft3D-Slurry, which is designed to predict the deposition behavior and consequent particle size distribution of thick sand-mud slurries or tailings. While it is recognized that a detailed description of flow, deposit build up and particle size distribution of a tailings, slurry, dredged material deposit is impractical, this model aims at reproducing the general main characteristics of the deposit (e.g.: amount of sand segregation, fines capture, areas with predominant sand or fines deposit) such to aid to the design, operation and management, of a tailings basin or land reclamation.

This module includes non-Newtonian as well as sand settling physics, and it is based on the Delft3D engine, including all its basic functionalities. Delft3D (https://www.deltares.nl/en/software/delft3d-4-suite/) is the open source numerical tool developed and maintained by Deltares that is used in hundreds of consultancy and research projects worldwide for coastal and riverine water quality, morphological, and hydrodynamic studies.

A comparable approach, but limited to a 1-D vertical numerical calculation of velocity- and concentration profiles, was pursued by Spelay (2007). Profiles were successfully calculated, but it appeared that it is not easy to solve the coupled system of equations in which flow field, particle settling and rheology are mutual dependent on each other.

The Delft3D-Slurry, module, while still under development, was successfully applied to a few test cases of subaereal dense and diluted tailings deposition, with satisfactory results. In this paper we present the theoretical background of this module together with some of the preliminary results. We then conclude with a trajectory forward for further validation and implementation, with opportunity for the engineering and scientific community to join in the model development, sharing knowledge, data or providing key questions to be addressed.

## 2. THEORETICAL BACKGROUND

In this section the theoretical background included in the Delft3D-Slurry module is presented with focus on the physics of sand settling in non-static fines-water mixtures (Talmon et al. 2014) and its influence on the rheology of the sand-mud-water mixtures.

Here the mud particles have very small (at the depositional temporal scale, virtually zero) settling velocity, constituting, together with the water phase, the carrier fluid. The sand particles float in the carrier fluid, settling at a velocity that depends on the density and diameter of the sand particles, the rheological properties of the carrier fluid and its shear rates. At the same time, the sand particles influence the viscosity of the slurry mixture. The entire water-mud-sand mixture behaves as a Bingham fluid. This general physics is included in Delft3D-FLOW (the hydrodynamic engine of the Delft3D suite) with the formulation described in the Section 2.2 for sand settling physics, and in Section 2.3 for the influence of sand to the rheology.

### 2.1 SUMMARY OF KEY FEATURES OF DELFT3D-FLOW

Delft3D-FLOW solves the horizontal momentum equations of an incompressible fluid flowing with a mobile air-water surface as well as solves the equation(s) for the mass-conserving advection-diffusion transport of a scalar property or constituent such as salinity, heat content (temperature) and sediment (fractions): a drift flux model. For the latter their settling velocity, bed erosion or deposition and optionally consolidation (Gibson equation) are included but can be eliminated by parameter settings on input.

We consider the water-mud-sand mixture as a quasi-single phase fluid of which their summed or total momentum equations are solved rather than the momentum equations per sediment fraction. The transport of each scalar constituent, however, is solved per fraction or scalar constituent because of their possible differences in mixing, settling and sources and sinks for salt, heat, and sediment.

Preferably, for turbulence exchange of horizontal momentum as well as for turbulence mixing of scalar properties, Delft3D-FLOW applies the k-ε turbulence model including damping of turbulence (mixing) by density stratification of salt, temperature as well as by suspended sediment concentration(s), considered as a quasi-single phase fluid. Similarly, in the momentum equations Deflt3D-FLOW applies the baroclinic pressure due to all previous contributions by density stratification in an incompressible fluid. We experienced that turbulence damping by density stratification dominates viscous damping of turbulence that occurs at its decaying state. Therefore, we apply the high-Reynolds number version of the k-ε model whit the option of including low-Re corrections.

### 2.2 SETTLING OF SAND IN WATER-MUD MIXTURE

The settling velocity of sand grains is determined by their diameter, density and fluid viscosity. For sand grains settling in a dense water-mud mixture, the low-Reynolds Stokes Law is assumed to be applicable by using the apparent viscosity of the clay-water mixture (Talmon and Huisman, 2005). The settling velocity of a single sand grain in a carrier fluid flow subjected to shear flow is:

$$w_{sand,0} = \frac{gd^2\left(\rho_{sand} - \rho_{\mathrm{cf}}\right)}{18\mu_{a,\mathrm{cf}}} \tag{1}$$

The local apparent viscosity of the carrier fluid $\mu_{\mathrm{a,cf}}$ is calculated on basis of local shear rate of the mixture.

The settling velocity of the solitary grain is reduced by the return flow imposed by the settling of all grains. Inspired by the Richardson & Zaki (1954) concept the final hindered settling velocity $w_{\mathrm{sand}}$ for the sand fraction, Sisson et al. (eq. 6, 2012) propose the following equation for hindered-settling of sand in mixtures:

$$w_{sand} = w_{sand,0}\left(1 - k\phi_{sand}\right)^{3.1} \quad ; \quad k = 1.72 \tag{2}$$

### 2.3 RHEOLOGY OF SAND, MUD, WATER MIXTURES

The rheological formulation for the influence of sand is currently based on the fractal theory developed by Winterwerp (Winterwerp and van Kesteren, 2004). This theory is originally developed for diluted to moderately thick mud mixtures that are typically found in marine or estuarine environment (e.g. fluid mud). While the authors recognize that there are formulations that are better suited for thick mixtures, this formulation is heritage of utilizing the Delft3D engine, hence a first logical choice. Additional formulations will be included as part of continuous development of this module.

This mixture behaves as a Bingham fluid with a yield stress as well as a (Bingham) viscosity. Both properties depend on the volume fractions of both the sand (coarse) plus fines through the ratio, whereas the latter is constant:

$$R_{mix} = \left(\frac{\phi_{mix}}{1 - \phi_{mix}}\right)^{\frac{2}{3-nf}} \quad ; \quad \phi_{mix} = \phi_{sand} + \phi_{fines} \tag{3}$$

The parameters for the fine fraction are set such that fines remain homogenous distributed in the carrier fluid. In (Eq.3) the volume fraction of all solids (coarse and fine) in the mixture is accounted for. The fractal dimension is set to $n_f = 2.15$ yielding $2/(3-n_f) = 2.35$. Using (Eq.3), the yield stress of the mixture reads:

$$\tau_{mix,y} = C_{mix,y} R_{mix} \tag{4}$$

And the (dynamic) Bingham viscosity (the slope in rheogram of shear stress versus shear rate):

$$\mu_{mix} = C_{visco} R_{mix} \tag{5}$$

## 3. APPLICATION OF THE MODEL

The new module, formulated as discussed in Section 2, was applied to simulate thick and diluted tailings deposition on subaereal beaches.

Based on previous experimental observations on oil sands tailings (Sisson et al., 2012) three different tailings mixtures were simulated with the new Deflt3D-Slurry module, approximating thick non-segregating tailings (NST), thick mildly segregating tailings (Weak NST) and diluted whole tailings (Whole Tailings). The rheological parameters of the tailings were calibrated through visual observation of the model results by changing the power of the fractal dimension parameters and the hindered settling (see Italic in Table 1) as to match experimental observations on Canadian oil sands tailings. In these experiments, little segregation was observed in thick NST, with the full depth of the flume flowing, yet at much smaller velocity near the bed (likely due to gelled bed). For the Whole Tailings case instead, full segregation of the sand occurred, which formed a thick steady granular bed and a fines-rich overlying flow with turbulent river-like characteristics. The input parameters for these three tests are given in Table 1.

Table 1: Parameters for the Delft3D-slurry simulations for NST, Weak NST, and Whole Tails. Beach length, Slope and Flow rate per unit width were kept constant at 400 m, 0.007 and 0.1 $m^2/s$ respectively.

| **Parameter** | **NST** | **Weak NST** | **Whole Tails** |
|---|---|---|---|
| Mixture density [$kg/m^3$] | 1700 | 1600 | 1200 |
| Volumetric concentration fines $\Phi_{fines}$ [-] | 0.074 | 0.074 | 0.074 |
| SFR [-] | 5 | 5 | 1.1 |
| Bingham yield stress carrier [Pa] | 1 | 1 | 1 |
| Bingham viscosity carrier [Pa s] | 0 | 0 | 0 |
| Median grain size sand $d$ [mm] | 0.2 | 0.2 | 0.2 |
| Bingham yield stress parameters mixture $C_{mix,y}$ [Pa], $n_f$ [-] | $C_{mix,y}=30$,<br>$n_f=2.15$ | $C_{mix,y}=30$,<br>$n_f=2.33$ | $C_{mix,y}=30$,<br>$n_f=2.60$ |
| Bingham viscosity parameter mixture [Pa s] | $C_{visco}=0.252$ | $C_{visco}=0.252$ | $C_{visco}=0.252$ |
| Bingham yield stress mixture at inlet $\tau_{mix,y}$ [Pa] | 17 | 17 | 0.5 |
| Bingham mixture viscosity at inlet $\mu_{mix}$ [Pa s] | 0.14 | 0.14 | 0.004 |
| Power Richardson-Zaki (eq.2) | *3.1* | *0.5* | *0.5* |

Figure 1 shows the results for simulations of subaereal tailings discharge of the new module in 2DV (two dimensional vertical) mode. A longitudinal cross section (x-z) of 400 m long subaereal beach deposit is depicted after about 40 minutes of slurry deposition for NST, Weak NST and Whole Tails. Note that these results are a snapshot of the model after 40 minutes during deposition, not a final stratigraphy. Specifically for the

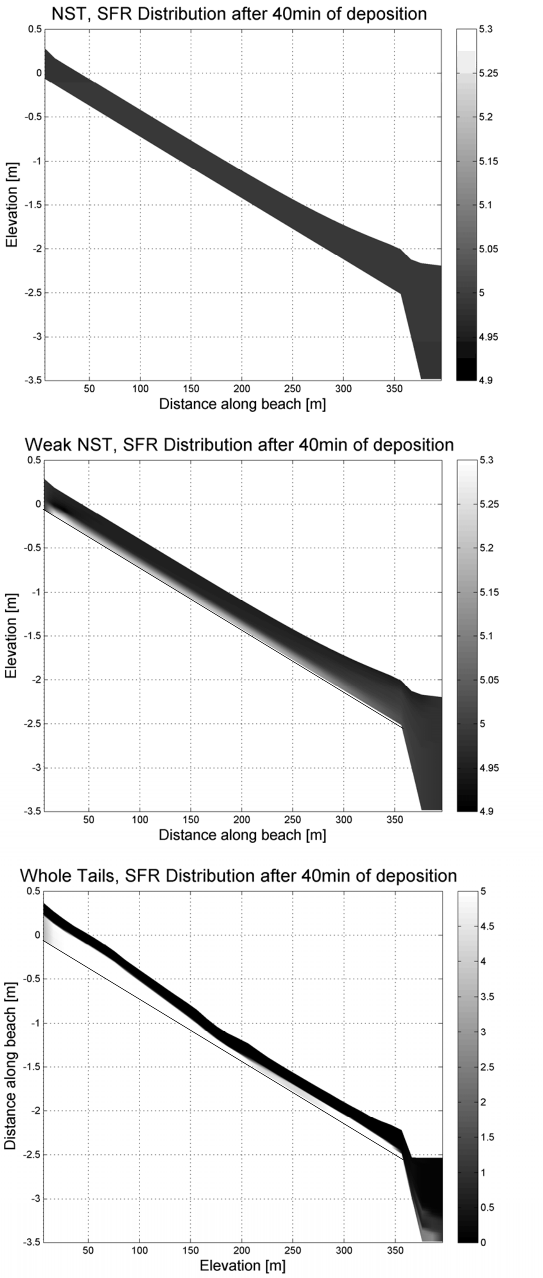

Fig.1 Delft3D-slurry results for NST (top), Weak NST (center), and Whole Tails (bottom) mixtures. These plots represent a x-z cross section along a 400 m beach after 40 minutes of slurry deposition. The grey scale indicates ratio between sand and fines (white indicates mostly sand).

Whole Tails case, the layer of fines is still flowing and would end up in the pond leaving the sandy bed behind when discharge is shut down. The Whole Tails has initial densities of about 1200 kg/m$^3$ and ratio between sand and fine fractions (SFR) of about 1; Weak NST and NST mixtures have initial SFR of 5 and densities of about 1600 and 1700 kg/m$^3$ respectively. These figures are depicted in SFR to highlight the particle size distribution of the deposit (in gray scale, dark indicates low SFR or large fraction of fines, and white indicates mostly sand).

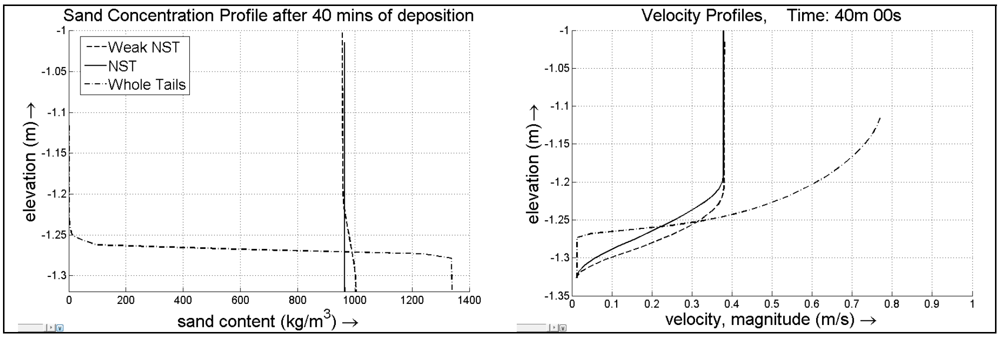

Fig.2 Sand concentration (left) and flow velocity x-z profiles for NST, Weak NST Whole Tails mixtures (right), after 40 minutes of slurry deposition and about half way along the 400 m beach.

In addition, Figure 2 illustrates two (x-z) profiles taken at mid-beach length and after about 40 minutes of deposition for velocity and sand concentration. NST (Figure 1, top) produces a uniform deposit with SFR distribution that remains almost equal to the SFR of the discharged mixture. At the same time, Whole Tails (Figure 1, bottom) produce a completely segregated deposit, with sand dropping from the mixture and forming a sand-rich bed layer, while most of the fines carry on into the basin. Weak NST has a behavior similar to the NST, however with some sand settling and sedimentation near the bed. This behavior is highlighted by the sand concentration and velocity profiles depicted in Figure 2. The concentration profile shows nearly uniform sand concentration for the strong mixture and partial segregation for the medium mixture. For the weak Whole Tails mixture, virtually all sand segregates forming a distinct sand bed layer. Consistently, the velocity profiles shows plug-flow profile for NST, while Newtonian profile for Whole Tails. It also shows that sand form a static (granular) bed that is not flowing with transport of sand and fines governed by classical river sediment transport physics.

## 4. DISCUSSION AND TRAJECTORY FORWARD

This new module was developed extending the robust and extensively validated and applied Delft3D code to reproduce non-Newtonian flow and sand settling behavior. As highlighted in the introduction, this module does not have the (unrealistic) purpose to capture the deposition pattern in details, but to reproduce its main and most important characteristics to aid management, design or reclamation of thick sand-mud deposits.

To date, this module has been tested simulating idealized tailings deposition of different density with focuses on sand settling and segregation pattern. As in previous experimental tests, this module is until now tested in 2DV model (long narrow channel) with constant input discharge and wet initial conditions, to verify reproducibility of rheology and sand settling. This is a logical first step in model development. Even if a proper validation and rigorous rheological analysis is necessary, this module well reproduces typical observed behavior, proving to be a good tool for this type of applications. This model is not yet tested (and designed) to reproduce the beach profile correctly, which need longer simulations and three dimensional effects.

The authors recognize that three dimensional effects (such as channelization, meandering, wet and drying and multiple discharges), as well as time dependent effects (thixotropy and consolidation) are important factors that influence sand settling and (especially) beach geometry (e.g. concavity). The Delft3D engine and schematization allows for easy expansion to 3D, and it is designed to handle drying and flooding. This module will be extended to 3D as soon as the 2DV version is properly validated. In addition, this module does not yet include thixotropic or time dependent effects. While Delft3D does have a simple function that includes consolidation and consequent increase of bed shear stress for erosion, this does not extend to influencing the rheology of the fluid. This represents additional material for model improvement.

Yet, the most proficient manner to test the model and make decisions about accuracy and necessary development is against (large scale) pilot (e.g. the recent Deltares slurry deposition flume test, van Kesteren at al. 2015) or field data, and together with the end user. It is our intent to apply this model to these data as they are made available. This paper is therefore also an invite to share the data and join in the development of this promising module.

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