OPTIMIZING TAILINGS DEPOSITION TO MAXIMIZE FINES CAPTURE: LATEST ADVANCE IN PREDICTIVE MODELING TOOLS

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ABSTRACT

Improving the understanding and predictability of tailings or slurry deposition reduces the risk, the liability and the cost of mining, dredging, and land reclamation activities. Some of the key questions refer to: deposition behavior; beach slopes and geometry; segregation of coarse and fine fractions.

In this paper we discuss flow and sand segregating behavior of fines and mixed tailings when flowing down a beach. We present preliminary numerical simulations performed with a new special module of Delft3D dedicates to tailings and non-Newtonian flow deposition, which includes slurry rheology and shear-induced sand settling processes. Delft3D is an open source numerical modeling suite developed and maintained by Deltares used world-wide for coastal, riverine and morphological studies. The tailings module is being thoroughly tested against analytical solutions and laboratory experiments. The model captures typical non-Newtonian plug-flow velocity profile, sand settling behavior and the formation of a slow-flowing sand rich gelled bed layer near the beach – slurry interface. Particle size (or sand to fines ratio) distribution and flow characteristics will be presented for different tailings of varying density and sand content, when flowing along a beach. When applicable, the results will be presented in sand to fine ratio to estimate sand capture along the deposit.

This model proves to be a useful tool to improve understanding of flow and segregating behavior of tailings and slurries. This model is especially beneficial to study how variation in critical parameters, such as rheological parameters, solids content, particles size distribution and flow rates influence deposition.

INTRODUCTION

Understanding and predicting the deposition behavior of tailings or slurries is critical for the mining and dredging industry, as well as for land reclamation and coastal or inland safety. Thousands of cubic meters of tailings are produced and deposited in tailings basins every day; land is being reclaimed for human developments or coastal protection at faster pace and in more remote areas; mud slides, caused by natural disaster or manmade structure failures, kill people every year. Yet, the understanding of tailings and slurries flow and depositional behavior, as well as comprehensive and validated tools to evaluate different management or protection scenarios are lacking. Deltares has set improving understanding and prediction of tailings and slurry deposition behavior as a key topic in its strategic agenda. This includes theoretical, laboratory and numerical enhancement activities.

This paper specifically focuses on the latest advance in numerical prediction of tailings deposition and sand segregation in beach above water environment. This project is a collaborative effort between Deltares, the Canadian Oil Sands Innovation Alliance (COSIA) and the Dutch Government sponsored program Topconsortium voor Kennis en Innovatie (TKI) Deltatechnologie, which promotes private – public research and development of socially impacting innovative technologies.

As part of this project, the numerical open-source software Delft3D[1], which is developed and maintained by Deltares, is being upgraded to simulate non-Newtonian fines dominated flow and sand settling behavior in non-Newtonian carrier fluids. Delft3D, in the currently open source version, includes 3D shallow water hydrodynamics (i.e. no vertical acceleration), sediment transport and water quality processes. Delft3D has been implemented to simulate delta deposits in alluvial environment, with good agreement between observed and simulated deposition characteristics, i.e. geometry and grain size distribution (van der Vegt et al. 2015) and slopes (Sheets, et al. 2014). The strategy is to build on the robust and tested numerical engine, the physical processes, and the

[1] https://oss.deltares.nl/web/delft3d

experience of Delft3D, towards the specific processes of tailings deposition behavior.

The end objective of this exercise is to provide the community with a numerical tool which is capable of predicting flow behavior and particles size distribution (i.e. fines capture) in 3D of a wide range of tailings and slurries, from diluted sand dominated tailings, to thick fine dominated non-segregating slurries. In this paper we will present the recent advance towards this objective and a strategy forward.

DELTAS AND BEACHES

Tailings or dredge material beaches have similar morphological features as natural deltas, even though the spatial scale may differ by few orders of magnitude. At very different scales, natural deltas have indeed similar features, i.e. channel pattern, delta geometry, slope. Figure 1 depicts the river delta of the Kachemak River in Alaska compared with the delta formed by cultivated field runoff. The first has extent on the order of one kilometer, the second in the order of few meters.

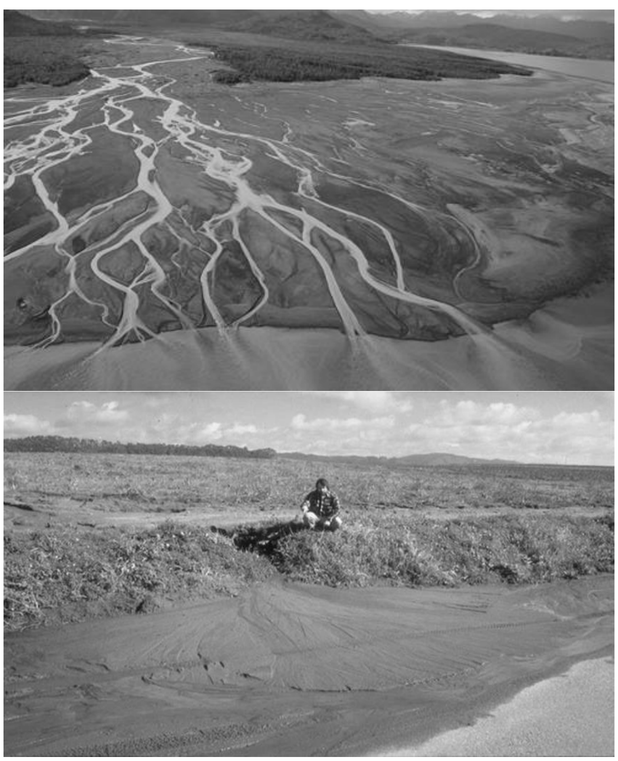

Figure 1. Natural deltas at different scales. Top: Kachemak Bay in Alaska. Source Flickr – NOAA; Bottom: Runoff from cultivated field near Pigeon Point, CA. Source: Gary Parker e-book morphodynamic.

Tailings or dredge material beaches present similar morphological features as natural deltas, where the input river is the end of a pipeline. Figure 2 shows a picture of an oil sands external facility beach, which is very comparable in morphological features to the natural deltas of Figure 1. Yet, tailings beaches may differ from natural deltas by solids densities and when fine dominated. Mining and dredging industry is indeed transitioning toward higher solids density slurries often dominated by fines (e.g. flocculated tailings, thicken tailings or non-segregating tailings). Fine dominated tailings beaches show different morphological features with less, long and stable channels terminating in flow widening lobes (Figure 3).

Figure 2. Sand dominated diluted tailings stream from oil sands external facility. Source: Google maps.

Figure 3. Fines dominated thick tailings beach, with long single channel and expanding flow. Source: B. Pirouz, ATC Williams, Australia.

TAILINGS SPECIFIC PROCESSES

Diluted sand dominated deltas are driven by typical alluvial processes that are rather well understood and implemented in numerical models such as Delft3D (van der Vegt et al. 2015). High solids concentration typical of tailings or slurry streams, and large quantity of fines induce specific tailings processes. Thick and flocculated tailings shows higher viscosity towards non-Newtonian, near-laminar or completely laminar behavior, where sand settles depending on the rheology of the carrier fluid (i.e. water plus fines) and flow regime. Settled sand form a high sand concentration layer near the bed. This layer is not static, but flows at lower velocity due to the increase viscosity induced by higher sand concentration. We call this layer gelled bed (Sisson et al., 2012). These tailings also show relatively rapid change of characteristic with time due to dewatering and thixotropy. These processes are detectable in 1D vertical or 2D vertical (e.g. a cross section along a beach). In 3D, channel width and avulsion (i.e. change in course) are likely determined by tailings rheology and sand segregation (Pirouz et al., 2013). While 2D processes have been documented, 3D behavior is still poorly understood and demand for further research.

In this paper we focus on rheology and sand settling processes, leaving thixotropy and 3D to a later stage. The theoretical framework to describe sand-fines slurry flow and segregation behavior includes a dual rheology approach (Spelay 2007, Talmon et al. 2014). The rheology of the sand-mud mixture is quantified for flow momentum simulations. The rheological parameters (inherent viscosity, Thomas 2010) of the carrier fluid (fines+water only) determine sand segregation (e.g. settling of coarse particles within the carrier fluid), which includes shear induced settling.

Three different existing rheological formulations which are traditionally utilized in different fields, i.e., industrial concentrates, tailings and fluid mud flow in natural environments, are compared and included in Delft3D. The implemented formulation utilizes Bingham-type model concept:

$$\tau = \tau_y + \mu\dot{\gamma} \qquad (1)$$

where τ is the shear stress, τ_y the yield stress, μ the plastic viscosity and $\bar{\gamma}$ the shear rate. More details on the theoretical description of the rheological models can be found in Talmon et al. (2016) and Hanssen (2016).

The shear induced hindered settling of a sand particle in a non-Newtonian flow can be described as:

$$w_{s,eff} = w_{s,0}(1-k\phi_{sol})^n = \alpha\frac{(\rho_s-\rho_{cf})gd^2}{18\mu_{apparent-cf}}(1-k\phi_{sol})^n$$

Where $w_{s,eff}$ is the effective settling velocity, $w_{s,0}$ is the non-hindered settling velocity, ϕ_{sol} is the volumetric concentration of solids, α a calibration parameter, ρ_s the density of sand particles, ρ_{cf} the density of the carrier fluid, d is the sand diameter and μ the apparent viscosity. The parameters k and n are determined empirically (Pennekamp et al., 2010; Sisson et al., 2012; and Spelay, 2007). The formula is verified with shear cell data in the work of Pennekamp et al. (2010). Confirmation is also found in shear cell tests by Sisson et al., 2012 and Talmon et al., 2014.

NUMERICAL APPLICATION TO OIL SANDS TALINGS

The three rheological analytical models and the sand settling relations were implemented in Delft3D, and verified in 1DV mode against theoretical derivations (Slatter and Williams, 2013) and experimental observations (Spelay 2007, Pirouz 2013). Details of numerical implementation and testing can be found in Hanssen (2016).

Upon verification against experimental data, the model was applied in 1DV to two typical oil sands tailings streams: low sand, high carrier fluid viscosity thickened tailings (TT), and high sand lower carrier fluid viscosity tailings streams (NST). Rheological parameters are assumed as typical tailings data to verify behavior, and are not referring to specific tailings. Table 1 reports the characteristics of the two streams.

Table 1. Characteristic of conceptual oil sands tailings mixtures.

	Cs_w*	SFR	τ_y	ρ
	%	-	Pa	kg/m^3
TT	40	0.25	40	1,330
NST	67.5	5	20	1,725

* Solids content by weight

The 1DV simulations were run to approximate simulation of tailings flow down a 1 km 1% slope at a constant 1 m^3/s flow rate and constant tailings discharge characteristics. Two fractions were included in the model: fines and sand, in addition to water. Water and fines form the carrier fluid, which in the model is not allowed to change its properties with time (i.e. zero settling of fines, no dewatering, no thixotropy). Tailings flow down a slope is a 3D process by definition, therefore 1DV simulations represents an approximation of a cross section along a beach, in one single profile that evolves in time following the flow.

Figure 4 and Figure 5 show the results of the 1DV simulations. A uniform mixture was discharged from the hypothetical pipe, and let run down the slope. The velocity (left) and sand to fines ratio (SFR, right) profiles are depicted at 100 m, 500 m, and 1,000 m along the slope. The three lines represent the three different rheological models (Hanssen 2016).

The TT simulations show a typical non-Newtonian plug-flow like velocity profile, with a sheared zone that extends for the lowest 25% to 30% of the flow. Sand settling is a function of the shear rate. The SFR profile shows decrease in sand concentration in the shear zone, and increase near the bed. Sand depletion in the shear zone and accumulation near the bed increases away from the discharge point. Flow velocity diminishes as sand concentration increases due to increase in mixture viscosity. However, even if much slower, the sand rich layer does not build a sand skeleton and continues to flow. This is consistent with the findings of Talmon (2010). Again, the three rheological models influence the sand settling behavior. The three models show rather different sand settling behavior, especially Model 1 (dashed line) from Model 2 (solid line) and Model 3 (dotted line). Model 1 is based on the Herschel-Bulkley rheological model, with exponent of the shear rate (Eqn 1) between zero and one. This model produces a less thick sheared region with locally higher shear rates. This causes a thinner layer where sand settles faster, yielding to lower sand concentration and sharper gradients. At this moment which rheological model is the most accurate for sand segregation is uncertain and under investigation. Verification likely requires specific high resolution data to be collected. Independently on the rheological models, all simulations show consistent behavior in line with theoretical expectations and experimental observations.

The NST simulation was run for a single rheological model only. This simulation shows different and, at first sight, counterintuitive behavior. The flow profile still displays a non-Newtonian plug flow profile. Since sand is only settling in the sheared velocity profile and no sand is supplied from the plug, the sand concentration directly under the plug decreases strongly. This allows for a greater velocity gradient. The sharp decrease of sand concentration at the bottom of the plug only occurs only at high sand concentrations because of a greater sensitivity of rheological parameters to sand.

As soon as sand settles, it packs up immediately with sharp increase mixture viscosity and decrease in flow velocity. The settled material comes to a halt. This is not too different from the TT simulations with Model 1, which expressed the largest sand concentration gradients. Because of the initially large sand concentration, additional sand accumulation near the bed is limited.

The last observation relates to flow velocity, which is lower in the TT case than the NST case. This is because in these concept simulations a rather viscous carrier fluid is imposed. The TT having a larger fraction of carrier fluid compared with the sand rich NST, the TT ends up with stronger mixture rheology, even at lower sand content. Rheology values where chosen in this study to highlight this behavior. This may not be the case in actual oil sands tailings.

As depicted in Figure 4 and Figure 5, this model can compute SFR profile, or average SFR if averaged, along any cross section. By comparing SFR along the beach with input SFR, fines capture can be estimated.

STEPS FORWARD TOWARDS 3D BEACH DEPOSITION PREDICTION

The latest numerical enhancement described in the previous section refer to upgrading Delft3D to simulate high solids content and thick non-Newtonian tailings, so to cover a wide spectrum of tailings properties.

Full 3D delta (or tailings beaches) simulations for alluvial systems or diluted whole tails are already possible in Delft3D open source. Delft3D includes also a full deposit stratigraphy scheme which allows keeping track of the deposited particle size distribution, as well as erosion and deposition functions with direct feedback to the morphology (Figure 6).

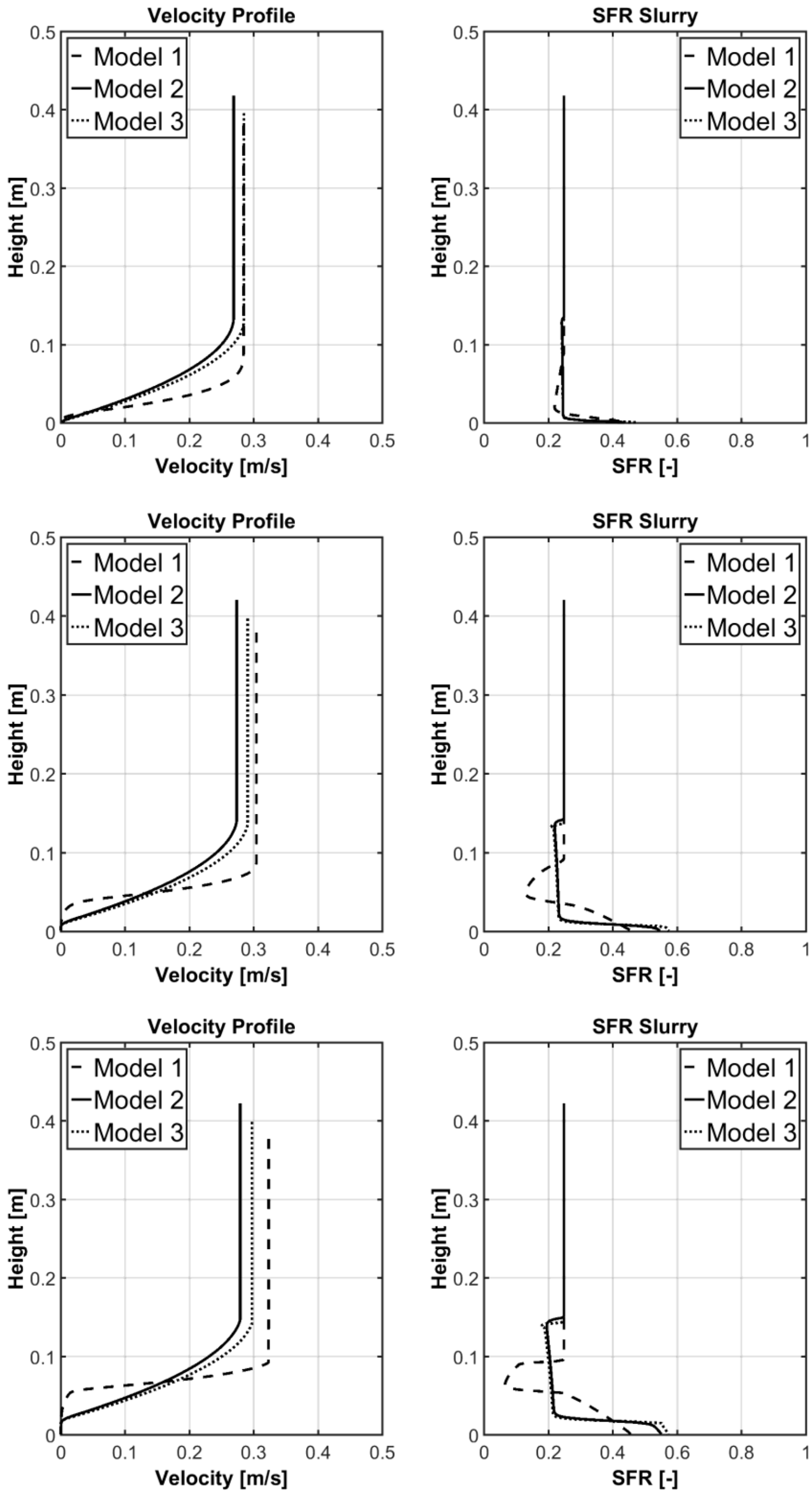

Figure 4. Results of concept TT simulations down a 1 km beach, after 100 m (top), 500 m (middle) and 1,000 (bottom). Left plots: velocity profile; right plots: SFR profiles. Three lines indicate three different rheological models.

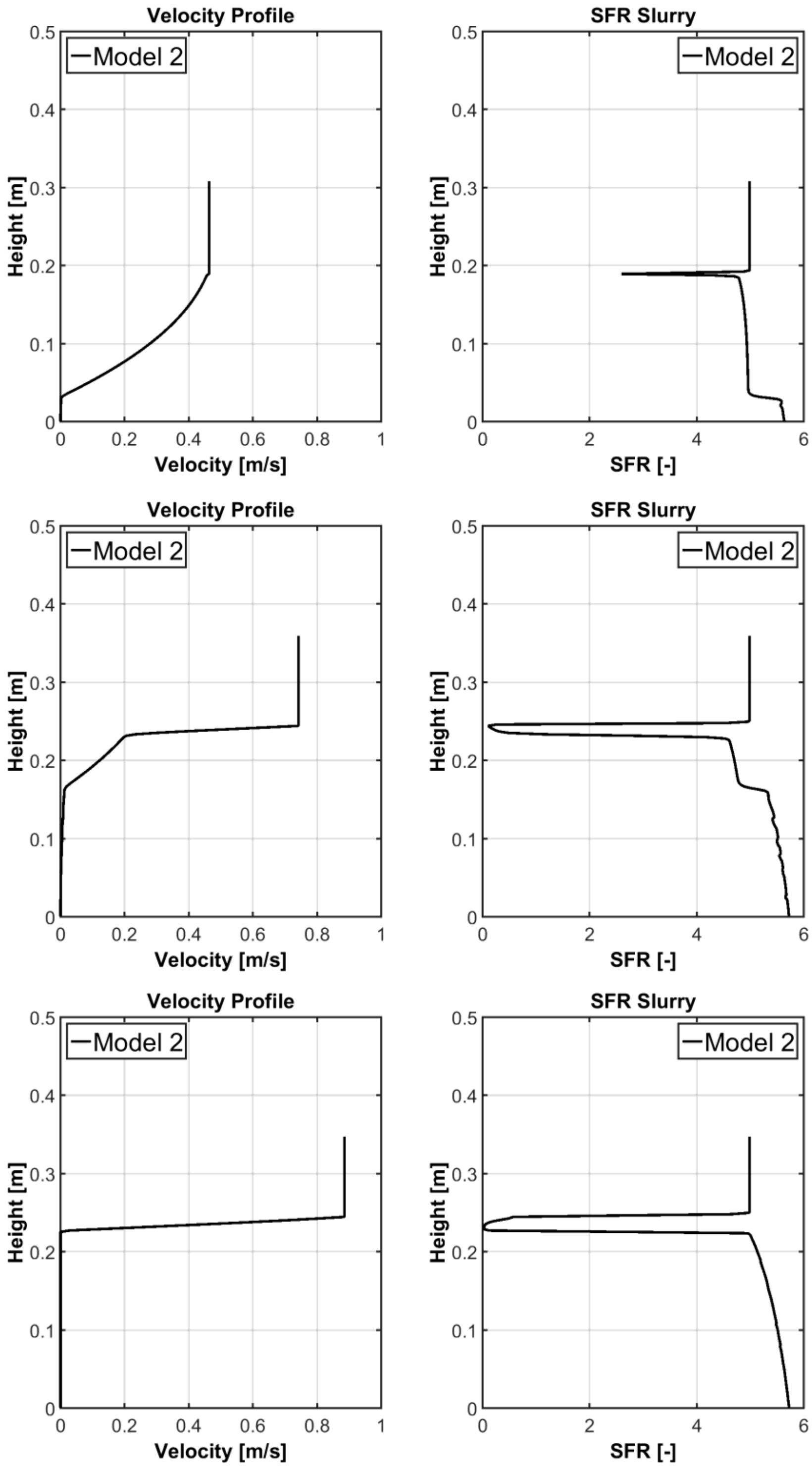

Figure 5. Results of concept NST simulations down a 1 km beach, after 100 m (top), 500 m (middle) and 1,000 (bottom). Left plots: velocity profile; right plots: SFR.

At the time of writing, the expanded Delft3D with the formulations described in the section above is being tested in 2DV mode (e.g. a beach cross section), and compared to oil sands fines capture data.

The strategy forward toward full simulation of 3D tailings deposition behavior has multiple possible paths, and can be steered by industry needs. This does not limit to numerical enhancement and simulation, but it is necessarily coupled with theoretical advance and laboratory or, better, pilot of field observations.

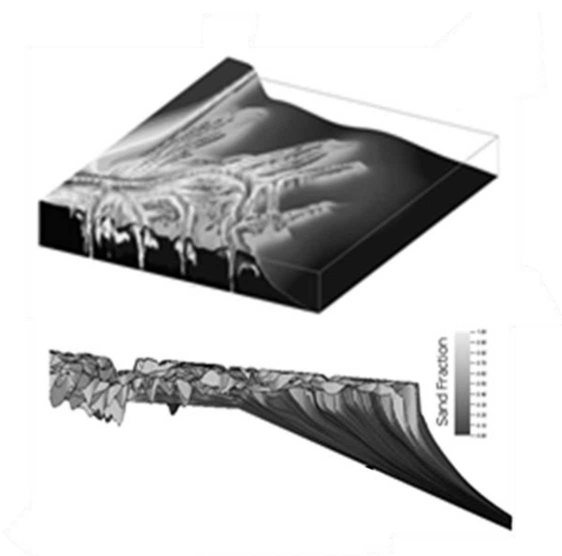

Figure 6. re-drawn from van der Vegt et al. (2015), Delft3D simulations of alluvial delta. Topography and bathymetry (top), where gray scale represents elevation; and cross section across the deposit (bottom), where gray scale represent fraction of fines (dark) and sand (light). Interesting to notice how most fines are trapped in the beach below water (BBW) section of the deposit, in line with fines capture observation in oil sands tailings beaches.

A logical path forward after testing in 2DV is to attempt 3D simulations (already within the capability of Delft3D), and to compare those to pilot or field observations. We especially expect channel width, erosion / deposition and avulsion patterns to be driving mechanisms for determining beach slope and deposit characteristics. Similarly, deposition of coarse tailings within existing fluid tailings basins represents another interesting application for which the upgraded Delft3D may be an ideal tool. In this case focus should be on 2DV processes, especially vertical mixing. If interaction with different tailings streams or co-disposal at different time intervals is the focus, dewatering and thixotropy may need to be included, driving development in this direction.

CONCLUSIONS

This paper described the most recent advance in simulating tailings and slurry flow deposition behavior for a wide range of tailings properties. The philosophy of this study is to enhance the capabilities of an existing tool, Delft3D, which is open source and used daily by thousands of people worldwide in engineering projects.

Latest results in 1DV mode were presented in this paper with direct conceptual application to typical oil sands tailings. The model reproduced non-Newtonian sand segregating behavior in agreement with theoretical expectation and laboratory observations. In depth testing and validation in 1DV and 2DV are on-going at the time of writing this paper.

Open source Delft3D has proven to be able to simulate alluvial deltas of high-level of complexity. This tailings and slurry extension has so far revealed to be adequate to simulate fundamental tailings and slurries deposition processes in 1DV. Especially this model proved to be a useful tool to show how changes in rheological parameters and sand content influence variation, sometimes pronounced, in flow and sand settling behavior, therefore implication to SFR and fines capture. As all models, this model is a tool with physically based assumptions and approximation, which, in this specific case, helps physical understanding and evaluation of possible tailings management scenarios. Therefore, it should be best utilized not alone, but aside to rheological and field tests, so to couple understanding, observations and predictions.

Here we have proposed different strategies for applications, which follow practical opportunities in line with specific industry needs. Indeed, while development never ends, the authors believe that each next step cannot be limited to numerical enhancement. An existing tool, such as the one presented in this paper, needs to be validated against pilot of field data designed for a specific application, judged on degree of accuracy, utilized accordingly, and further developed as necessary. Therefore, when properly calibrated against actual data from specific applications, this model can be utilized to evaluate different scenarios, technologies and aid tailings management decisions.

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