A research trajectory towards improving fines capture prediction with Delft3D-slurry

Phase 1

Deltares

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Title
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Delft3D-slurry, oil sands, deposition, soft sediments

Summary
Downstream the bitumen extraction process, oil sands tailings are a diluted mixture of sand, fines (silt and clay), residual bitumen, and process water. Depending on the tailings treatment technology implemented, tailings are disposed in external tailings facilities, dedicated disposal facilities, deep deposits, etc. The ability to improve the prediction capabilities of the distribution of sand and fines in a tailings deposit (as a function of, i.e. tailings densities, sand to fines ratio (SFR) and discharge rate, location and time variation) offers to the oil sands industry a cost-effective opportunity to optimize current operations and closure landscape.
This project represents a first phase of a larger research trajectory that has the general objective to improve understanding and modelling of tailings and slurries depositional flow behaviour in order to: optimize deposition operations; minimize segregation and production of fluid fine slurries (i.e. maximize fines capture); and support the design of the closure landscape or land reclamation projects. The specific objective of Phase I is the development and testing of the new Delft3D-Slurry (D3Ds) to predict tailings flow behaviour and sand segregation for various rheological properties and SFR along a typical beach cross section in two-dimensional configuration (i.e. 2DV).

This first phase includes:
1 A review of COSIA oil sands tailings fines capture data;
2 A review, modification and embedding in D3Ds of rheological and sand settling analytical models to specifically describe depositional flow and sand settling behaviour of tailings and soft sediments; and
3 The application of the new D3D-2DV model to oil sands tailings.

This study concludes with an assessment of model accuracy and purpose, data needs and steps forward.
This first phase produced various separated deliverables: two MSc. theses (Hanssen, 2016 and van Es, 2017), three conference publications (e.g. Talmon et al., 2016, Sittoni et al., 2016 and Sittoni et al., 2017), and a potential D3Ds workshop organized in Calgary in the fall of 2017. This report represents an overarching executive summary document that summarizes the most important findings of this phase, with specific reference to all these separate deliverables.

Reference
- COSIA contract #: 40-TE0028-16-145-0;
- TKI reference #: DEL035;
- Deltares Project #: 1220182

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	Oct. 2017	Arno Talmon		Bas van Maren	BM	Frank Hoozemans	
		Luca Sittoni					
		Jill Hanssen					

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Contents

1 Introduction

This report summarizes the activities and the findings of the project “A research trajectory towards improving fines capture prediction: verification, application and improvement of Delft3D-slurry – Phase I”, a collaborative project between COSIA and Deltares with COSIA reference number: 40-TE0028-16-145-0. This project is co-financed by COSIA and the Topconsortium voor Kennis en Innovatie (TKI) Deltatechnologie program with TKI reference number: DEL035. The TKI program is a Dutch Government sponsored program that supports knowledge and tools development in collaboration with industry partners. This project is performed by Deltares in close collaboration with the Delft University of Technology (TUD), Department of Mechanical Engineering, Marine Technology & Materials Science under the guidance of Prof. Cees van Rhee, with IMud (Prof. Han Winterwerp) and with contribution of Barr Engineering Co..

While this report refers specifically to oil sands tailings and oil sands terminology, the major findings of this study, the tool and the developed knowledge can be applied to slurries, sludges and mud flows in a broader sense. Potential alternative applications are the utilization of mud to build flood defences, artificial islands or land reclamation as part of “building with mud”.

1.1 Objectives of this project

This project represents a first phase of a larger research trajectory that has the general objective to improve understanding and modelling of tailings and slurries depositional flow behaviour in order to: optimize deposition operations; minimize segregation and production of fluid fine slurries (i.e. maximize fines capture); and support the design of the closure landscape or land reclamation projects.

The specific objective of Phase I is the development and testing of the new Delft3D-Slurry (D3Ds) module (see Section 2.2) to predict tailings flow behaviour and sand segregation for various rheological properties and sand to fines (SFR) ratio along a typical beach cross section in two-dimensional configuration (i.e. 2DV).

1.2 Project organization and major activities

This project is managed by Deltares, with Luca Sittoni, MSc. in the role of Project Manager and Dr. Arno Talmon as Principal Technical Investigator. Two Master of Science (MSc.) Theses were produced during this project (Hanssen, 2016 and van Es, 2017) under the supervision of Prof. Cees van Rhee (TUD), and co-supervision of Prof. Han Winterwerp (Deltares and IMud). Jill Hanssen and Hugo van Es were hosted at the Deltares office in Delft during their thesis and daily supervised by Deltares staff. The two MSc. theses are an integral part of the deliverables within this project phase.

The scope of Phase I as described in the proposal:

- Task 1: COSIA data collection and analysis;
- Task 2: Optimization of the 2DV model:
  1. Comprehensive rheological and sand settling analytical model assessment;
  2. Implementation of the rheological and sand settling models described in Task 2.1 in D3Ds-1D (1DV);
  3. Implementation in and improvement of D3Ds-2DV

4. Upgrading D3Ds to main stream Delft3D

Task 3: Verification and validation of D3Ds against oil sands data

D3Ds is developed from an existing research version of Delft3D (Delft3D-slib) originally developed to simulate underwater concentrated mud flows (Delft Hydraulics, 2007). This version was modified to model laminar thick tailings flow, of which a demo version was reported by Sittoni et al., (2015). Starting from this version as modelling foundation, the main activities of this study include:

- Collection and analysis of oil sands data received by COSIA (in van Es, 2017) – Task 1;
- Literature survey for rheological models for fines – sand tailings flow, and theoretical formulation adapted to D3Ds (in Hanssen, 2016) – Task 2.1;
- Definition of sand settling formulation based on existing literature (in Hanssen, 2016) – Task 2.1;
- Embedding of three rheological models and the sand settling formulation in the one-dimensional version of D3Ds (1DV) and verification of model behaviour against literature data (in Hanssen, 2016) – Task 2.2;
- Embedding of the development verified with the 1DV model in D3Ds, by Deltares software department – Task 2.3;Testing and verification of D3Ds in two-dimension (2DV) (in van Es, 2017) – Task 2.3;
- Upgrade D3Ds to the standard Delft3D development line, by Deltares software department – Task 2.4;
- Concept test cases on oil sands tailings (in van Es, 2017) – Task 3;
- Initial comparison of these data to model results (in van Es, 2017) – Task 3;
- Application of the new D3Ds to an Imperial Oil (IOL) case study – parallel to this project partially financed by IOL.

The summary of the major finding per activity are presented in this report. For detailed information the reader is referred to the various deliverables of this project, described in the following section.

1.3 Deliverables

The deliverables of this project include:

1. This report;
2. The MSc. theses of Jill Hanssen (Hanssen, 2016) and Hugo van Es (van Es, 2017);
3. Three conference publications developed during this project:
   - 3.1 Talmon et al. (2016), presented at PASTE 2016 in Santiago del Chile;
   - 3.2 Sittoni et al. (2016), presented at IOSTC 2016 in Lake Louise, Canada;
   - 3.3 Sittoni et al. (2017), presented at the 2017 COSIA Innovation Summit.
4. The executable of D3Ds, version of March 2017 (the latest version available);
5. A workshop on D3Ds background and basic setup to be organized in Calgary in November 2017.

Deliverable 1, this report; this includes the summary description of the project objective, organization and major findings. This report is effectively an overarching executive summary.

Deliverable 2, the two Master Theses; these include the detailed theoretical and numerical description of the model development, verification and results. These also include the available data utilized for model verification. The Hanssen (2016) thesis focuses on the theoretical description of the non-Newtonian rheological and sand settling models and their implementation in a one-dimensional version of D3Ds (the so-called 1DV model). The thesis of Van Es (2017) brings the work of Hanssen (2016) forward to two-dimensional implementation and conceptual verification of flow and sand settling behaviour for a range of rheological properties and sand concentrations (i.e. SFR), and conceptual modelling of co-deposition. The work of van Es concludes the scope of this Phase I. Hanssen and van Es' theses also touch on general slurry and tailings deposition behaviour based on the available international literature, giving an overview of the available theory and most important processes. In addition, these theses go in more depth about Delft3D and the underlying physics and equations.

Deliverable 3.1 is developed from Hanssen's thesis; it focuses on the rheological models and their implementation in 1DV. Deliverable 3.2 is developed from both Hanssen and van Es' theses; it describes the sand settling formulation and it conceptually applies the new 1DV model to thickened tailings (TT) and non-segregating tailings (NST) cases. Deliverable 3.3 shows various applications of D3Ds to tailings deposition along a beach cross section (i.e. in two dimensional mode – 2DV). These include deposition of tailings with various rheological properties, deposition of fresh tailings over old tailings and long term deposition (i.e. fresh tailings over fresh tailings). Deliverable 3.3 is developed with the results of van Es' thesis and the results of a conceptual study performed for Imperial Oil (IOL). It describes the application of the new D3Ds model to simulate deposition and co-deposition of TT and fluid fine tailings (FFT). The detailed description of this study can be found in the Deltares report titled "Task 2A: IOL TT and FFT flow, segregation and mixing dynamics" delivered to IOL (Dave Rennard) in June 2017 (Deltares, 2017).

Deliverable 4 is the executable file of the latest version of D3Ds (version March 2017) developed during this project, all input files needed for model setup and the post-processing tools for basic visualization and analysis of the results. These files can be delivered together with this report or during the November 2017 D3Ds workshop.

Deliverable 5 refers to the November 2017 workshop about application and use of D3Ds, developed during this project, in the oil sands industry context.

2 Background

This section includes: a general description of the fundamental theory underlying tailings flow deposition and sand settling; a brief overview of Delft3D and D3Ds; a list of possible applications of D3Ds as well as examples of where D3Ds should not be used; and a list of data necessary to setup and run D3Ds and to verify or calibrate the model.

2.1 Fundamental non-Newtonian flow and sand settling theory

As the solids concentration of tailings increases and SFR decreases (i.e. higher fines content, where fines are defined as particles with a diameter less than 44 um), tailings transition from diluted Newtonian behaviour to thick non-Newtonian. The transition from Newtonian to non-Newtonian is still open research ground.

With the objectives of minimizing production of fluid fine tailings, decreasing water volumes and accelerating consolidation time, the oil sand industry is producing more and more tailings in the thick non-Newtonian regime. Thick oil sand tailings show non-Newtonian, near-laminar or completely laminar behaviour. Sand is observed to settle depending on tailings density and discharge operations. Thick non-Newtonian sand – fines tailings mixtures can be described as a two-phase flow:

1. The carrier fluid, which includes fines and water; and
2. Coarse sand particles which are suspended within the carrier fluid

The carrier fluid is characterized by its rheological properties, i.e. yield stress and viscosity, solids content and density (or specific gravity, SG). The coarse sand particles are characterized by their density and particle size.

Different mathematical descriptions of non-Newtonian materials exist (e.g. Bingham, Herschel Bulkley, see Hanssen 2016). The type of material is determined by the viscous behaviour and results in different flow curves. Consequently, the flow along a beach will vary for different non-Newtonian slurries.

Depositional flow and sand settling behaviour is determined by the coupled interplay of carrier fluid and (coarse) sand particles. When tailings flow down a beach (Figure 2.1), a non-Newtonian plug flow velocity profile develops. The flow velocity is vertically uniform for shear stresses below the yield stress, whereas a parabolic velocity profile develops for shear stresses above the yield stress. The rheological parameters of the mixture (carrier fluid + coarse sand particles) determine the exact shape of the velocity profile, and therefore the characteristics of the flow. The velocity profile includes two regions: the unsheared region (shear stress is below the yield stress threshold) and the sheared region. Shear causes settling of coarse sand particles which, for carrier fluid stronger than few Pa, would otherwise remain suspended in the carrier fluid (Talmon, 2014a and Talmon, 2014b). Shear occurs within a flowing substance when a (vertical) gradient in the flow velocity profile develops (i.e. friction between a layer of higher flow velocity in contact with a layer of lower flow velocity). Coarse sand particles settle from the sheared region toward the beach forming a sand rich layer. The sheared layer, depleted of sand, manifests weaker rheological properties. This results in a higher flow velocity and shear. Vice versa, the coarse sand particles in the sand rich layer produce an increase in rheological properties, with a significant decrease in flow velocity. Depending on the amount of coarse sand particles which deposits in the near-bed layer, a gelled or granular bed may form (Figure 2.2). In gelled bed, coarse sand particles are suspended in the carrier fluid. A gelled bed layer flows (albeit very slowly). In a granular bed the (mechanical) behaviour of the bed layer is dominated by (coarse) sand particles touching each other. A granular bed does not flow (but can be eroded).

Therefore, flow and sand settling behaviour as well as the generation and stability of a deposited sand-rich layer depend largely on the rheological parameters of the carrier fluid, the characteristics of the (coarse) sand particles and their interaction with the flow. A detailed theoretical background is given in Spelay 2007, Pennekamp et al., 2010; Thomas 2010, Sisson et al., 2012; Talmon et al. 2014a; Talmon et al. 2014b; Hanssen 2016, Talmon et al. 2016, van Es 2017.

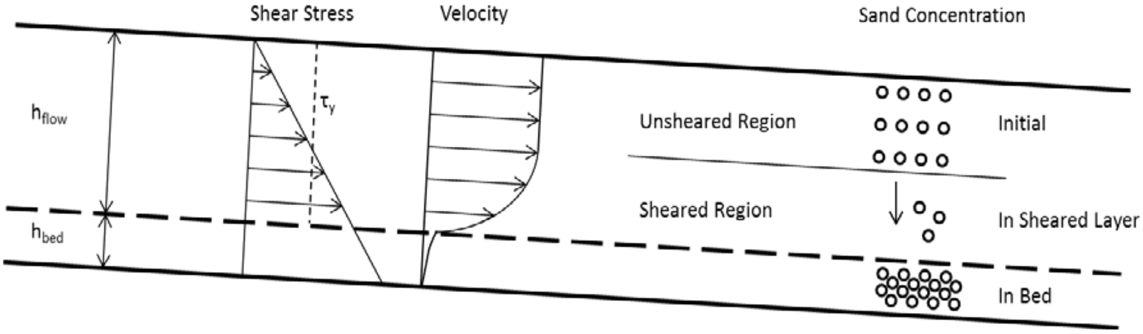

Figure 2.1 Illustrative sketch of tailings flowing down a beach. Shear is developed when the shear stress is higher than the yield stress, resulting in a plug-flow non-Newtonian velocity profile. Sand settles in the shear layer, and accumulates near the bed. Sand concentration influences both the shear stress as well as the velocity profile, in a positive feedback loop. As sand settles a sand-rich layer is formed near the bed. Note that the shear stress line will not continue with the same angle through the bed after sand segregation.

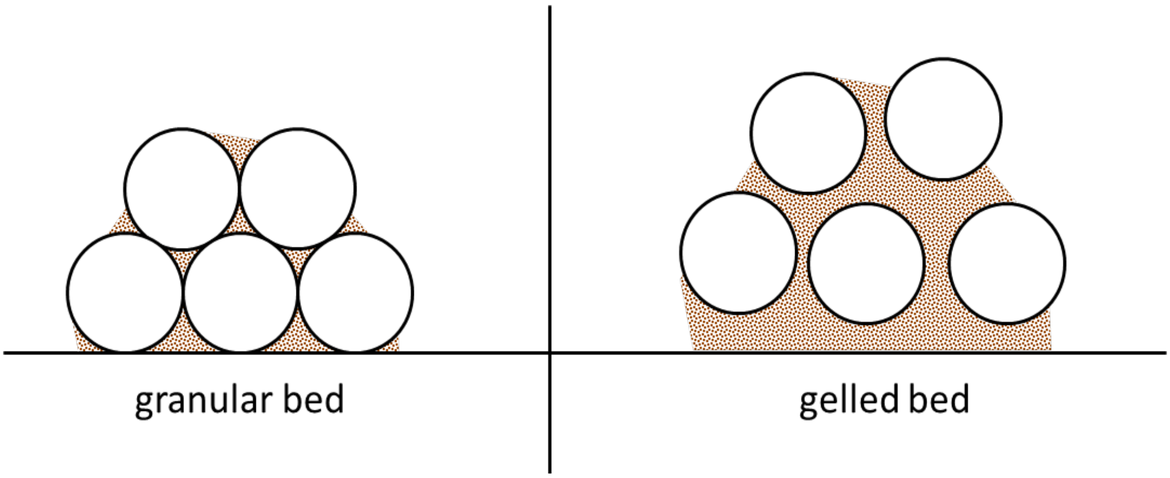

Figure 2.2 Illustrative sketch of granular and gelled bed. In a granular bed the CSP touch each other, while the CF fills the pore spaces between the sand grains. A granular bed is dominated by the mechanical properties of the sand and it does not flow. In a gelled bed coarse sand particles are suspended in the carrier fluid. A gelled bed flows, even if generally much slower than the flow above it.

2.2 Deflt3D-Slurry

Delft3D[1] is an open source numerical model developed and maintained by Deltares and utilized in hundreds of hydrodynamic, sediment transport and water quality studies worldwide for (applied) research and consultancy purposes. As part of this project, D3Ds is developed by upgrading Delft3D to simulate non-Newtonian fines dominated flow and sand settling behaviour 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 diluted high SFR delta deposits in alluvial environments, with good agreement between observed and simulated deposition characteristics, i.e. geometry and grain size distribution (van der Vegt et al. 2015 – Figure 2.3) and slopes (Sheets et al. 2014). The strategy behind this project is to develop D3Ds (i.e. the non-Newtonian or tailings deposition version of Delft3D) building on the robust and tested numerical engine, the physical processes, and the experience of Delft3D.

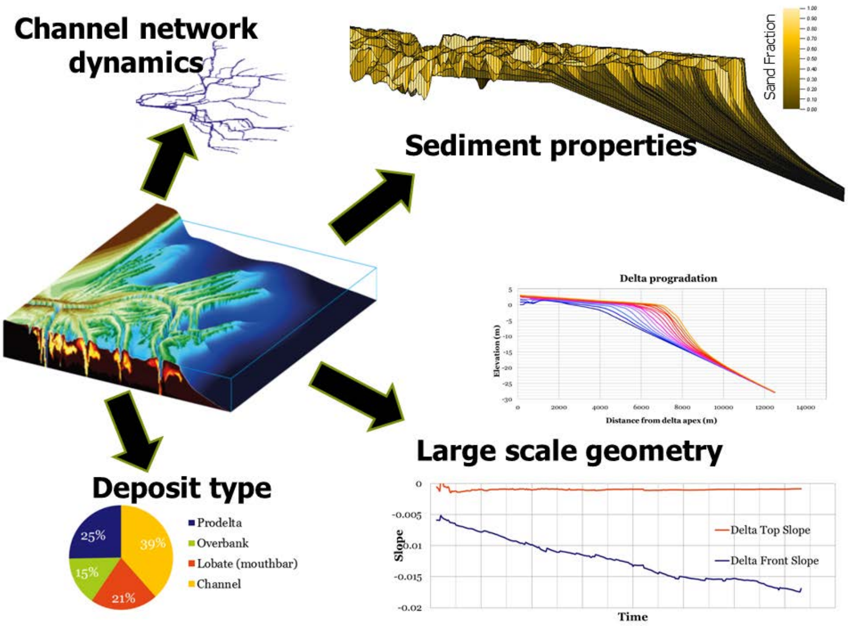

Figure 2.3 Development of alluvial deposit with open source Delft3D (from van der Vegt et al. 2015). Deposit morphology, stratigraphic grain size distribution, beach slope profile and channel development.

D3Ds is initially developed in one dimensional mode (the 1DV model). The most current D3Ds version is developed in three dimensions (with shallow water approximation), but has so far only been tested in two dimensions (i.e. 2DV). While all 3D functionalities are routinely utilized in standard Delft3D simulations and fully implemented in D3Ds, the latter has not yet been tested in 3D. This may be part of the Phase II of this research trajectory. Table 2.1 gives an overview of the processes included in Delft3D, those added to D3Ds as part of this Phase I and those planned for the upcoming Phase II.

[1] https://www.deltares.nl/en/software/delft3d-4-suite/

Table 2.1 Overview of the physical processes included in Delft3D, D3Ds during Phase I (this project), and those planned for Phase II (starting in Q4 2017)

	Delft3D	**D3Ds – Phase I**	**D3Ds – Phase II**
Shallow water, quasi 3D	X	X (not tested in 3D)	X (testing in 3D)
Coupled hydrodynamic, sediment transport and morphology	X	X (coupling with morphology not tested)	X (basic testing with morphology possible)
Track bed changes and composition	X	X	X
Multiple grain size, different equations for fines (cohesive) and sand (non-cohesive)	X	X	X
Variable input in time series, liquid and solids discharge, sediment composition, number of discharges	X	X	X, further testing w.r.t. Phase II
Density driven flow, i.e. turbidity currents	X	X	X
Non-Newtonian	X, fluid mud	X, specific for tailings	X, specific for tailings, further testing w.r.t. Phase II
Open source	X	Released to COSIA	Released
Specific tailings / slurry rheology		X	X
(Sheared-induces) Sand settling		X	X
Thixotropy			X
Laminar – turbulent transition			Possible, out of current scope
Consolidation			Possible, out of current scope

2.3 Applications

D3Ds can be utilized in a series of applications regarding prediction of tailings flow to optimize tailings operation, tailings basin management and closure.

Typical applications of D3Ds include:

- Tailings run out time and distance (time-dependent aging and dewatering not yet included, but part of future development);
- Predictions of tailings flow thickness;
- Conditions for sand settling, fines production and non-segregating;
- Co-deposition and mixing of various tailings type;
- Characterisation of deposits, i.e. the spatial distribution of sand and fines. These will influence closure planning, i.e. consolidation rate, total settling and bearing capacity;
- A computational domain that includes beach above water (BAW) and beach below water (BBW).

Within these applications, D3Ds can be utilized to:

- Design flume tests or field trials;
- Extrapolate flume tests or field trials to field operations;
- Evaluate various deposition scenarios, e.g.:
  - Effect of solids content, SFR, rheological properties, discharge rates;
  - Effect of beach slope or deposit geometry;
  - Number of discharges;
- Design or evaluate various closure landscape scenarios.

Behind typically a depositional flow model, D3Ds in not suitable for long term sedimentation and consolidation prediction (the 1DV version is utilized in this case) and for geotechnical stability or failure analysis.

2.4 Data Needs

Data are generally needed to (1) setup the model and (2) calibrate the model. The first datasets provides the necessary data to setup and run the model; the second to verify the model performance and adjust specific parameters to improve predictions.

To setup the model the most important data include:

- Geometry and bathymetry of the site (e.g. beach length, slope);
- Discharge rate;
- Tailings composition (i.e. solids content, SFR, specific gravity of the solids, sand diameter)
- Rheological properties (i.e. yield stress *and* viscosity).
- Initial conditions: presence of fresh tailings on the beach, water level in the pond (if present)
- Beach or existing tailings composition and characteristics.

Calibration data includes a combination of laboratory, flume and field data if available:

- Sand settling velocity as a function of shear rates (using shear cells);
- Hydrodynamic and sedimentary data from flume and field tests:
  - Flow pattern (i.e. channels, lobes, etc);
  - (indicative) Flow velocity and depth;
  - SFR distribution or areas / depth of prevalent fines and sand;
  - The same data described for the model setup above.

3 Main activities and findings

This section includes the main activities and findings reported in agreement with the original scope of the project. These include: analysis of the data provided by COSIA; collection and modification of rheological and sand settling models formulations; implementation and verification in 1DV; implementation and verification in 2DV; comparison of 2DV model results against oil sands data; and application of the 2DV model to IOL tailings.

3.1 COSIA Data

The data received by COSIA include:

1. The 2013 AMEC beach fines capture study (AMEC, 2013))
2. The 2011 Total flume tests study (SRC, 2011)
3. The 2013 Shell[2] beaching trials (AMEC, 2014)
4. The 2016 Imperial flume tests (Imperial, 2016)

References 1 through 3 were used in this study. Reference 4 was delivered too late for direct application to this study, however it was used indirectly in relation to Deliverable 3.3.

Reference 1 gives an overview of fines capture on BAW and BBW water for various external tailings facilities (ETF) of various oil sands operators, as well as for some flume tests and field trials. Reference 2 refers specifically to eleven Total flume tests, which were also reported in Reference 1. Reference 3 includes four beach field trials.

These reports intend to investigate the main parameters that influence fines capture: SFR and fines concentration of the tailings; deposition methods (e.g. pipe versus spigot); or deposit beach geometry (i.e. BAW, BBW or beach confined by a dike).

Fines capture is defined as the ratio between the SFR of the slurry and the SFR of the beach, in percentage, assuming that all sands remains on the beach. For a more specific definition and formulation of fines capture is it referred to the data Reference 1.

While it appears difficult to converge to precise ideal deposition conditions, these studies indicated that:

- Higher SFR in the discharged slurry produces higher fines capture (Figure 3.1). This is however largely related to the fact that high SFR slurries contain little fines. Therefore a relatively high capture percentage does not imply a higher mass of fines captured or higher concentration of fines in the beach;
- In fact, when fines capture is related to fines concentration in the beach the correlation inverts (Figure 3.2);
- In general BBW captures more fines than BAW. This is consistent with sand segregation dynamics, where sand settles at higher shear rates. These are generally encountered in BAW rather than BBW;
- A downstream containment dike enhances fines capture;
- Fines can be captured by sand flowing into a fluid tailings pond, by mixing or entrainment under sand.

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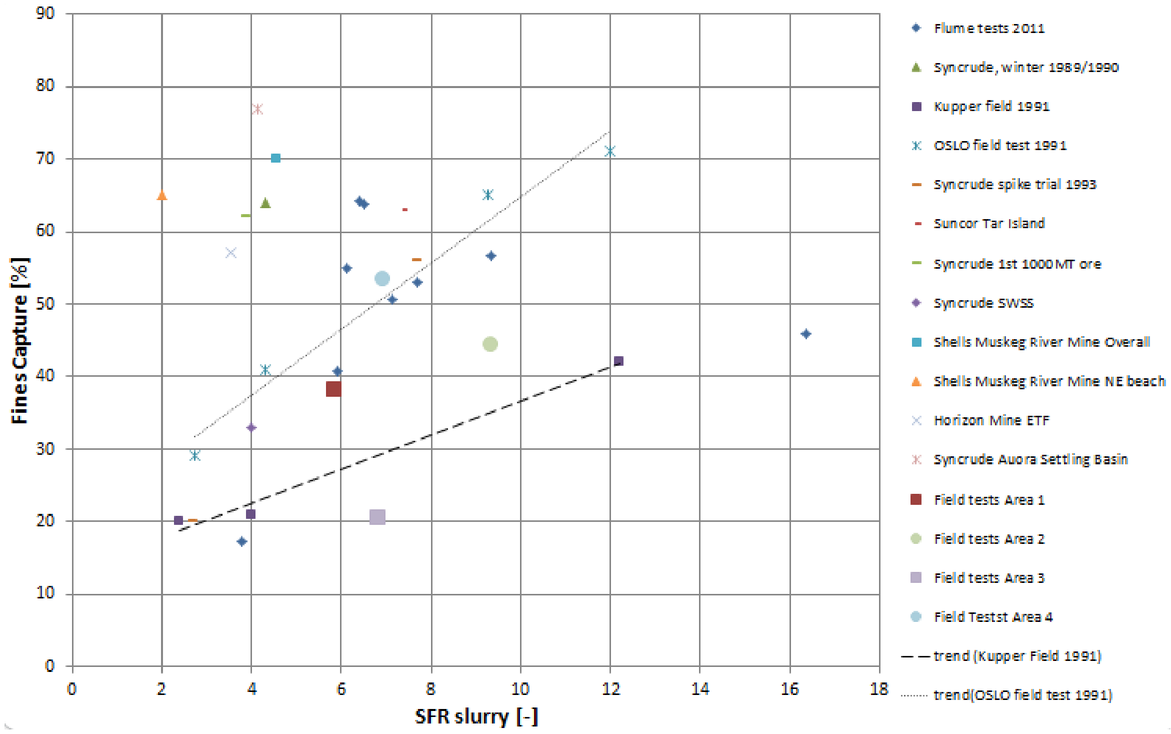

Figure 3.1 SFR of slurry versus fines capture for all data received from COSIA

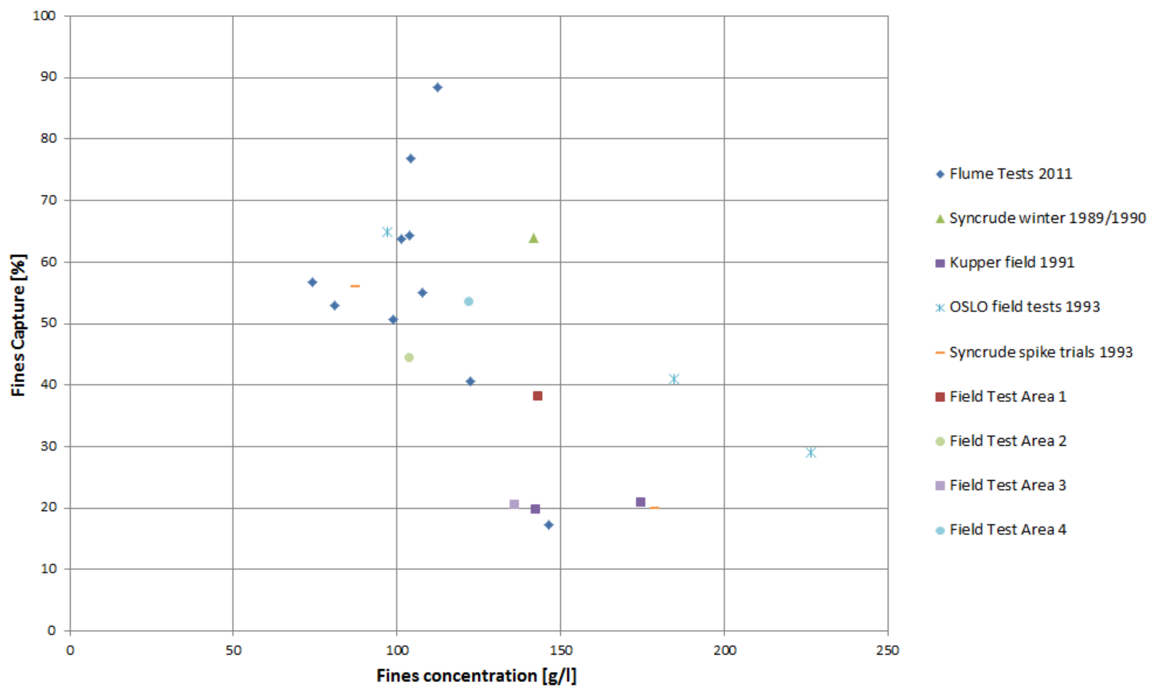

Figure 3.2 Initial fines concentration in the slurry versus fines capture, computed from the COSIA dataset when the specific data are available.

The data in References 1 through 3 refer to generally high sand content flows, often beyond the limit where the carrier fluid dominates the physical behaviour of the flow. Many of these data also likely refer to turbulent or near-turbulent flow. These are beyond the current scope of D3Ds, which focuses on non-Newtonian laminar or near-laminar flow where the rheological properties of the carrier fluid dominate the flow and sand settling behaviour. No rheological data are included in these dataset. Rheological data are necessary to the setup of the model.

Even if possibly referring to conditions at the limit or outside the current scope of D3Ds, these data were utilized for an initial comparison with the results of D3Ds. Specifically, the model is compared to the Kupper (1991) report, which refers to the Kupper 1988 tests reported in Reference 1 (see Section 3.4.2 for D3Ds – Kupper comparison).

The Reference 4 data were utilized as input to the IOL study, which will be described in Section 3.5. . While the IOL flume tests were not specifically modelled, D3Ds performance on IOL tailings were compared against theoretical expectation and general observations.

3.2 Rheological and sand settling models

Three rheological models were selected to describe the rheological behaviour of tailings mixture. In all three models, the rheological properties of the tailings mixtures are determined by the carrier fluid (i.e. water and fines) and influenced by the concentration of sand (i.e. coarse particles).

These models are:
1. Winterwerp and Kranenburg, based on the fractal theory developed by Kranenburg (1994). This model was originally developed for fluid mud and harbour siltation;
2. Jacobs and van Kesteren, based on Jacobs et al. (2008). This model has been frequently utilized by Deltares in oil sands tailings characterization, for example in non-segregating tailings (NST) studies;
3. Thomas (1999), a traditional rheological model utilized in tailings flow studies, originating from the Australian mining experience.

Model 1 is based on an exponential model, whereas Models 2 and 3 are Bingham models.

Based on Thomas' data, the three analytical models predicted similar behaviour up to 40 % solids (by volume), and then slightly deviated. In general, the accuracy of prediction differs for different total volume concentrations and SFR (or Sand to Total Solids ratio – STS – as Thomas defines it). At high STS the accuracy decreases. This is due to three main reasons:
- The mixture tends to shift towards granular regime dominated by the sand skeleton at high STS, changing the dominant physical processes beyond the validity of the formulas;
- The particles size distribution and shape of the sand grains influence the internal friction, processes that are not captured in details by the analytical models causing larger deviation as they become dominant; and
- The accuracy of the measurements generally decreases for high sand concentrations, because the sand particles tend to segregate during the measurements.

Figure 3.3 shows the performance of the three rheological models superimposed on Thomas' data. Thomas' experiment also clearly reveals the dependence of the yield strength on the solids and fines content. The blue line does not contain sand particles (i.e SFR = 0). As expected, for higher fines content the yield strength increases. Interestingly however, a slurry with equal solids content but were fines are replaced by sand (i.e. high SFR), has lower yield strength. In Figure 3.3 this means jumping from two lines with different STS, but at the same total volume concentration. The effect of adding sand is better seen in Figure 3.4 created with the Jacobs and van Kesteren model. At the same water content with respect to the fines, higher SFR produce higher yield strength. All models will react similarly to adding fines and sand, as highlighted in Figure 3.3.

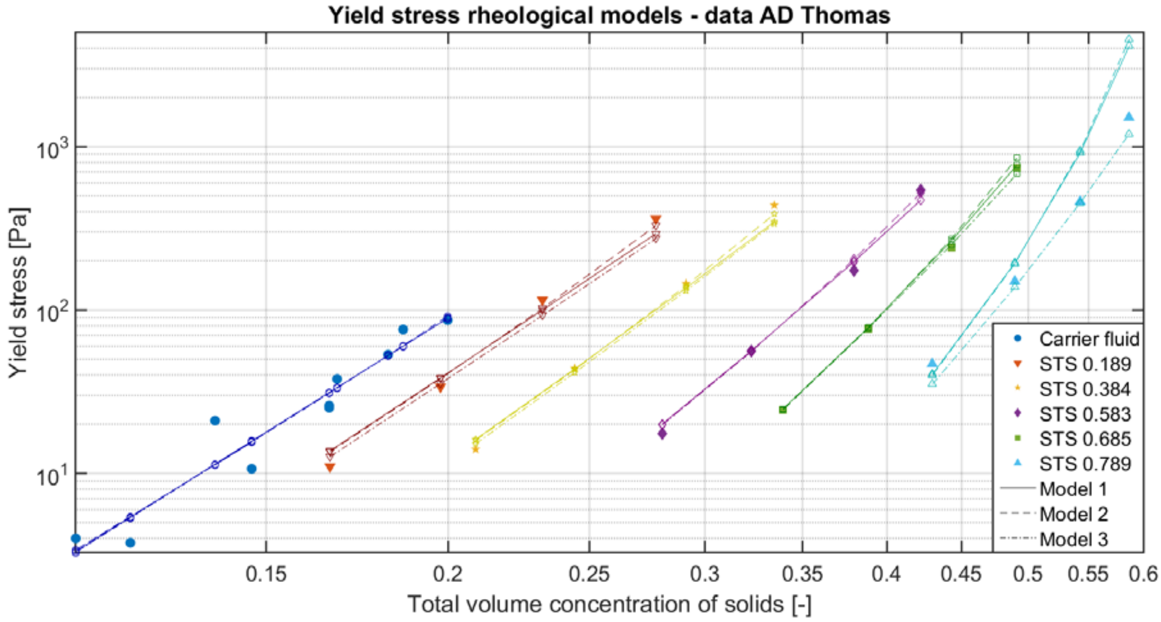

Figure 3.3 Performance of the three analytical rheological models (solid lines and not-filled markers) over Thomas' data (filled markers). Model 1 = Winterwerp and Kranenburg; Model 2 = Jacobs and van Kesteren; Model 3 = Thomas.

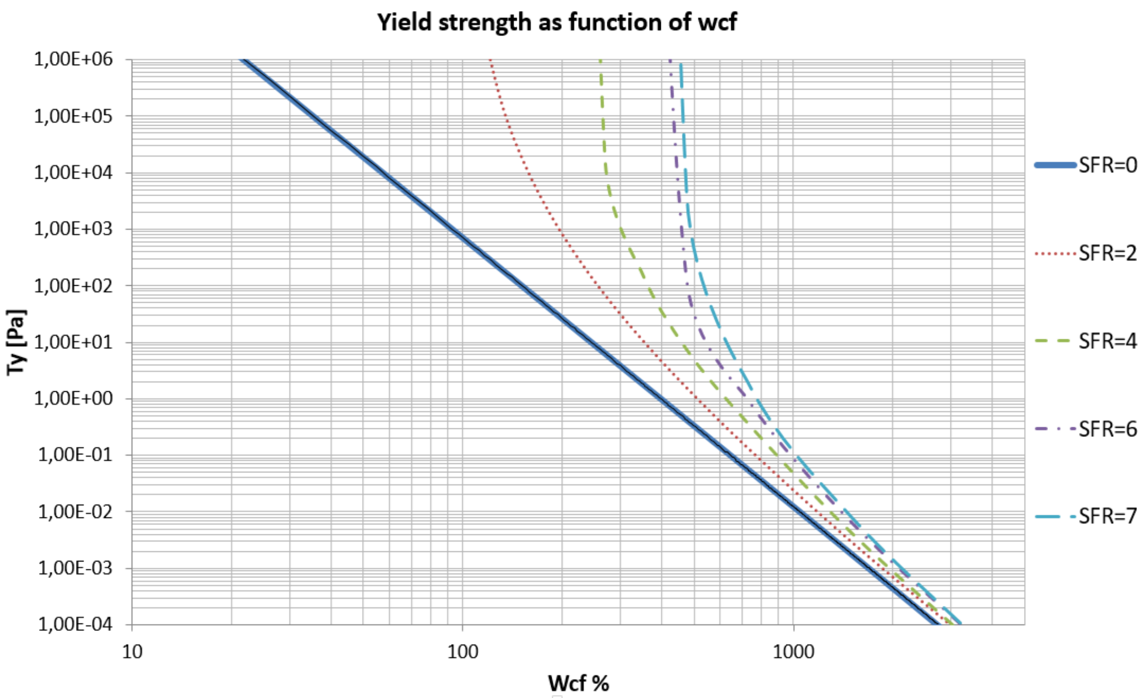

Figure 3.4 Yield strength dependency on water content with respect to fines (x – axis) and SFR following the Jacobs and van Kesteren model.

As stated in the theoretical background (Section 2.1), a concentrated static non-Newtonian carrier fluid with shear strength above a few Pascal is able to keep coarser silt or sand solid particles in suspension because of the yield stress. Shear, which always occurs in flowing tailings, induces sand settling, which increases at higher shear rates. The presence of many sand particles (i.e. locally high SFR) hinder sand settling. Based on previous research (Talmon et al., 2014a&b, Winterwerp and van Kesteren, 2004, Winterwerp et al., 2004, Sisson et al., 2012) an analytical model has been readapted in this project for shear induced hindered sand settling. This is described in detail by Hanssen (2016) .

These three rheological and the sand settling models are included in D3Ds and initially tested in 1DV.

3.3 1DV model development and results

The 1DV model is essentially a single vertical column of Delft3D to which a horizontal velocity is prescribed as a horizontal pressure gradient (i.e. it is not a static single column). This 1DV model is utilized to implement and test new processes and formulations before including them in the 2D/3D version. The three rheological models and the sand shear settling formulation are coded in 1DV and tested versus analytical idealized scenarios and laboratory data.

This modified 1DV model is subsequently applied to approximate TT and NST tailings flow down a 1,000 m long beach. Figure 3.5 shows velocity profile, settling velocity and modelled and measured sand concentration profile for TT 1,000 m down the beach. A 1 m^3/s, 40% solids content, 0.25 uniform SFR TT is discharged down a 1% sloped beach. The three lines show the 1DV model results for the three rheological models at the end of the beach. All three models show a non-Newtonian velocity profile (i.e. plug flow) with sheared region up to about 15 cm from the bed, and higher shear rates close to the bed. Sand settles mostly in the sheared region with largest settling velocities (negative downwards) in the regions with largest shear. The sand concentration profile remains about uniform in the non-sheared region. Sand is dropped in the sheared layer and accumulates near the bed. This behaviour is similar to what has been observed by Spelay (2007).

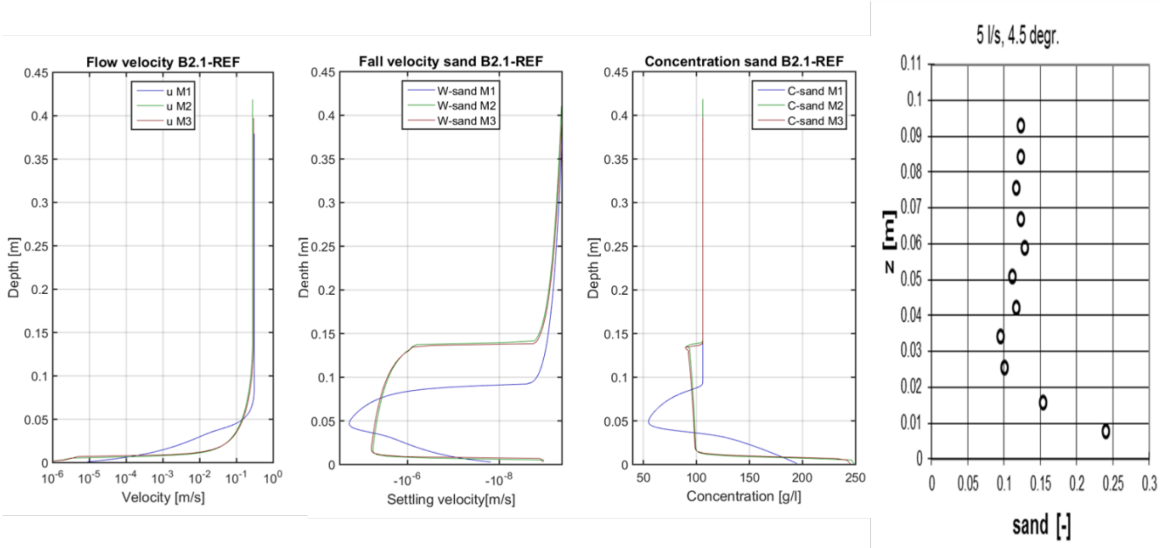

Figure 3.5 1DV model results for 1 m^3/s, 40% solids content, 0.25 initially uniform SFR TT 1,000 down a 1% sloped beach. Velocity profile (left panel), settling velocity (second panel from left) and modelled (third panel from left) and measured sand concentration (Speley, 2007, right panel) for the three rheological models (1 = Winterwerp and Kranenburg; 2 = Jacobs and van Keteren; 3 = Thomas).

The new 1DV model reproduces the general rheological and sand settling processes in line with theoretical expectations and laboratory measurements. The results vary depending on the rheological model implemented. More detailed measurements and more experience with the model are needed to assess which rheological model performs better in line with observations. At this stage, the predictions obtained with of the three rheological models represent the limit of a reasonable sensitivity analysis.

As sand is added to the mixture the model becomes more sensitive to the local SFR and the transition to a sand skeleton. When sand segregates a thick bed is formed, which flows at much lower velocity. Sand deposition introduces longitudinal variability and therefore the need for 2DV simulations.

3.4 2DV model development and results

The same theory and formulations used in the 1DV model were applied in the D3Ds model code and tested in 2DV mode, as a longitudinal section along a beach. D3Ds is capable of 3D simulations; however these have not yet been tested with the updated tailings physics.

After upgrade, D3Ds in 2DV is first verified against expected behaviour on generic slurries, then applied to typical oil sands tailings properties (this section), and finally applied to IOL TT and FFT tailings (Section 3.5).

Model verification is carried out through a sensitivity analysis (with a matrix illustrated in Figure 3.6) to verify D3Ds behaviour to changes in:

- Rheological properties (red);
- Clay (or fines) content (green);
- Sand concentration (or SFR) (blue); and
- Sand diameter (purple).

The parameters are reported in Table 3.1. All results are presented in detail in van Es (2017). Here we only report on the example case of adding different sand concentrations to an initial carrier fluid consisting of only fines and water (i.e. intersect REF – Sand 2 – Sand 3 – Sand 4 in Figure 3.6, marked red in Table 3.1).

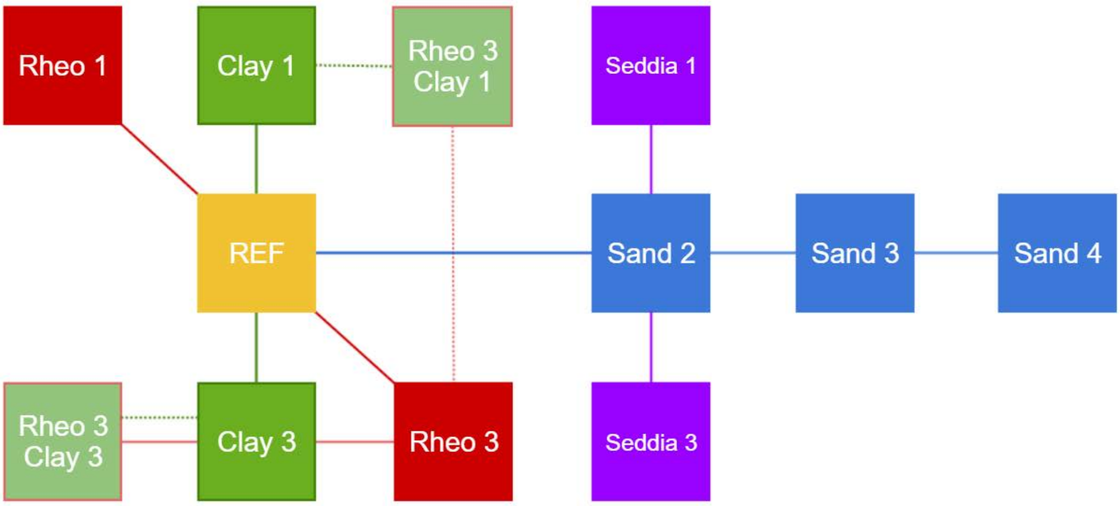

Figure 3.6 Sensitivity analysis for behaviour of D3Ds in 2DV for generic slurries. The variation parameters include rheology (Rheo), fines content (Clay), SFR (Sand) and sand diameter (Seddia).

Table 3.1 Parameters utilized in the sensitivity analysis. Sand and clay (i.e. fines) are given in volume concentration; FOFW = fines of fines plus water; Sand D. = diameter of sand particles in micron; rheology type indicates the rheological parameters set (see van Es, 2017 for more details); Rheology model indicates the rheological model utilized in these simulations, M2 = Jacobs and van Kesteren. Marked in red are the runs discussed in this report. All other runs are discussed in van Es (2017).

	Sand [g/l]	**Clay [g/l]**	**SFR**	**FOFW [%]**	**Sand D. [um]**	**Density [kg/m3]**	**Rheology Type**	**Rheology model**
REF	0	260	0	22.4	-	1160	REF	M2
Clay 1	0	100	0	9.4	-	1062	REF	M2
Clay 3	0	415	0	33.1	-	1255	REF	M2
Rheo 1	0	260	0	22.4	-	1160	1	M2
Rheo 3	0	260	0	22.4	-	1160	3	M2
Rheo 3 / Clay 1	0	100	0	9.4	-	1062	3	M2
Rheo 3 / Clay 3	0	415	0	33.1	-	1255	3	M2
Sand 2	100	260	0.38	23.2	200	1222	REF	M2
Sand 3	450	260	1.73	26.3	200	1440	REF	M2
Sand 4	900	260	3.46	31.7	200	1720	REF	M2
Seddia 1	100	260	0.38	23.2	100	1222	REF	M2
Seddia 3	100	260	0.38	23.2	400	1222	REF	M2

Figure 3.7 compares the velocity and sand concentration profiles for REF, Sand 2, Sand 3 and Sand 4. Figure 3.8 illustrates the SFR cross sectional distribution for the Sand 2, Sand 3 and Sand 4 (REF has no sand).

All simulations have identical discharge (1 m^3/s/m) and beach slope (1.7%). The velocity profile plot illustrates how sand modifies the rheological properties of the mixture, with slower and thicker flow (from above 1 m/s to 20 cm/s, and from just above 10 cm thickness to about 70 cm thickness). The velocity profiles reveal that plug flow, typical of non-Newtonian behaviour, occurs. This is more apparent with thicker mixtures (i.e. higher SFR). The concave profile near the bed at higher SFR indicates sand segregation and a gelled bed. The sand concentration profiles confirm loss of sand in the sheared zone and deposition of sand near the bed. This is qualitatively in line with theoretical and experimental observations and with the results of the 1DV model.

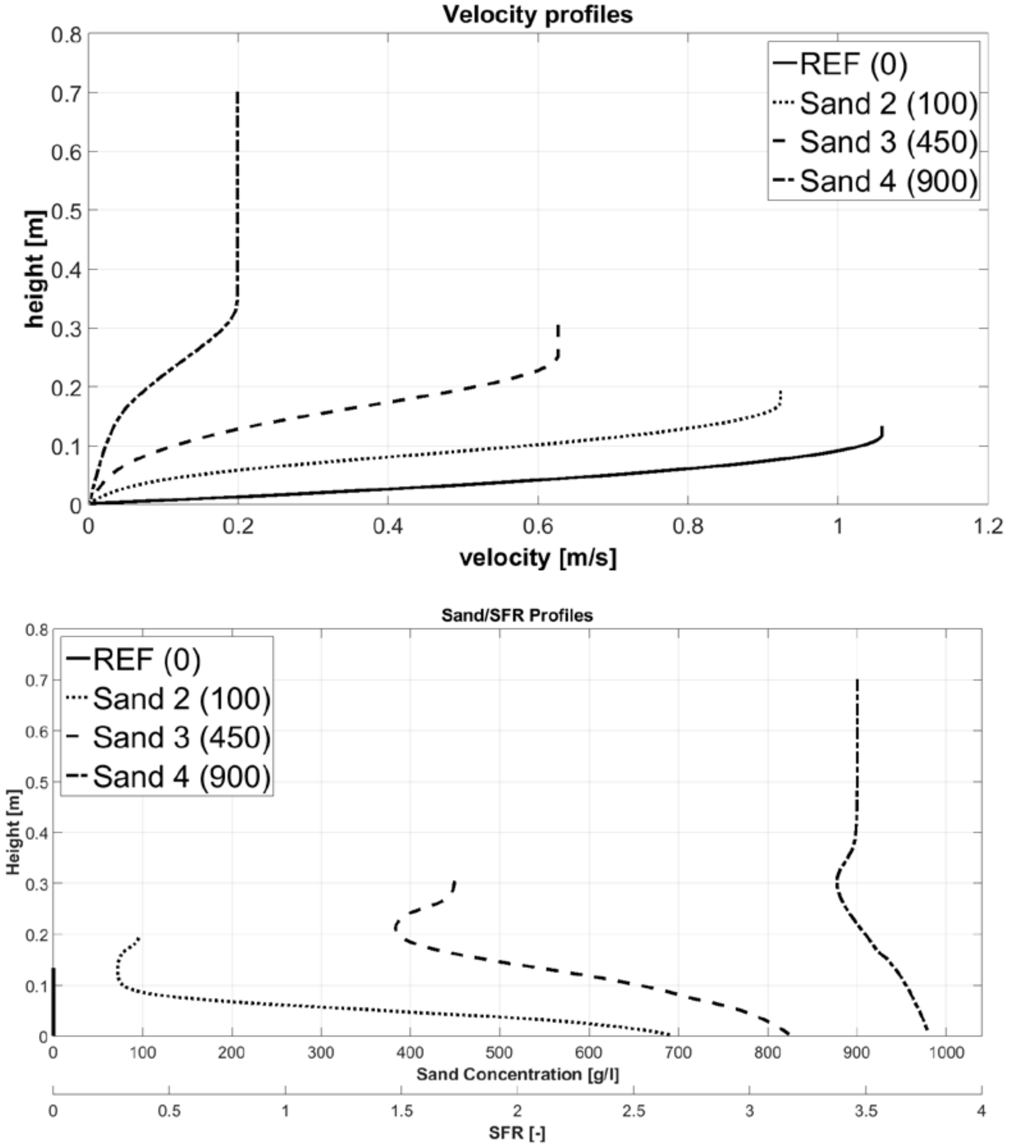

Figure 3.7 Velocity (above) and sand concentration / SFR (below) profiles for runs REF, Sand 2, Sand 3 and Sand 4. These profiles are produced by the 2DV model about 200 m away from the discharge. The sand concentration is initially uniform in depth.

Figure 3.8 illustrates the same behaviour but for the entire transect. All runs show loss of sand to the bed, which is more pronounced in thinner slurries. Run Sand 4 shows more clearly a low SFR layer at mid-flow depth, where the shear rates are highest. All runs show a sand-rich bottom current flowing into the pond. From these SFR distributions it is possible to back-calculate fines capture.

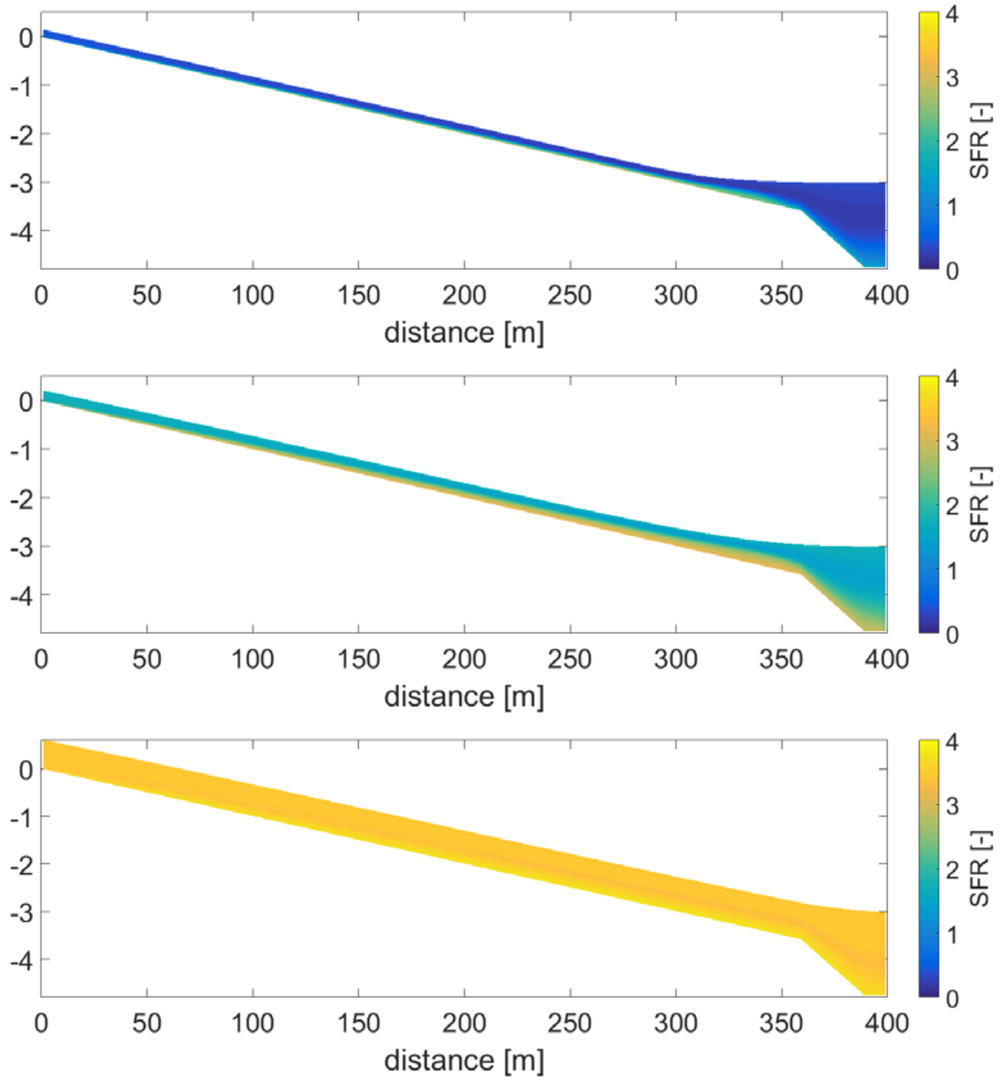

Figure 3.8 SFR cross sectional distribution along the beach and in the pond for runs Sand 2 (above), Sand 3 (middle) and Sand 4 (bottom).

3.4.1 Comparison between 1DV and 2DV models

1DV and 2DV velocity profiles for all the three rheological models were compared at a specific location along the beach (Figure 3.9). The 1DV results are produced by the 1DV model, the 2DV results by D3Ds. Our analysis focusses on the differences between the 1DV and 2DV models rather than on the effect of the specific rheological models.

While both 1DV and 2DV simulations produce results in line with theoretical expectations (i.e. plug flow, sand settling and reduction in flow velocity of the sand-rich near bed layer), the velocity profiles are overall rather different. The 1DV model seems to be more effective in reducing the flow velocity of the sand-rich layer. There are a few reasons that may explain this difference, some of them are still under current investigation. The two main reasons currently identified are:

1 In the 2DV model, material transported by water with a low flow velocity is deposited, whereas all sediment remains in the computational domain of the 1DV model. Therefore the 2DV model carries a different amount of sand than the 1DV due to longitudinal variability. The sand is lost as the tailings flow down the beach; and

2 The numerical schematization of sand settling. In the 1DV model this process is stabilized by adding a down-wind numerical approach (van Es, 2017), which improves the stability of the model. This is not yet included in the 2DV model.

The differences in flow velocity profiles directly influence the sand concentration profiles (Figure 3.10), which is expected, as sand settling is related to shear rates. The sand depleted layer coincides with the largest gradient in flow velocity (i.e. highest shear rate). This is more pronounced in 1DV than 2DV. The sand concentration profile impacts fines capture calculations directly, therefore this is an important topic for further verification.

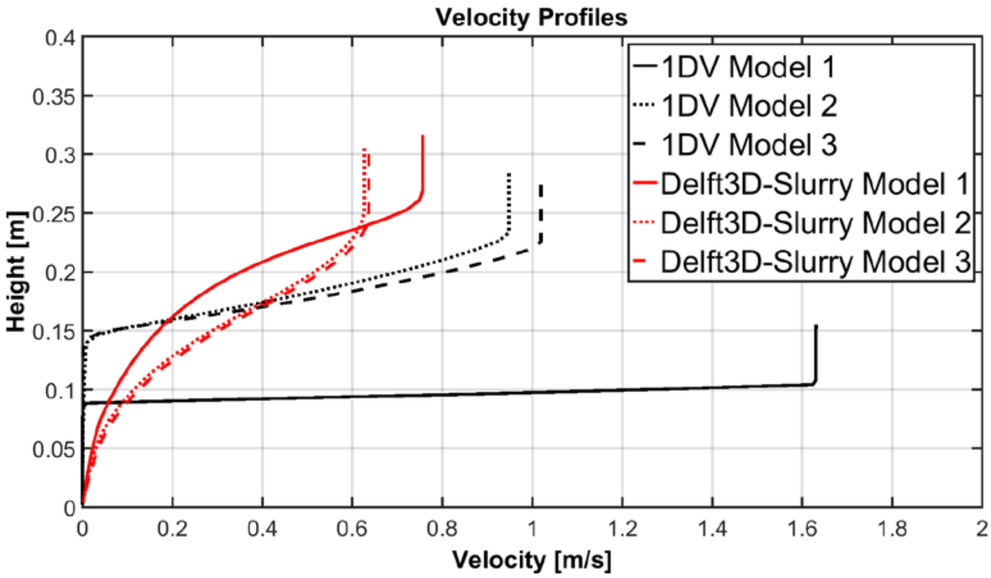

Figure 3.9 Comparison of velocity profiles produced by the 1DV and the D3Ds-2DV models for the three rheological models for Run Sand 3. Line type indicates rheological model, with the same numbering as indicated before. Line color indicates 1DV (black) and D3Ds-2DV (red).

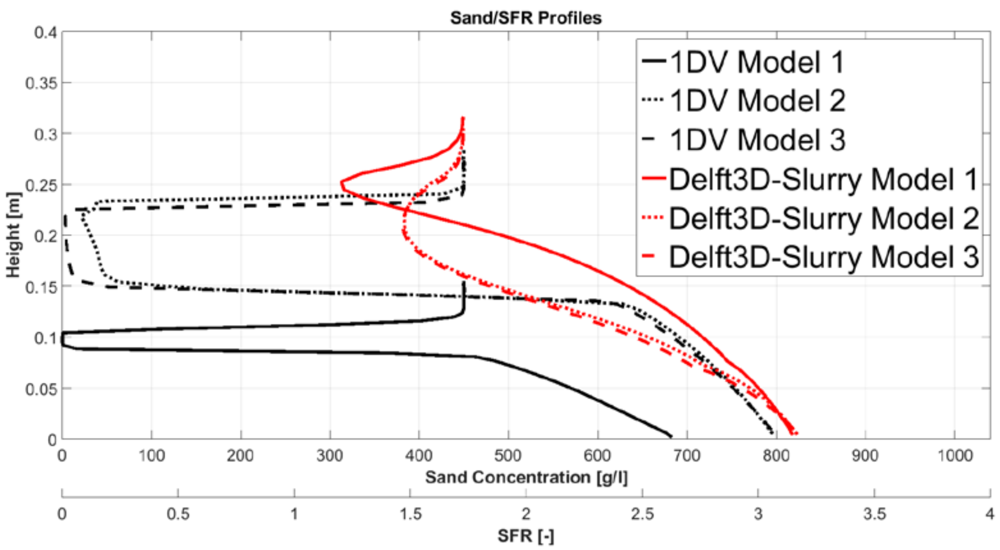

Figure 3.10 Comparison of sand concentration profiles produced by the 1DV and the D3Ds-2DV models for the three rheological models for Run Sand 3. Line type indicates rheological model, with the same numbering as indicated before. Line color indicates 1DV (black) and D3Ds-2DV (red).

3.4.2 Conceptual comparison to oil sands data and fines capture estimates

The new version of the D3Ds is utilized for an initial conceptual comparison with the oil sands data received from COSIA and described in Section 3.1. This comparison is performed to illustrate how D3Ds can be applied for estimating fines capture.

For this preliminary exercise, the analysis is limited to the three Kupper runs, i.e. Kupper 1, Kupper 2 and Kupper 4 of the Kupper (1991) dataset. The Kupper tests were beaching field trials of various SFR. These resemble the D3Ds current beach geometry and parameter setting the closest, even though at relatively low density which suggests the possibility of turbulent flow. Within the dataset received by COSIA, this dataset also has the most complete model input data set, even though rheological data is absent. The model geometry is setup from the Kupper (1991) topography, with slopes varying from 2 % to 3 %. The discharge rate is 0.3 m^3/s, which is divided equally across the 100 m width of the beach. This assumes unchannelized flow. The rheology is assumed to be similar to the Rheo3 set of the sensitivity analysis of Section 3.4, based on other oil sands data. The tailings composition is reported in Table 3.2 for Kupper 1, Kupper 2 and Kupper 4 trials.

Table 3.2 Tailings composition in the Kupper trials

	Sand [g/l]	**Clay [g/l]**	**Water [g/l]**	**Density [kg/m³]**	**SFR [-]**	**Fines Capture [%]**
Kupper 1	981	82	598	1660	12.2	42
Kupper 2	684	174	675	1533	4	21
Kupper 4	338	142	818	1298	2.4	20

Following the COSIA definition, fines capture is calculated as the ratio of the SFR of the tailings at discharge over the SFR of the beach. Because the current D3Ds outputs a continuous SFR profile with depth, the distinction between beach deposit and flowing tailings is defined by the sand concentration profile. The beach versus flowing tailings transition is defined by the vertical position at which the uniform sand concentration starts increasing with depth (Figure 3.11, blue circle). The sand value in the beach is approximately taken at the closest third of the beach profile (red circle). One sand concentration profile is chosen to be representative for the entire beach. While acceptable for a first demonstrative estimate, these choices are rather arbitrary at this stage and deserve a better sensitivity analysis to determine a more rigorous procedure. These choices indeed impact the value of the computed averaged fines capture directly.

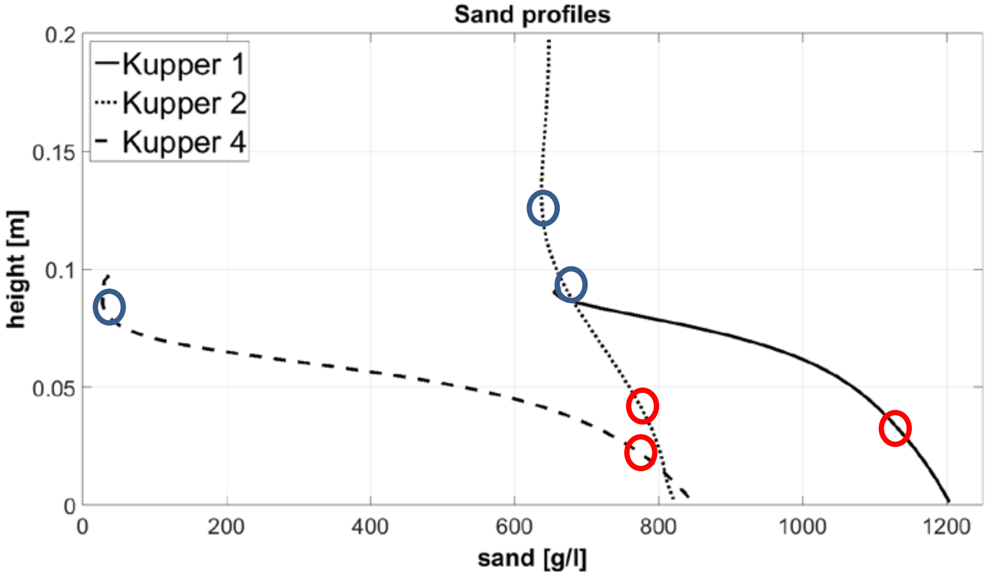

Figure 3.11 Modelled sand concentration profiles for Kupper 1, Kupper 2 and Kupper 4 scenarios. The blue circles indicates the estimate transition from flowing tailings (above) to beach (below). The red circles indicate the average value chosen to compute fines capture (i.e. 1120 for Kupper 1, 780 for Kupper 2 and Kupper 4). These are used to compute the average fines capture.

The results of this conceptual and first exercise are depicted in Figure 3.12. This figure shows measured fines capture for Kupper (1991) and OLSO (1991) field trials, together with the results of D3Ds model realizations for Kupper. D3Ds appears to capture the overall trend (although only three model realizations are available), but to overestimate fines capture, reaching very high capture already at SFR slurry 4. There are few reasons for this mismatching, some of which are:

- In D3D, the flow to beach transition is related to the rheological model utilized and its sensitivity to sand concentration. The sensitivity range to this parameter will be studied in more detail during the follow-up phases. This is consistent with the discussion in Section 3.4.1 regarding the comparison between the 1DV and the 2DV simulations;
- These simulations approximate the beach versus flowing layer transition based on crude arbitrary choices;
- For SFR below 4 the rheological properties of the carrier fluids are critical. No rheological properties were included in the dataset initially provided by COSIA. The rheological properties utilized in this exercise are chosen based on general experience with oil sands.
- These simulations assume that the flow is spread uniformly across the beach. This is less and less valid towards high SFR, coarse-tailings like streams;
- This version of D3Ds is specifically developed for laminar non-Newtonian tailings. This is the case in high fines / low SFR tailings. When SFR becomes larger than 4 it tends to transition to a coarse tailings mixture, with sand dominating the flow behaviour. A combination of Delft3D and D3Ds may be able to cover this range, but this is not tested yet.

Therefore, while D3Ds can indeed be utilized to compute fines capture estimates, more testing and sensitivity analysis should be performed to improve predictive capabilities. Additional rheology data and field data on deposit composition will also help predictions, especially in the range of SFR up to 5, typical for most non-segregating tailings.

As part of this project phase, D3Ds was also upgraded to standard Delft3D. This is important to guarantee the continuity of D3Ds and its compatibility with the main Delft3D for ultimate release to open source beyond COSIA for everybody's free use.

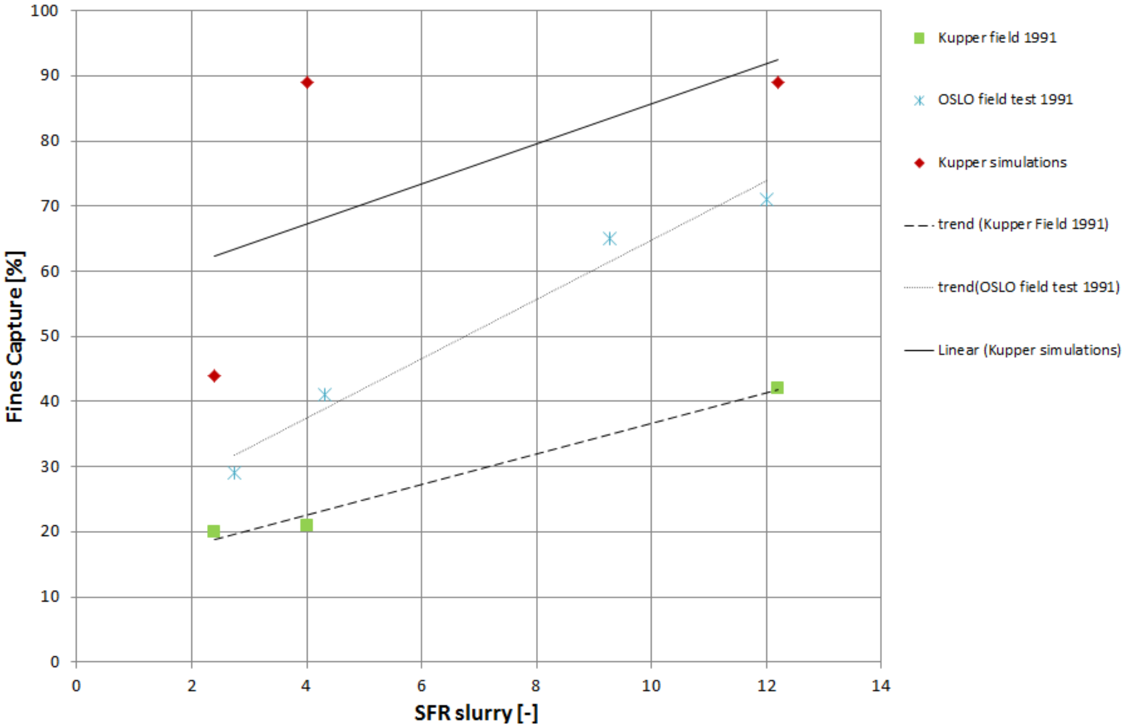

Figure 3.12 Fines capture versus SFR$_s$ reported for the Kupper 1991 field trial (green), the OSLO 1991 field trial (blue) and computed with D3Ds for the Kupper scenarios (red). Lines indicate trend lines between the three available points.

3.5 Reference to IOL work

As a first application case of D3Ds to a specific oil sands case study, the latest version of D3Ds is utilized to simulate IOL TT and FFT flow, sand segregation and mutual interaction during subaerial beach deposition.

This application is performed for and partially financed by IOL. This application takes advantage of the ongoing D3Ds development described in this COSIA study. On the other hand, this COSIA study benefits from testing the new model on a real case scenario. The detailed description of this study can be found in the Deltares (2017) report, delivered to IOL (Dave Rennard) in June 2017. This section summarizes the major activities and findings of the IOL study.

The main objectives of this study are to:

- Evaluate the capability of D3Ds to dynamically simulate:
  - IOL flocculated TT and FFT deposition and sand segregation;
  - The interaction between TT and FFT: mixing, displacement, etc.;
- Identify the required steps forward to improve understanding and prediction of deposition and mixing of TT and FFT.

IOL TT and FFT show non-Newtonian, near-laminar or completely laminar behaviour. Sand is observed to settle depending on tailings density and discharge operations. The results of ten simulations of tailings deposition along a beach transect (i.e. 2DV) are included in this application, designed to illustrate:

1. Fresh TT flow and sand settling behaviour;
2. The effect of various yield stresses on TT flow and sand settling behaviour;
3. Fresh FFT flow and sand settling behaviour, with respect to TT;
4. Flow of fresh TT over aged FFT;
5. Long term TT deposition and beach deposit development.

The properties of the TT and FFT tailings and the beach geometry are based on flocculated IOL TT and FFT tailings. The current D3Ds does not yet include rheological (i.e. yield stress) enhancement (or weathering) in time due to dewatering or aging, which is observed to be significant in IOL tailings, especially TT. This feature is planned to be included as part of the follow up D3Ds development phase. For the time being, various simulations were performed with different initial yield stresses that cover the expected range of variation in IOL TT and FFT.

In this report the results regarding variation in rheological properties, co-deposition and long term deposition are shortly described. More details can be found in the Deltares (2017) report to IOL.

Figure 3.13 shows the effect of rheological properties (increasing yield stress and viscosity) on TT flow height, propagation speed along the beach and sand segregation. The simulations are frozen after about 14 hours of constant tailings deposition along a 1% slope 1,000 m long beach. This exercise reveals how the rheological properties change the flow behaviour significantly with thicker flow, slower propagation and less sand segregation for stronger TT. In the next development phase we plan to include variable rheological properties during the flow to mimic thixotropy or dewatering during flow.

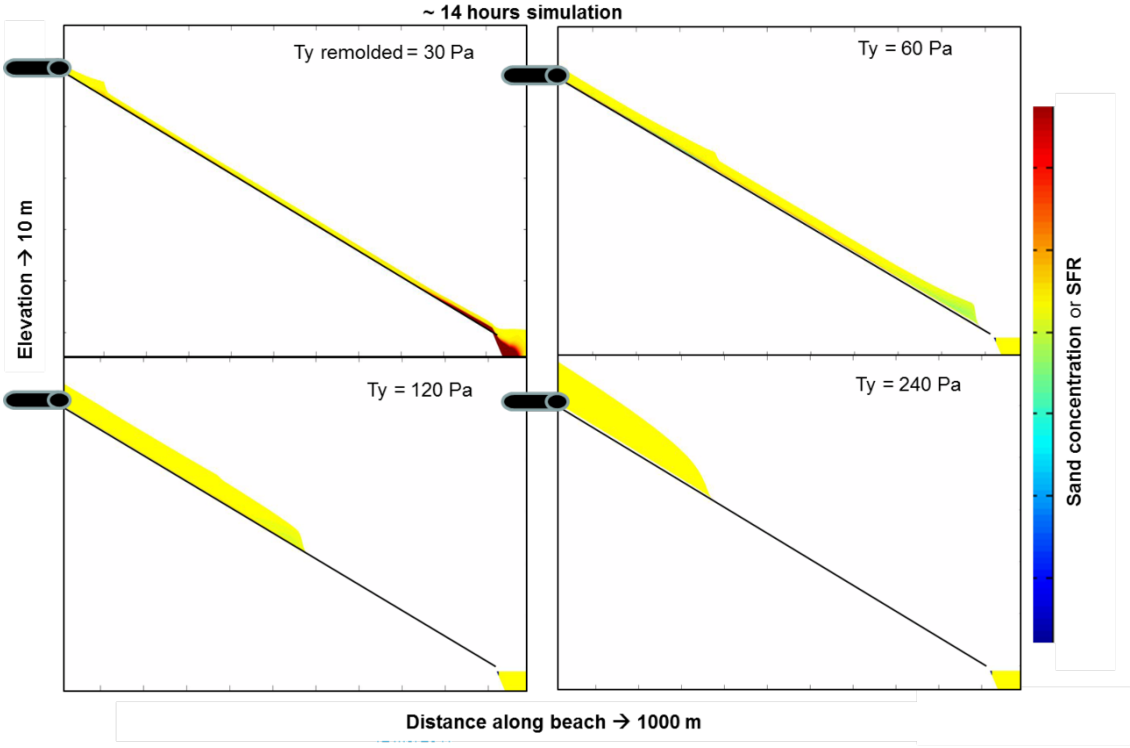

Figure 3.13 Flow of TT with different initial yield stress (i.e.: top-left = 30 Pa; top-right = 60 Pa; bottom-left = 120 Pa; bottom-right = 240 Pa), after about 14 hour of constant discharge. Colours represent sand concentration in the same scale.

Figure 3.14 illustrates deposition of fresh TT over aged FFT to qualitatively assess the interaction between the two tailing types. In these conceptual scenarios fresh 30 Pa yield stress TT is discharged over FFT that was deposited on the beach 24 hours before and has increased strength to 750 Pa.

The results are presented in four time laps: after about 1.5 h; 3 h; 4 h; and 4.8 h of fresh TT deposition. The colours indicate sand concentration in TT, meaning that dark blue (i.e. zero sand concentration) represents aged FFT and all other colours represent fresh and segregating TT, or mixed TT / FFT. The aged FFT does influence the propagation behaviour of TT, which slows down and increases in thickness upstream of the aged FFT front. After mixing with the aged FFT front, the TT continues down the beach until reaching the pond. A layer of aged FFT is covered by fresh TT.

Mixing is a complex process. In laminar flow, mixing is mainly driven by yield stress and density. Yield stress is dominant in tailings with strong rheological properties, density in weaker tailings or, for example, saline flow. The relative importance of the two is under current investigation.

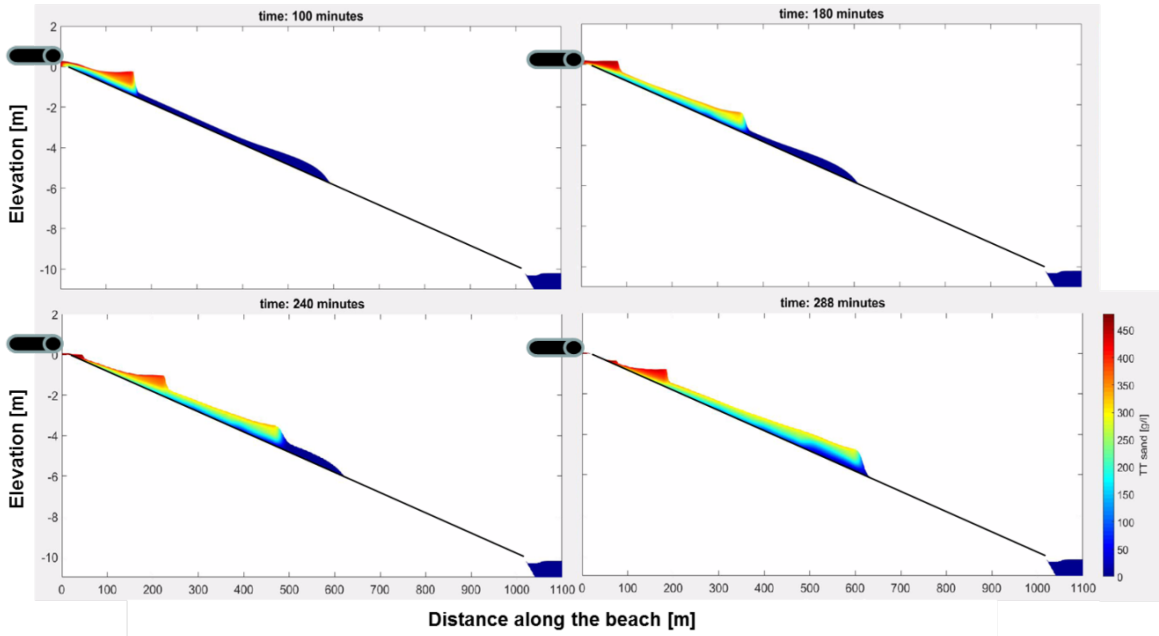

Figure 3.14 Flow of fresh TT (yield stress = 30 Pa) above aged FFT (~24 h) after about 1.5 h, 3 h, 4 h and 5 h of fresh TT deposition. Colours indicate sand concentration in TT. Very dark blue represents aged FFT. All other colours represent segregating TT (or mixed with aged FFT).

Figure 3.15 shows continuous and constant TT deposition with initial yield stress of 30 Pa for about 6 hours. The TT does not gain strength during this simulation. The purpose of this simulation is to observe flow patterns, sand settling and built-up of deposits. These simulations are performed on a shorter 400 m beach to allow for quicker deposit built-up.

Deposition appears to proceed as a sequential feedback between sand settling and rheological properties. Flow produces shear, which causes sand settling. Sand settling generates a layer with higher sand concentration below a layer with lower sand concentration. The upper layer has a weaker rheology, it flows faster and generates sand settling. The lower layer has a stronger rheology and it flows slower. These processes generate a positive feedback in the upper layer: sand settles, rheology weakens, velocity increases, shear increase, sand settling increases, which is likely responsible for the surface waves and alternating deposition and erosion of the beach. As deposition and sand settling continues, a deposit builds up. At the same time a large amount of sand reaches the pond where it accumulates.

Also in this case, D3Ds simulates continuous tailings deposition and build-up, in general agreement with expectations. The deposited sand is, however, more mobile than anticipated. It is indeed expected that when sand settles, it forms a layer that is either granular or gelled (Figure 2.2) which is static (if granular) or flows much slower (if gelled). The newly formed deposit is therefore more fluid than originally foreseen from previous experience. This is consistent with what is observed by comparing 1DV and 2DV model and should be investigated further.

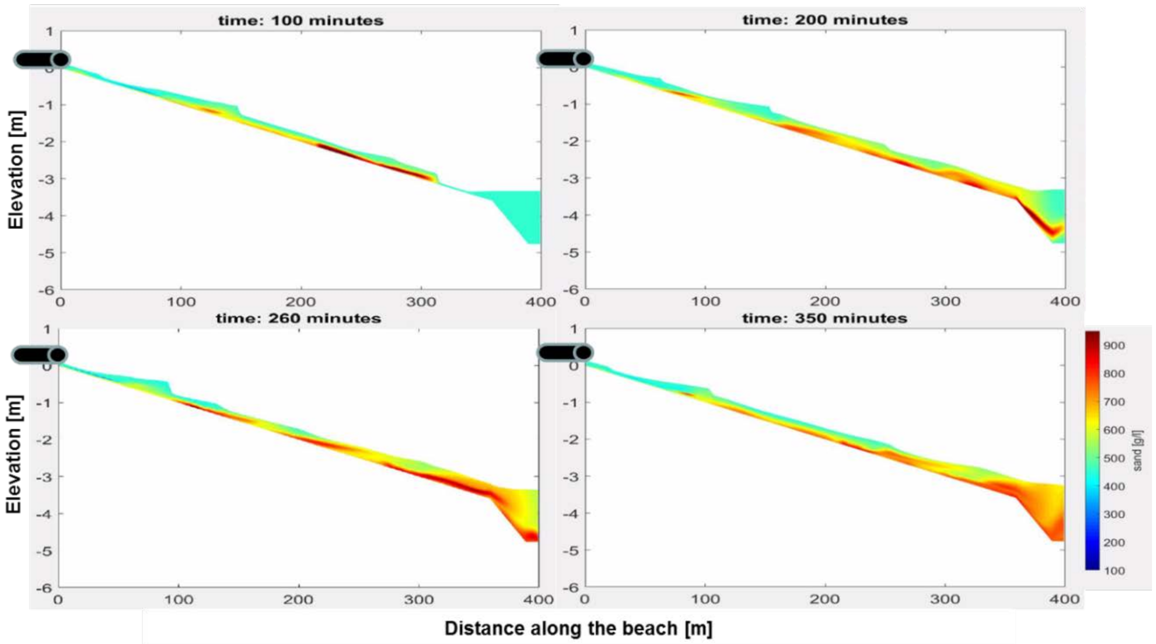

Figure 3.15 Continuous flow of fresh TT (yield stress = 30 Pa down a 1% 400 m slope, after about 1.5 h; 3.5; 4.5; and 6 h from the beginning of deposition. Colours indicate sand concentration. The colour scales differ due the very different initial sand content in TT and FFT.

This IOL application shows that the general deposition and sand segregation behaviour is well represented and reproduced by D3Ds. The model reacts as expected to the increase in rheological properties (i.e. yield strength). D3Ds is able to model the interaction between tailings of different types or ages, i.e. fresh TT over aged FFT.

While this first application showed interesting preliminary results, it also raised various items which need attention, further investigation and possibly development. Some of these items have already been highlighted in other sections of this report:
1. Sensitivity of the model to the rheology of the carrier fluid and its dependency on sand concentration (i.e. SFR). This influences the flow behaviour (i.e. likely the surficial flow waves observed so far) and the bed generated by sand settling;
2. Erosion or pick-up of the aged or underlined tailings layer by the fresh incoming flow;
3. Mixing mechanisms between the two layers, and the resulting rheological properties if the two layers are of different initial rheology (i.e. different carrier fluids);
4. The role of density stratification versus yield stress when determining mixing or displacement of existing tailings.

4 Current status and steps forward

This study delivered a D3Ds version that can model tailing depositional flow and sand settling in 2DV mode, in line with theoretical expectation and laboratory observations. This model can at this stage be utilized for general assessment of oil sands tailings deposition behaviour (see IOL application). These achievements build trust on D3Ds as an important tool to model tailings depositional behaviour. At the same time, this study and specific oil sand industry needs have highlighted the need for additional verification and development necessary to bring D3Ds to quantitative engineering prediction level.

The next verification and development steps should focus on:

1. The current version of D3Ds to verify and improve predicting capabilities, specifically related to:
    a. The sensitivity of D3Ds to rheological parameters, sand settling and mixing of sand and fines;
    b. The flowing tailings – sand bed interaction, and the strength of the sand bed;
2. Adding the time dependent strength component due to thixotropy or dewatering
3. Extend the simulations to 3D

These verification and developments are foreseen for the Phase II of this project, which is currently starting in collaboration with the Institute for Oil Sands Innovation (IOSI), the TUD (Dr. Arno Talmon and Prof. Cees van Rhee) and Carleton University (Prof. Paul Simms)

Finally, it must be mentioned that numerical models, such as D3Ds, are a tool that can be effectively utilized for example to: perform various operational scenarios evaluation quickly and economically; help design flume tests; or extrapolate flume or field trials to reality. However, numerical models must be used always in combination with data and theory, and need to be setup consistently with the question to be answered. This means that knowledge of the model characteristics and limitations, and an adequate dataset to setup and verify the model are crucial.

Necessary data include input parameters (e.g. rheological properties) as well as validation information (e.g. flume tests or field data topography). In this sense, the first and most important need is the development of an appropriate dataset of rheological properties (i.e. yield stress *and* viscosity) and their variation with time (i.e. dewatering) and sand concentration. It is recommended to develop a robust laboratory dataset that follows procedures designed for polymeric treated tailings, so that rheology and strength can be measured as dewatering or aging occurs. It is further recommended to implement this numerical model in parallel to flume and field tests. This model can be utilized a-priori to design the test, and after the test to verify and interpret the results, validate the model and perform simulations of other alternatives, which may save the need to perform numerous flume tests or field trials.

Finally, as done for IOL in parallel to this study, it is encouraged to use D3Ds on actual oil sands applications during and in parallel to its development stage. When the limitation of the models are known and kept into account, this can provide useful insights to the specific applications (see IOL). At the same time it contributes to building up experience with the model and highlight aspects that may need further verification and development that can be brought back into the model development trajectory.

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