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Comparing various thixotropic models and their performance in predicting flow behaviour of treated tailings

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Abstract

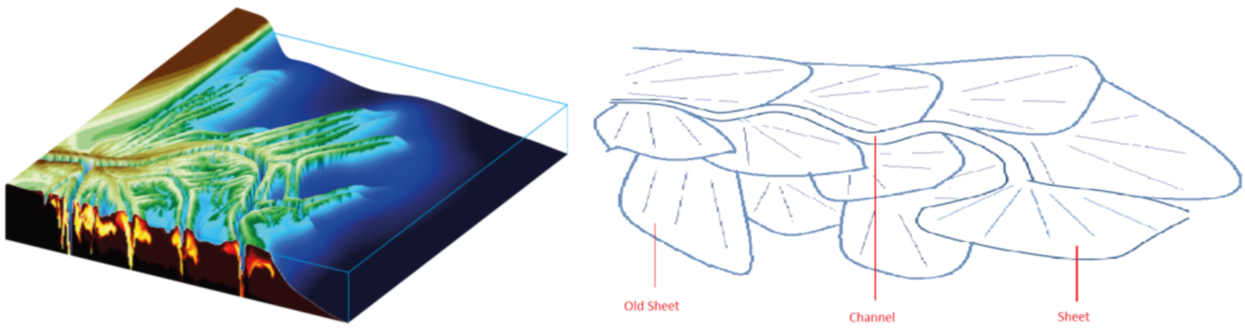
Treated tailings are known for their thixotropic rheological characteristics under flow, i.e. strength loss with time under constant shear rate, and strength gain at rest. Understanding and accurately quantifying the time-dependency of strength in treated tailings is crucial to sediment management operations such as mixing, pumping, hydraulic transport, flow and deposition. The are several thixotropic models available in the literature. This paper sheds light on the similarities and differences of representative thixotropic models and their pros and cons. Particular attention is paid to the model's limitations/advantages in flow modelling. The performance of the models in predicting the flow behaviour of flocculated mature fine tailings (f-MFT) down a deposit's beach is investigated. Particularly the free-surface profile is affected, which will have many practical implications for deposit management.

1 Introduction

1.1 Problem statement

Tailings management is critical for the mining industry, especially in the context of heightened scrutiny by the public and investors in the light of recent dam failures and environmental concerns. Increasing scientific understanding of tailings flow deposition likely has potential large payoffs in improving tailings deposit performance. To this end, Deltares has been introducing non-Newtonian fluid dynamics into its proprietary Delft3Ds Computational Fluid Dynamics (CFD) code, which has originally been developed for the simulation of free surface flows in rivers, estuaries and seas. This implementation is recently driven by the need of the oil sands industry to manage complex tailings deposition schemes, such as deposition of sand-fines mixtures where estimating segregation is important, or introduction of one type of tailings into a pre-existing impoundment with different characteristics (such as a high sands content tailings into a fines dominated deposit).

Tailings behaviours involves a range of complex phenomena, including non-Newtonian rheology, segregation of the coarse fraction (i.e. sand), the release of fines, laminar flow and channel formation. These commonly observed tailings attributes are similar to those seen in deltaic depositions, as illustrated in Figure 1.



(a) (b)

Figure 1 (a) Mississippi type sand delta deposit calculated with Delft3D (van der Vegt et al. 2015); (b) Typical deposition pattern observed in subaerial tailings disposal (van Es 2017)

In addition to Figure 1a, in deposition, lobe formation is seen as well, followed by channel formation, which may fan out to lobes again transporting the material to distant corners of the deposit, Figure 1b.

The 3D and 2DV simulations with Delft3Ds have been shown to accurately capture and model sand segregation. By virtue of the modelled shear settling, calculated sand concentrations are found to be the highest in a self-formed bed layer. Typical results have been presented in earlier conferences and workshops, e.g. Talmon et al. (2018), Figure 2.

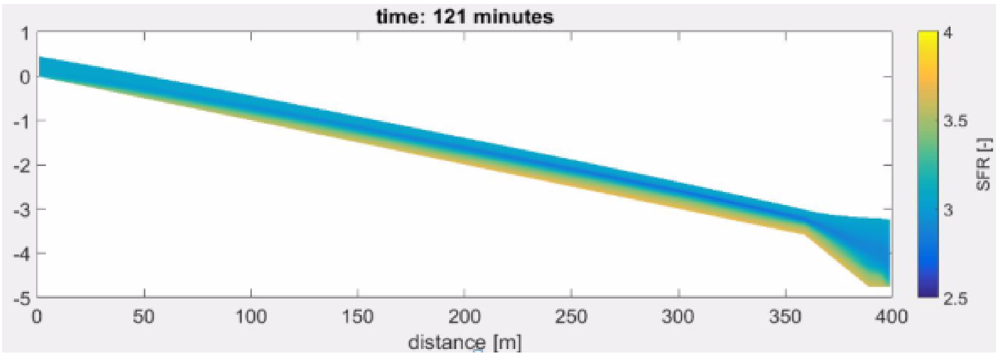


Figure 2 Calculated segregation with Delft3Ds quantified by the sand-to-fines ratio (SFR), van Es (2017), Talmon et al. (2018)

Parent & Simms (2019) applied Material Point Modelling (MPM) utilising a thixotropic model to simulate a pipe depositing tailings at a flow rate of 0.1 m^3/s from a 0.30 m diameter pipe onto an inclined subaerial plane with a slope of $i = 0.03$. The tailings have a density of $\rho = 1{,}500$ kg/m^3. The result is shown in Figure 3. The flow is interrupted for a short while when the pipe is hoisted.

Deposition flow modelling is important to understand the build-up of deposits in TSFs (Tailings Storage Facilities) and how this can be influenced by operational measures (tailings deposition management). This paper addresses the development from the already mentioned steady state rheology with segregating sand through to time-dependent properties (i.e. thixotropy). The layering of deposits and release of fines can be attributed to shear settling, while thixotropy eventual in combination with settling, may be responsible for the typical deltaic formation often seen on tailings beaches, influencing channel width, internal profiles and transients. Analytical theory (Talmon 2023) and recent Material Point Method (Parent & Simms 2019) calculations indicate that channel formation may be caused by thixotropy. In this study, we explore the influence of thixotropy through the use of a numerical flow model with free surface, incorporating time-dependent rheology, to simulate flows in TSFs.

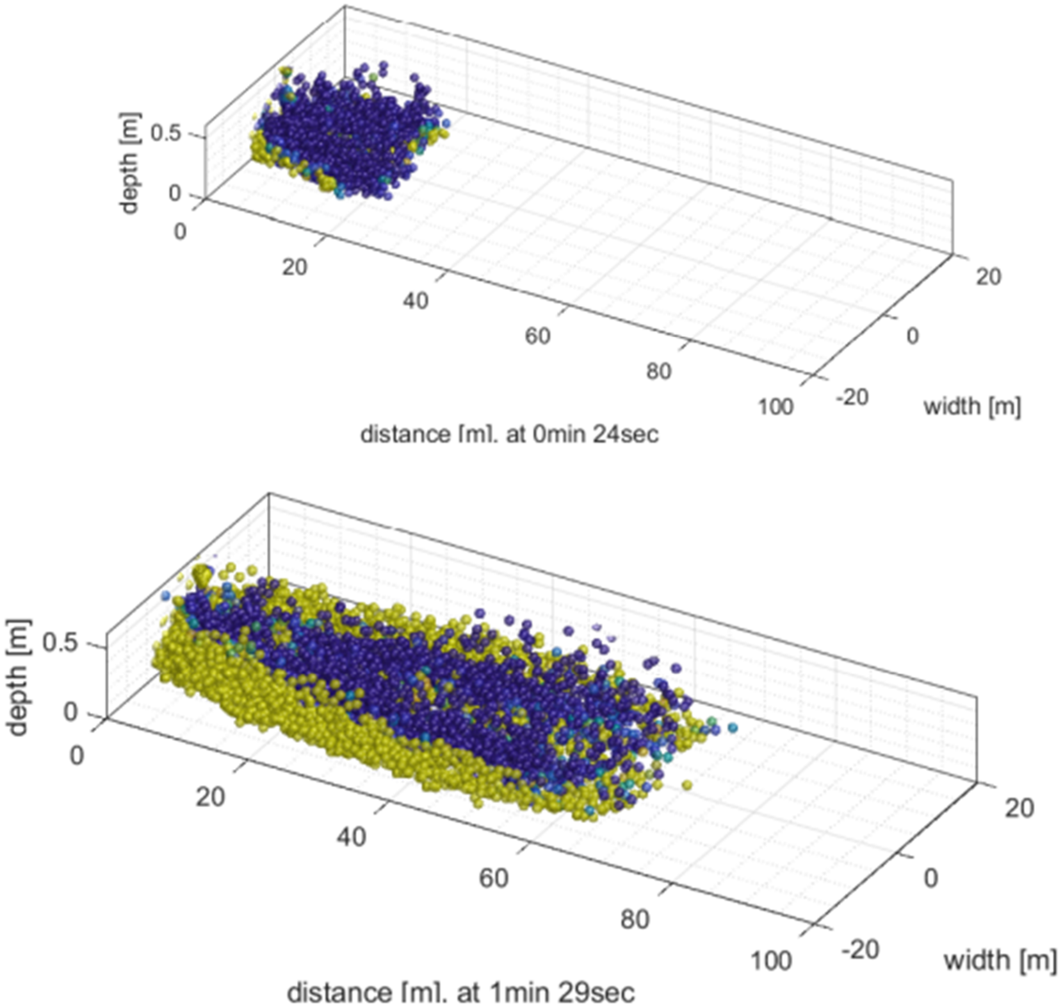


Figure 3 MPM simulation, yellow represents aged material of high viscosity, blue material is discharged after a short pause and flows at with low viscosity, Parent & Simms (2019)

1.2 Objective

The aim of this study is to increase the realism of flow and deposition behaviour through the potential inclusion of thixotropic rheology, by comparing different rheological approaches pursued at various institutes (Parent & Simms 2019; Talmon et al. 2018, 2021), with a particular focus on their application to oil sands materials.

The present research was borne out an industry question (Meshkati & Nik 2020, pers. comm.), noting different approaches in constitutive thixotropy modelling in preparation for implementation in the Delft3Ds model of Deltares (Talmon et al. 2019), in actual MPM modelling of sand capping by Deltares (Martinelli et al. 2022) and the thixotropy modelling by Parent & Simms (2019). For vehicle, we have chosen a CFD approach.

1.3 Approach

To study the effect of various thixotropic models, we utilised a dedicated CFD code. This numerical code is in principle developed in 3D, though calculations are restricted to 2DV (V for vertical) to capture essentials, for simplicity and efficiency. Analytical code verifications are often conducted in 1DV, i.e. steady flow. The definitions of these dimensions are given in Figure 4.

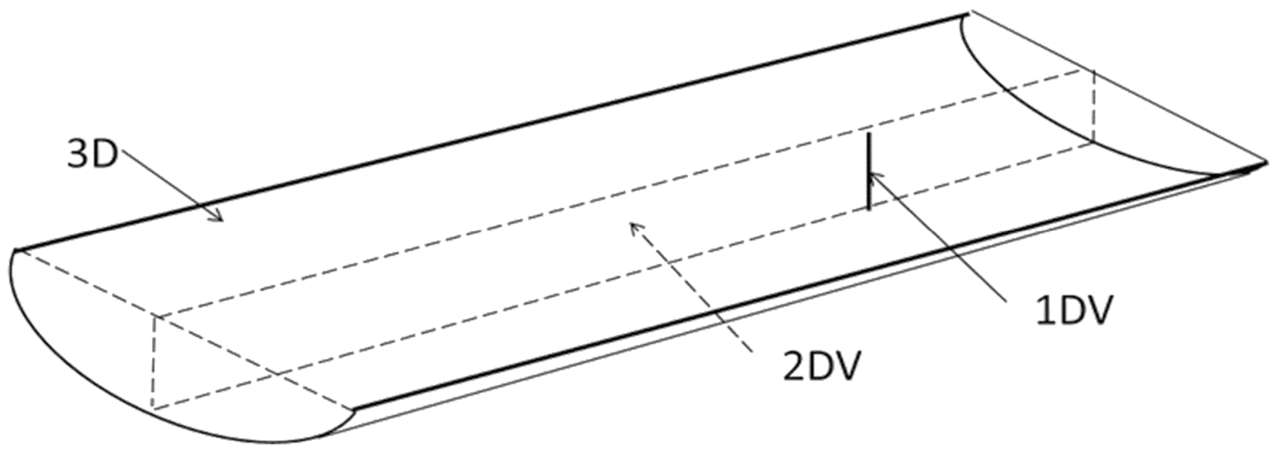


Figure 4 Definition sketch model domain

2 Theory

2.1 Rheological models

There are several thixotropic rheological models available which can be broadly grouped into two categories:

1. Explicit expressions for shear stress and how thixotropy affects those (e.g. Moore 1959; Houska 1981; Toorman 1994).
2. Explicit expressions for apparent viscosity and how thixotropy affects those, known also as viscosity bifurcation models (e.g. Coussot et al. 2002; Hewitt & Balmforth 2013; Mizani et al. 2017; Parent & Simms 2019).

The thixotropy in these models is quantified by the so-called structure parameter λ, which varies in time and space (Moore 1959) and affects local rheological parameters. The structure and flow field calculation are coupled in a two-way manner. The Moore model includes a (bounded) self-growth term and a decay term governed by shear and is linear in its structure parameter λ: the kinetic equation. This allows studies into the influence of:

- Self-recovery with time.
- Decay of properties/structure with shear rate.
- Equilibrium of both.

However, it is important to note that this is of course a simplification and such models do not consider the effects of shear on the aggregation of clay platelets or the irreversible shearing down of flocculated materials under intense shearing. For instance, some kaolinite mixtures have been seen to strengthen during the course of rheometry (van de Ree 2015; Sun 2018) which is a deviation of common experience with clay-only systems. It is also known that flocculated materials are irreversibly sheared down (rheomalaxis) under intense shearing. We do not consider these effects in our model study.

2.2 Equilibrium flow curve (EFC) – the unique characterisation

For thixotropic materials, the flow curve in the rheological diagram is characterised by the equilibrium flow curve (EFC), which is the unique rheological condition that is reached when transient effects have ceased (i.e. where the growth of structure and decay of structure equilibrate), Toorman (1994). In (highly) thixotropic substances the EFC has a distinct minimum, Figure 5.

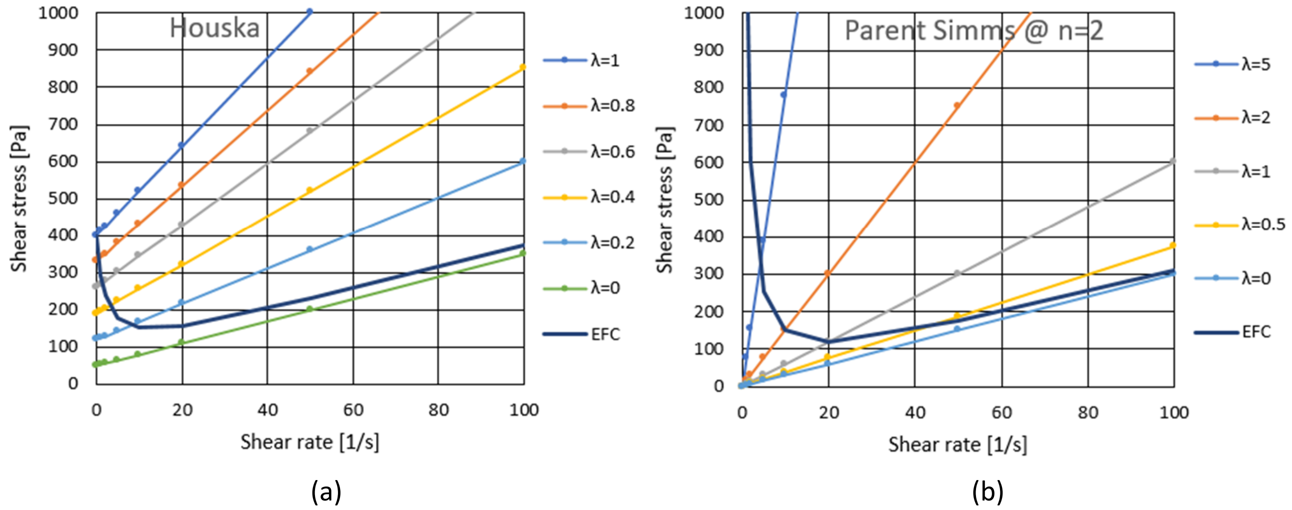


Figure 5 EFC (equilibrium flow curve) of a strongly thixotropic material drawn against a background of constant λ curves, e.g. constant structure curves (CSC)'s: (a) Houska; (b) Parent Simms constitutive model

For shear stresses below this minimum, the structure will increase and the shear rate will drop to zero and stagnant material or bulk flow may develop. Above this minimum, dual solutions for shear rate can exist for a single shear stress, which may trigger pattern formation. For 2DV flow, stratigraphic pattern formation can be expected when the flow rate is intermittent, allowing the already deposited material to age somewhat (Parent & Simms 2019). In a 1DV velocity profile, a combination of high shear at the wall and a virtual absence of shear in the upper part of flow may be expected (because of high structure), potentially resulting in an unsheared plug riding over weak or sheared down material. A configuration reminiscent to Bingham plug flow, but without the parabolic sheared profile along the wall, but rather a nearly linear steeper velocity profile.

The plotted series of CSC curves in Figure 5 is akin to the influence of sand on rheology, which can strengthen the material's flow characteristics (modelled in Delft3Ds). These complex thixotropic behaviours must be taken into consideration when designing and modelling tailings management systems, particularly in the context of oil sands materials.

2.3 Mathematical formulations

The thixotropic models used in this study are listed in Table 1, including the constitutive equations for structure and state. These equations form the basis for understanding and predicting the flow and rheological behaviour of thixotropic materials.

Because of its generality, the Houska model is best suited to be added to the already existing steady state rheological models in the Delft3Ds code, Talmon et al. (2018). The value of the structure parameter in the Houska model falls within the range of $0<\lambda<1$ (or λ_0) in contrary to the Parent Simms model (Coussot type) which has no upper bound and can extend from 0 to infinity ∞. As depicted in Figure 5, this lack of an upper bound is evident in the flow curve diagram for the Parent Simms model. The Houska model has a distinct static yield stress (SYS) and dynamic yield stress (DYS) that are defined at $\lambda = 1$ and $\lambda = 0$, respectively. The Coussot model and the Parent Simms model are models with fewer model input parameters, but their equation of state (a viscosity model) does not align well with the existing models in Delft3Ds.

Table 1 Applied constitutive thixotropy models.

Name	Structure equation	Equation of state	Parameters
Houska (1981)	$\frac{D\lambda}{Dt} = a(\lambda_0 - \lambda) - b\lambda\lvert\dot{\gamma}\rvert$	$\tau = \tau_\infty + \lambda(\tau_0 - \tau_\infty) +$ $+(\mu_\infty + \lambda c)\lvert\dot{\gamma}\rvert^n$ $\mu_a = \frac{\tau}{\lvert\dot{\gamma}\rvert}$	τ = shear stress τ_0 = upper yield stress (@λ = 1) τ_∞ = lower yield stress (@λ = 0) μ_a = apparent viscosity μ_∞ = plastic viscosity (@λ = 0) λ = structure parameter λ_0 = initial structure (0–1) *a* = recovery parameter *b* = shear down parameter *c* = increment viscosity *n* = flow index (*n* = 1 Bingh. CSC)
Parent & Simms (2019)	$\frac{D\lambda}{Dt} = \frac{1}{T} - \alpha\lambda\lvert\dot{\gamma}\rvert$	$\mu_a = (1 + \lambda^n)\mu_0$	*T* = timescale recovery *α* = shear down parameter μ_0 = minimum viscosity (@λ = 0) *n* = non-linearity index

2.4 Fitting/comparing EFC of rheological models

To incorporate thixotropy into a flow model equipped with rheology, additional parameters besides yield stresses must be determined (*a, b, c,* λ_0 or *α, T, n*), see Table 1. There are different ways to determine these parameters, a practical method is to fit the constitutive model through the times series of a rheological test, by mimicking its testing protocol, eventually supplied with information of a dedicated additional test. Mizani et al. (2017) present rheological data for flocculated MFT and associated fit by a thixotropic model. Talmon et al. (2021) provide data for flocculated MFT including a fit by the Houska model, see Figure 6. In our numerical work, which will be presented later in this paper, we choose to use this data and the associated Houska fit, Figure 6. A stress ramp-up (CSS: red curve) was utilised to determine the SYS. A cyclic increase and decrease in shear rate (CSR) were applied to determine the time-dependent flow curve and the convergence to remoulded conditions.

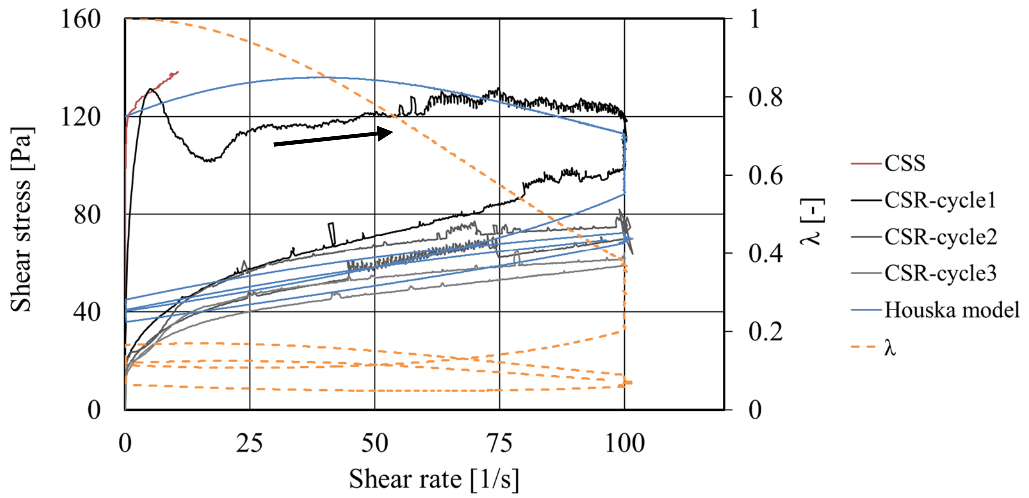


Figure 6 Flocculated MFT 34%w rheological measurement including rheological fit by the Houska model: shear stress and associated structure lambda λ, after Talmon et al. (2021)

The minimum in the EFC is important to fluid flow because at lower shear stresses the material tends to solidify. The mathematical expressions for this are given in Table 2. For both models, if the λ values are higher than the values listed in the table, the flow becomes unstable and can either bifurcate to high shear rates or almost no shear.

Table 2 Coordinates of the minimum in the EFC of the two rheological models

Houska	Parent Simms
$\lambda_{\min} = \sqrt{\dfrac{\lambda_0 \mu_\infty}{(\tau_{y,0} - \tau_{y,\infty})\beta - c}}$	$\lambda_{min} = (n-1)^{-1/n}$
$\dot{\gamma}_{min} = \dfrac{\lambda_0/\lambda_{min} - 1}{\beta}$	$\dot{\gamma}_{min} = \dfrac{1}{\alpha T}(n-1)^{1/n}$
$\tau_{min} = \tau_{y,\infty} + 2\dfrac{\mu_\infty}{\beta}\dfrac{\lambda_0}{\lambda_{min}} - \dfrac{\mu_\infty}{\beta}\left(1 - \dfrac{\lambda_0 c}{\mu_\infty}\right)$	$\tau_{min} = \dfrac{\mu_0}{\alpha T} n(n-1)^{\frac{1-n}{n}}$

With the EFC as the unique characterisation of the flow curve, the Parent Simms model is fitted to the EFC of the Houska model, Figure 7. The Parent Simms model will underestimate the rheology of the rheometric time-series at low shear rate, because of its Newtonian CSC's.

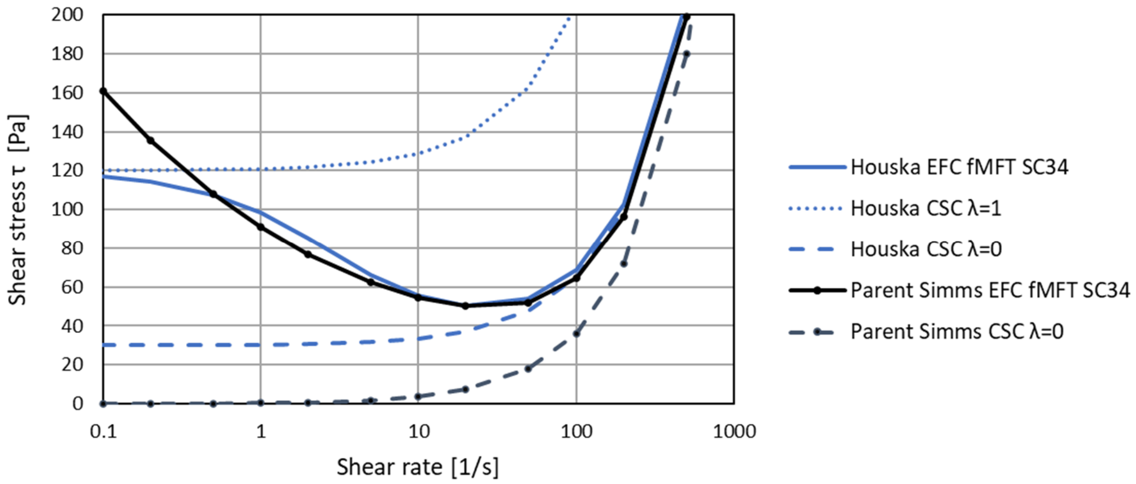


Figure 7 Equilibrium flow curves (EFC) by Parent Simms and Houska for flocculated MFT at a Solids Content (SC) = 34%wt

It is deemed important that the right-hand side branches near the minimum are similar, because the conditions of the bottom shear layer are expected to be situated here. The parameter values of both models are listed in Table 3.

Table 3 Parameters for the simulation of rheological behaviour of flocculated MFT at SC34%wt (Talmon et al. 2021). The rheometry was fitted with the Houska model and Parent Simms's EFC was fitted to Houska's EFC

Houska model	value	Parent Simms model	value
yield stress (at λ = 0): $\tau_{y,\infty}$ [Pa]	30		
plastic viscosity (at λ = 0): μ_∞ [Pa s]	0.35	viscosity (at λ = 0): μ_0 [Pa s]	0.36
yield stress (at λ = 1): τ_0 [Pa]	120	non-linearity index: *n* [-]	1.25
viscosity increment (λ = 0 to 1): c [Pa s]	0.5		
structure self-recovery: *a* [1/s]	0.0003	timescale recovery: *T* [s]	120
structure shear breakdown: *b* [-]	0.0001	structure shear down: α	0.0001
viscosity regularisation: *m* [s]	1,000		

Starting from an unremoulded sample, the CSR rheometric test emphasises the decay of structure. The self-recovery component commences to play a role at the low shear rates. So, the parameter values for recovery are less accurate than the shear down coefficients (*b* or α). Additional intermittent rheometric tests would provide better data for self-recovery of the sample.

3 Flow calculations

3.1 Analytical prediction

A typical prototype tailings discharge is 1 m^3/s. Upon assuming a 10 m wide channel, the discharge per unit width is q = 0.1 m^2/s. We discharge over a beach with a slope of i = 0.02 (which is in between the shown Delft3Ds and MPM simulation) and a mixture density of 1,500 kg/m^3. For prediction and reference, the 1DV velocity profile of the Houska model is calculated by means of the analytical theory of Ahmadpour and Sadeghy (2013), Figure 8.

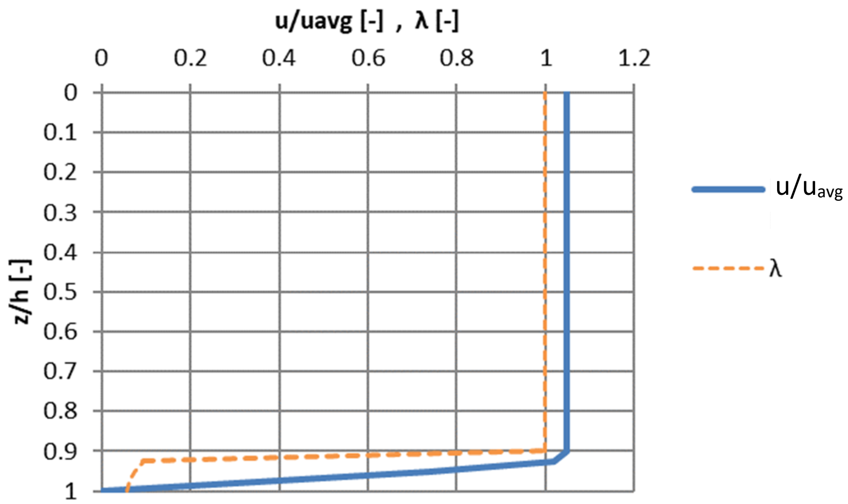


Figure 8 Predicted equilibrium profile for Houska fMFT SC34, q = 0.1 m^2/s, slope i = 0.02 [-], density 1,500 kg/m^3, output: h = 0.18 m, U_{avg} = 0.55 m/s

The predicted theoretical velocity profile characterises by a 90% unsheared portion (also called plug), where the structure parameter has risen substantially over its value in the shear layer, with a maximum attainable value of 1 (but not necessarily equal to 1). The theory assumes that the shear stress at the underside of the plug is equal to the shear stress at the minimum of the EFC.

The downstream adaptation lengths of structure in the shear zone of both models are (assuming the existence of an EFC flow profile over the entire travelling distance):

- Houska: $x_0 = \frac{\lambda_e}{\lambda_0}\frac{u}{a}$ = 0.08/1 0.55/2 /0.0003 = 60 m (velocity taken in the middle of the shear layer).
- Parent Simms: $x_0 = \lambda_e T u$ = 31 T 0.55/2 = 90 m (in this model at n = 1.25, $\lambda_e \sim \lambda_{min}$ = 3).

So, we see here that the length scale of thixotropy is determined by the recovery timescale and equilibrium structure. This equilibrium structure is though a function of shear, recovery coefficients and shear rate. With flow conditions close to this minimum, λ_{min} is a good estimate for equilibrium structure.

Note that the value of the structure parameter is remarkably different between the two constitutive models, but it is just a mathematical parameter. For upstream condition, it could be relevant how to initiate: above λ_{min} we start in an unstable regime (left branch of the EFC) or below λ_{min}, ending up in the right-hand side branch of the EFC, if structure does not adapt quickly.

3.2 Simulation of thixotropy by CFD model

The new CFD model is a fully implicit flow solver with free surface, with a currently employed calculation domain of 128 × 32 × 1 grid cells, a vertical stretchable grid(cosine) and a maximum applied grid stretching factor 10. It has a no-slip bottom boundary condition, viscosity regularisation and flow rate and structure parameter λ are given on inflow.

We simulate beach deposition with a constant flow rate at inlet, a uniform velocity at inlet, a uniform density throughout the whole domain, a variable local depth (calculated by the model) and a constant uniform (low) structure at inlet. This initial structure represents a certain shear condition originating from a plunge pool or other discharge construction. The material may hence gain strength in the upper part of the flow where shear is less and may lose further strength in the lower sheared part of the flow. Depending on initial conditions this is expected to be accompanied by (slight) surface level variations which we want to understand, because those may be important to 3D flows (pattern formation).

The calculations are conducted for two different types of constitutive rheological models: the Houska model as well as the Parent Simms model. We simulate the deposition of fMFT at SC34% over a 200 m long base (beach), its rheology is derived from fitting of the rheometric test and associated EFC's are displayed in Figure 7.

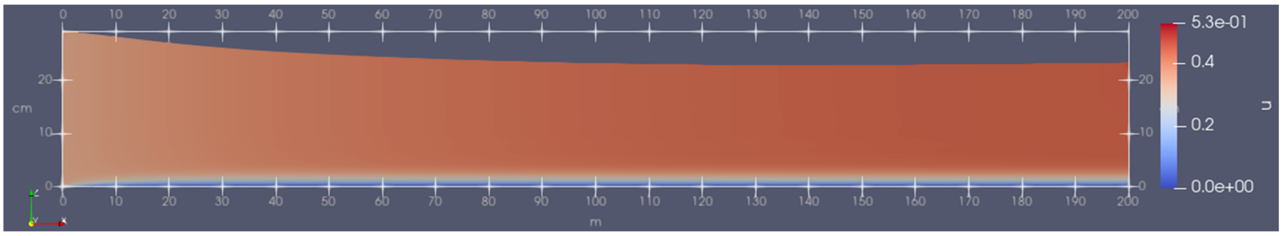
In case of the Houska model viscosity regularisation is necessary. The Papanastasiou (1987) method was applied to the yield stress terms of the equation of state, and to prevent the risk of dividing by zero in the calculation of apparent viscosity, a small number was added in the denominator. Such a measure is not necessary for the Parent Simms constitutive model.

The mentioned reference flow rate per unit width of q = 0.1 m^2/s is expected to produce mayor plug flow, Figure 8. To test model behaviour flow rates of 0.2 and 0.5 m^2/s have also been simulated. The initial flow depth at start was 0.2 m (whole domain), as this is about what is expected for equilibrium flow down the beach for given equilibrium rheology.

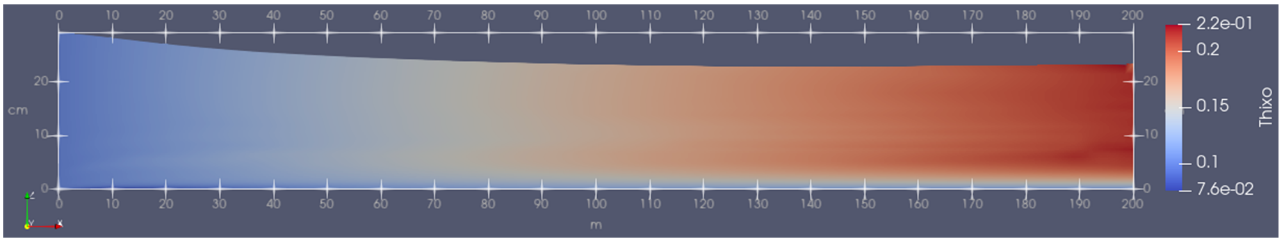
In most of the simulations a greater tailings depth is generated near the inlet, decreasing over a distance of about 50 m or more. Particularly the Houska model revealed a development of downstream travelling surface waves, leading to a continuous harmonic variation of flow depth at the inlet.

3.2.1 Full rheological calculations

Figure 9 shows the calculation results by the Houska model, visualised by ParaView software. The thixotropy plot shows increasing λ values in the uniform bulk velocity region. The structure has decreased a bit in the shear layer compared to inlet conditions. Given the slope and density, it follows that the shear stress in the lower half of this region is about equal to the minimum (50 Pa) of the EFC curve, shown in Figure 7. Basically, the conditions in the bulk are situated at the unsheared vertical axis of the flow curve diagram, Figure 7. The shear rate in the shear zone corresponds to those around the minimum of the EFC, as indicated in Figure 7. The calculated flow profile and depth correspond to the theory, see Figure 8. After initial start-up waves left the computational domain, downstream travelling surface waves continued to develop.



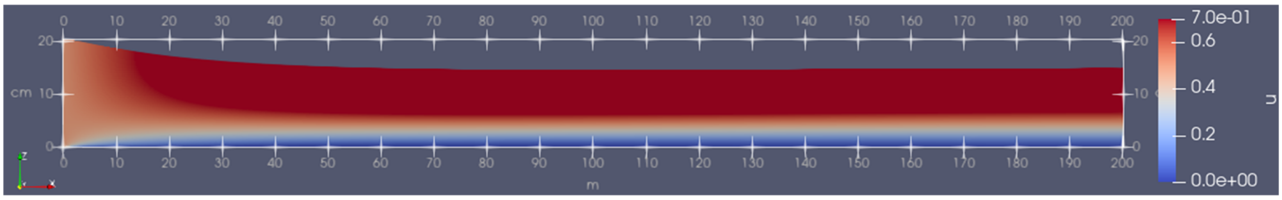
(a)



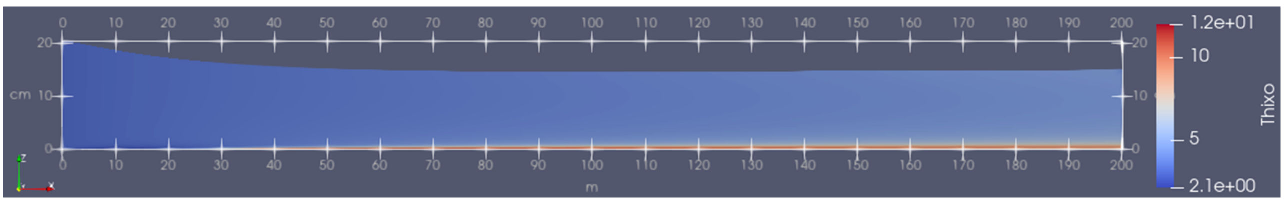
(b)

Figure 9 Calculation results after 60 minutes (flow: left to right): (a) Flow velocities u [m/s]; (b) Structure λ [-] 'Thixo'. Houska constitutive model, vertical scale 100× magnified.

The full thixotropy calculation with the Parent Simms constitutive model, Figure 10, leads to a smaller tailings depth and higher flow velocities than the Houska model. The velocity profile is smoother, e.g. velocity gradients are smaller than with the Houska model. The structure in the upper and central part of the flow grows from its initial value (λ = 3) at the minimum of the EFC to about λ = 5. In the bottom boundary layer λ has grown much higher: to 12. This material is comparably older than in the upper part of the flow. This pattern is the opposite of that calculated by the Houska model. The shear stresses find themselves below the minimum of the EFC. Shear rates are smaller than at the minimum of the EFC. Compared to the Houska model, the flow conditions are at and below the remoulded flow curve (CSC λ = 0: blue dashed curve) of the Houska model, Figure 7. After start-up waves no further waves were observed.



(a)



(b)

Figure 10 Calculation results after 60 minutes (flow: left to right): (a) Flow velocities u; (b) Structure λ. Parent Simms constitutive model, vertical scale 100× magnified

3.2.2 *Simplified conditions*

Tests have been conducted with both models for different simplifications of the constitutive model: Newtonian (Figure 11), Bingham (Figure 12), at different flow rates. It appeared that after an initial transient, the flow depth of the Newtonian calculation was according to theory. A Bingham calculation with the Houska model fixated at $\lambda = 0$ resulted in only a slightly thicker tailings layer than according to theory, which is attributed to discretisation errors. Grid refinement in the bottom area, by grid stretching, did not have any detectable influence. No surface waves occurred for Newtonian conditions.

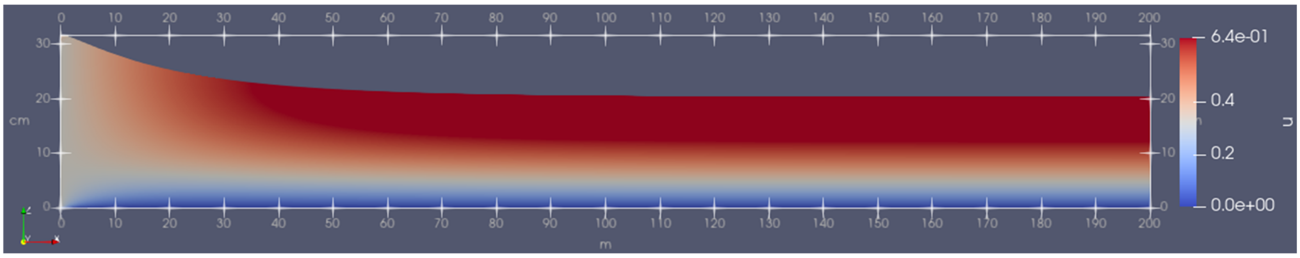


Figure 11 Newtonian configuration of Parent Simms model, plastic viscosity 8 [Pa s] (identical result for Houska reduced to Newtonian), vertical scale 100× magnified.

For n = 1 there appear for equilibrated structure a yield stress and a plastic viscosity in the Parent Simms model: e.g. Bingham EFC conditions. For the utilised parameter values these are respectively 30 [Pa] and 0.36 [Pa s]. Given bottom slope and density, the theoretical flow depth is 0.15 m. The Parent Simms model calculates a smaller non-varying depth, but thixotropy might still be developing downstream. The Houska model configured as a Bingham model produced surface waves and a periodic variation of flow velocities. Flow depth varied around 0.15 m, corroborating with its theoretical value.

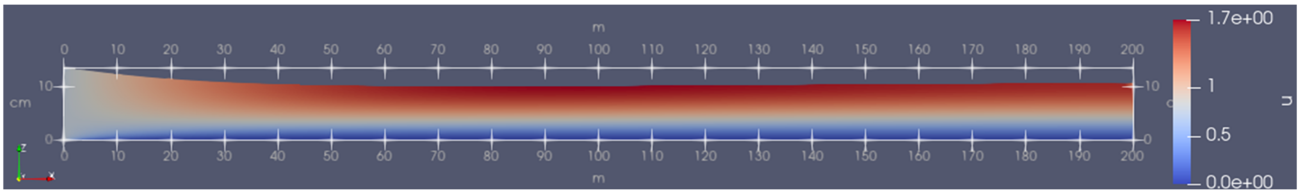


Figure 12 Bingham EFC configuration of Parent Simms model (non-linearity index changed to *n* = 1), after 50 min, vertical scale 100× magnified

It has also been investigated what occurs when the inlet is shut off, Figure 13, utilising the Houska model: the tailings surface level drops a bit to the point where down-pull down the slope is being balanced by a shear stress of the order of the minimum in the flow curve. Flow velocities approach zero (CFD is a flow model after all).

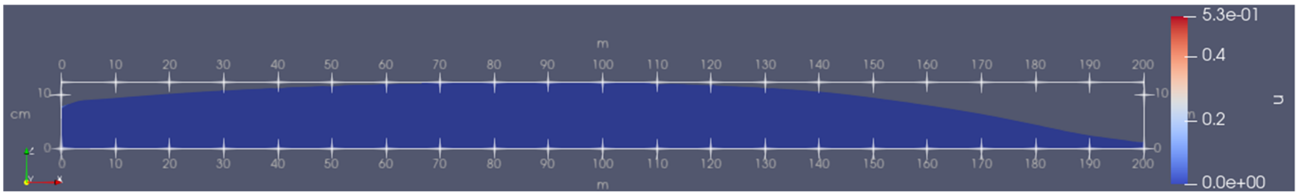


Figure 13 Houska constitutive model, t = 20 min. Calculation domain initially consisted of 0.2 m thick layer of material, material influx zero, vertical scale 100× magnified, span of velocities in legend reflects initial flow velocities at start up

3.2.3 Evaluation

The results of the Houska thixotropic simulations differed from Parent Simms thixotropic simulations. This is attributable to a different span of their rheological characterisation, despite identical EFC. Different dynamic behaviour might be attributable to different courses of their EFC's, typical Newtonian for the Parent Simms model.

Our calculations show that thixotropy steepens/emphasises internal gradients in the Houska model, which may have consequences when settling solids are involved, affecting fines capture.

Flow depths at the inlet increase due to a non-equilibrated inflow combined with transient internal development. The resulting free-surface profile qualitatively corroborates with the concave shape of tailing deposition profiles forming the basis of for instance the high level entropy based modelling of McPhail and Blight (1998).

To achieve a simulation as realistic as possible of tailings deposition, we need to consider more than just the remoulded rheology, to which we usually limit ourselves in CFD models for practical reasons.

We learned how the choice of constitutive model influences results. We might also need to acknowledge the presence of rheomalaxis in follow-up, suppressing recovery capacity of structure.

Deposition trials of treated tailings are part of the industry's efforts to optimise their management of tailings. Deposition flows are observed to channelise and lobe formation is observed. Sand settles to a certain degree. The Delft3Ds model captures sand segregation, but appears to fall short in pattern formation. MPM thixotropy based simulations by the group of Simms reveal pattern formation tendencies. The impression is that if we extent to 3D we will find it also in the current CFD approach. If so, a strategy could be to merge both approaches, with the risk of being too heavy, it is also possible that segregation is calculated in 2DV along the channel axis, conditions being indicated by thixotropy calculation. Whichever route is taken, it is important that the rheology is well characterised in such site deposition trials, including thixotropy. Examples are given in Talmon et al. (2021).

4 Conclusion

We simulated the subaerial deposition of flocculated MFT by means of a free-surface CFD model, including thixotropy.

Despite the intentionally forced coincidence of their equilibrium rheological properties, the Houska and Parent Simms thixotropic models yielded significant differences attributable to a different span of their rheological constitutive models at low shear rates and the course of their constant structure curves.

The simulations revealed remarkable dynamics providing new insights into the dynamics of deposition flows. The calculations show that thixotropy steepens internal velocity gradients when a yield stress is involved. Particularly the free-surface profile of the deposit is affected, which will have many practical implications for deposit management.

Suggestion to the industry is to acquire rheological measurements including thixotropy in deposition trials or other campaigns to enable research studies which ultimately may lead to simpler high level modelling approaches.

References

Ahmadpour, A & Sadeghy, K 2013, 'An exact solution for laminar, unidirectional flow of Houska thixotropic fluids in a circular pipe', *Journal of Non-Newtonian Fluid Mechanics*, vol. 194, pp. 23–31.

Coussot, TP, Nguyen, QD, Huynh, HT & Bonn, D 2002, 'Avalanche behaviour in yield stress fluids', *Phys Rev Lett,* vol. 88, Article number 175501.

Hewitt, DR & Balmforth, NJ 2013, 'Thixotropic gravity currents', *J Fluid Mech*, vol. 727(2013), p. 5682.

Houska, M 1981, *Engineering Aspects of the Rheology of Thixotropic Liquids*, PhD thesis, Czech Technical University, Prague.

Martinelli, M, Meshkati, E, Luger, D, Talmon, AM, Greenwood, J & Tamagnini, C 2022, 'Modelling of time dependency of strength in tailings using Material Point Modelling (MPM) – Deltaic sand capping application', in *Proceedings of the 7th Int. Oil Sands Tailings Conference*.

McPhail, GI & Blight, GE 1998, 'Predicting tailings beach profiles using energy and entropy', in *Tailings and Mine Waste '98*.

Mizani, S, Simms, P & Wilson, W 2017, 'Rheology for deposition control of polymer-amended oil sands tailings', *Rheol Acta*, doi:10.1007/s00397–017–1015.

Moore, F 1959, 'The rheology of ceramic slips and bodies', *Transactions British Ceramic Society*, vol. 58, pp. 470–494.

Papanastasiou, TC 1987, 'Flows of Materials with Yield', *Journal of Rheology*, vol. 31, no. 5, pp. 385–404.

Parent, E & Simms, P 2019, '3D simulations of dam breach and deposition using viscosity bifurcation rheology', in *Proceedings of Tailings and Mine Waste 2019*, Vancouver, Canada.

Sun, Y 2018, *Recovery of thickened kaolinite suspension properties through shear*, MSc thesis, UoA, Edmonton, Canada.

Talmon, AM 2023, 'Bed pattern initiation in non-Newtonian laminar deposition flow', *Edmonton Hydrotransport 2023* (submitted).

Talmon, AM, Hanssen, JLJ, van Maren, DS, Simms, PH, Sittoni, L, van Kester, J, Uittenbogaard, R, Winterwerp, JC & van Rhee, C 2018, 'Numerical modelling of tailings flow, sand segregation and sand co-deposition: latest developments and applications', *IOSTC*, Edmonton, Canada.

Talmon, AM, Meshkati, E, van Kessel, T, Lelieveld, T, Goda, APK & Trifkovic, M 2021, 'On thixotropy of flocculated mature fine tailings: rheometry and lumped structure parameter modelling', in *Proceedings of Tailings and Mine Waste Conference,* Banff, Canada.

Talmon, AM, Sittoni, L & Meshkati, E 2019, A research trajectory towards improving fines capture prediction in with Delft3D-slurry – Phase II, rep. 11201392–000-ZKS-0004_v0.1, project IOSI 2017–08.

Toorman, EA 1994, 'An analytical solution for the velocity and shear rate distribution, of non-ideal Bingham fluids in concentric cylinder viscometers', *Rheol Acta*, vol. 33, pp. 193–202.

van de Ree, THB 2015, *Deposition of high density tailings on beaches*, MSc thesis Delft University of Technology.

van der Vegt, H, Storms, JEA, Walstra, DJR & Howes, NC 2015, 'Analysis tools to quantify the variability in deltaic geological model using Delft3D simulation results', in *Second EAGE Conference on Forward Modelling of Sedimentary Systems*.

van Es, HE 2017, *Development of a numerical model for dynamic depositioning of non-Newtonian slurries*, MSc thesis, Delft University of Technology.