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Rheology for deposition control and deposit failure risk analysis

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Abstract

Application of rheology to the post-deposition behaviour of tailings is important for the design of the slope of the impoundment, control of layering for purposes of strength enhancement through desiccation, properly describing the mixing of different tailings streams and for dam breach consequence analysis. This paper aims to advance the understanding of tailings rheology in the post-deposition context to aid all of these applications. Firstly, thixotropy and its quantitative implications for beach slope and layer geometry are explored using a simple treatment. Secondly, method dependency in yield stress measurement is discussed, along with how such uncertainty can be practically handled by considering the appropriate stress path and timescale for a particular application. Finally, numerical simulation using a thixotropic rheology of channel flow down a beach and runout from a dam breach experiment, conducted in a centrifuge, is used to highlight the utility of advanced rheology to such problems. The paper uses data collected from published work on both hard rock and oil sands tailings over the last 15 years.

Keywords: r*heology, tailings geometry, beach slope, rheometry, surface deposition, thixotropy, tailings flow modelling*

1 Introduction

The application of rheology to tailings management is relatively mature in some areas of practice, notably pipeline transport and perhaps thickening, but becomes more empirical once the tailings exit the pipe. In particular there remains uncertainty regarding how rheology correlates with deposition behaviour in the impoundment, and probably much more uncertainty as to how rheology relates to evaluation of potential runouts resulting from a dam breach or failure of a closed landform. For deposition management, the deposition process is complex and includes phenomena such as channelling. Practice seems to be based on preparing some intermediate rheology that prevents tailings backing up and overwhelming of a spigot (yield stress too high) while also preventing the tailings running downslope and accumulating at a low point (yield stress too low). Adequate spreading of tailings is operationally regulated through the use of multiple deposition points and/or deposition in cells. Prediction of the overall slope of thickened tailings impoundments is based on several methods that give relatively consistent results: a good first order estimate appears to be 2 to 3%. Beach slopes at some sites are presented in Simms (2017). Other recent examples are Wenberg et al. (2020) at –3%; Pirouz et al. (2015), who found a 1.5% beach slope for a large pilot trial but for a yield stress of ~10 Pa; and Ruhanen et al. (2018), who found a high beach slope for a pilot paste plant (~6%). Similar sites show depression of the beach slope as the scale of the deposit decreases (for example, Addis & Cunningham (2010)).

More quantitative predictions of tailings geometry involving computational fluid dynamics (CFD) are conducted for certain kinds of deposition and for estimating runouts in the event of an impoundment failure. Figure 1 shows an example of the intrusion of sand tailings into a centrifuge deposit, as happens in some oil sands tailings operations. Here the extent of the mixing and distribution of the sand is strongly affected by the yield stress of centrifuge cake. For the case of dam breach, the rheology is critical to evaluation of the potential runout distance. For models typically employed in practice, the rheology is characterised by yield stress and viscosity, often using the Bingham model. However, as shown by Rana et al. (2021), the yield stress estimated from back analysis to the runout data is model dependent and does not necessarily conform to the expected values from rheology measurements.

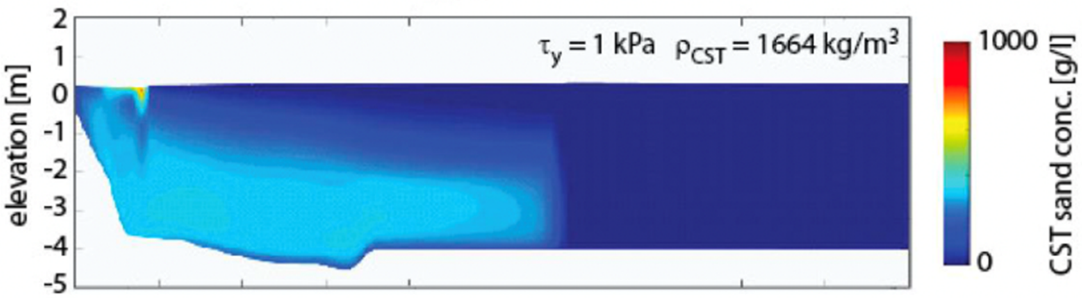


Figure 1 Hypothetical intrusion of sand slurry into centrifuge cake deposit (Deltares, with permission)

This paper summarises a body of work on the rheology of tailings with applications to the post-deposition behaviour of tailings, including reanalysis of data published in this conference series and in several journal papers over the last 15 years. From this reanalysis emerge some interesting and potentially useful findings related to deposition control as well as dam breach consequence analysis. Examples from hard rock mining and oil sands are included.

2 Rheology and post-deposition geometry

As summarised in Simms et al. (2011) and Simms (2017), beaching behaviour is complex, with the thickened tailings following a complex deposition process (initially spreading flow followed by channelled flow, with some backwards deposition occurring as tailings back up in a channel (Li 2011). As stated in in the introduction, there is a growing database of what is achievable for beach slopes at full scale. Multiple methods that analyse the problem from different perspectives are currently used, and include limiting erosion of the deposit by channels, energy dissipation of the flow and stabilising fresh layers. The basics of the more common methods are reviewed in Simms et al. (2011) and in Li (2011).

Beyond estimation of the beach slope, Simms (2007), Henriquez & Simms (2009) and Mizani et al. (2013) have shown that elevation-runout profiles of paste or thickened tailings at different scales can be described by equations based on lubrication theory (LT) assumptions (thin flows, inertia neglected, hydrostatic pressure profiles). These equations were developed by Yuhi & Mei (2004) for analysis of mudflows and assuming a Bingham rheology. From such analyses, equations describing stable elevation-runout profiles have been derived, based on different geometries and different approaches to steady state. Approaches to equilibrium include either the fluid ‘becoming a solid’ from top to bottom, with the shear stress falling below the yield stress at the top of the flow first and then progressing towards the bottom, or the immobilised part of the fluid rising upwards to progressively stop the tailings draining downslope. The former shows a ‘bullnose’ shaped profile where the slope increases towards the toe, while the latter shows an increasing large slope upwards towards the deposition point, or what is generally called ‘concavity’ in this conference series. For the purpose of this paper, we present only the general equation for deposits on a flat slope, suitable for 2D or axisymmetric analyses. In LT theory, the curvature of the slope arises from considerations of equilibrium at the onset of stoppage or flow, where the driving forces are the integration of the hydrostatic pressure and the resisting force is the yield stress:

$$\frac{\partial h}{\partial x} = \frac{\tau}{\rho g H} \tag{1}$$

where:

∂h/∂x = slope of the free surface.

τ = yield stress.

ρ = density.

H is the height of flow about to come to a stop or about to start flowing, which leads to the highest slope being either at the toe for the bullnose shape or at the deposition point, giving a concave profile. Integrating Equation 1 gives:

$$h^2 - h_0^2 = -(x - x_0)\,\frac{2\tau}{\rho g} \tag{2}$$

where h_0 is the height above the base (depth below deposition point) at some horizontal distance x_0. A profile can be predicted by setting $x_0 = 0$ and varying h_0 until the volume of the profile matches the true volume of the deposit. The alternative shapes of the profiles are hereafter termed 'downward' for the bullnose shape at the toe and 'upward' for the concave profile with slope highest at the deposition point.

Simms (2007), Henriquez & Simms (2009), Mizani et al. (2013) and Mizani et al. (2017) showed that the downward profile very well predicts early deposition for bench scale deposits of hard rock and oil sands tailings in flumes and in axisymmetric deposits, including multilayer deposits, up to a some maximum height. Mizani et al. (2013) showed that this is true even for early deposition at the Bulyanhulu site in Tanzania: at least the qualitative shape of the early age deposits resembles the downward profiles predicted by LT. In Mizani et al. (2013), multilayer deposits were handled as if the old layer became the new base; implicitly assuming it had an infinite strength. In this paper we show better success in predicting larger/higher deposits based on analysing the whole deposit using a representative value of yield stress.

To help with this analysis consider Figure 2, where the yield stress/vane shear strength for gold tailings is shown using two datasets. A line shows a best fit through 50 slump tests, each conducted less than 30 s after remoulding for a range of water contents, down to the water content at which these tailings will cease to settle. The original data is from Mizani et al. (2013). Also shown are 5 vane tests conducted at two different times after the tailings have settled following remoulding. The tailings are covered with water up until the vane test. This gives a crude but simple measurement of thixotropic increase in the strength (Daliri et al. 2014).

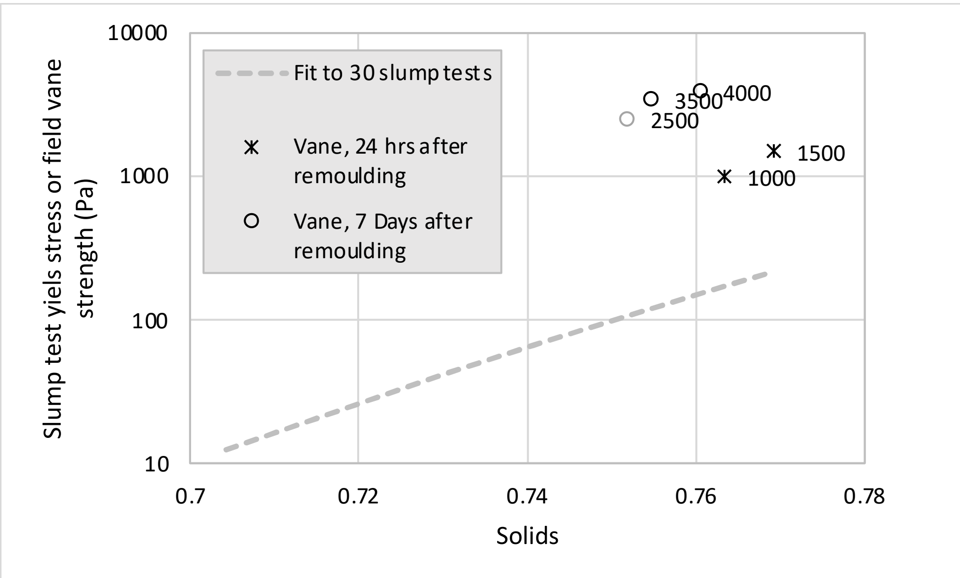


Figure 2 Yield stress/vane strength in a thickened gold tailings

2.1 Reanalysis of profiles by analysing the deposit as a single layer of gold tailings and using a bench scale experiment

Presented here is the data from the bench scale experiment simulating central discharge, as reported in Mizani et al. (2013), which simulated central discharge depositing 2.6 L per layer. There were 24 hours between the deposition of each layer. Figure 3 presents a visualisation of the geometry at layer 11. In Figure 4, profiles from layers 5 and 10 are fitted by employing Equation 2, using the same density and yield stress (500 Pa), except expect that that the downward profile is used to fit the deposit after 5 layers, while the older deposit with 10 layers is fitted with the upward profile. The fits could be slightly improved by varying the yield stress used in the individual prediction of each layer, but it seems a single characteristic value of yield stress can be used to characterise the deposit at these two different stages.

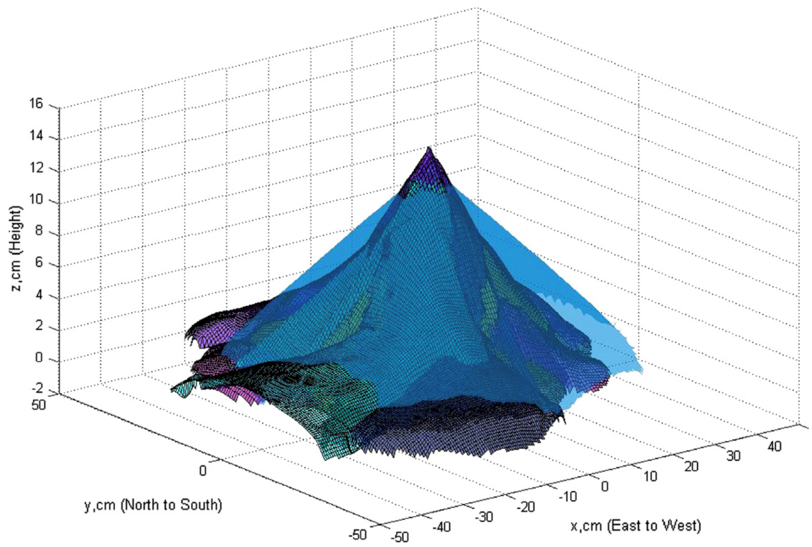


Figure 3 Shape of simulated central discharge bench scale experiment: 2.6 L per layer, 11 layers. Blue cone is a fit, not real data. Adapted from Mizani et al. (2013)

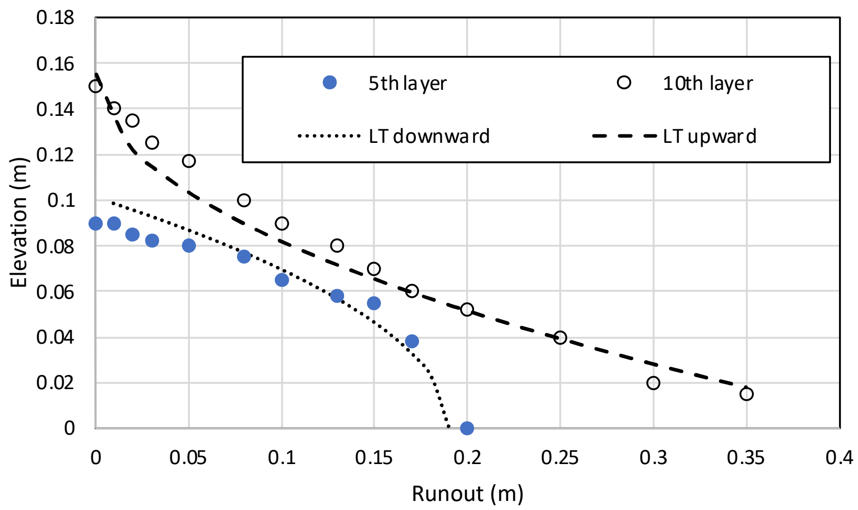


Figure 4 Fit of layers 5 and 10 profiles to a bench scale simulation of central discharge using the same yield stress (500 Pa) and density, employing Equation 2

2.2 Gold tailings – early field deposition

Early deposition profiles at the Bulyanhulu mine are reported in Simms et al. (2011) as well as Mizani et al. (2013). Figure 5 shows fits of Equation 2 to the deposit on 26 March and 3 April 2002, by which time deposition had occurred between 25 or 30 days. Once again, both layers can be reasonably fit using the same value of yield stress, here 1200 Pa, though the switch between downward and upward profiles. Readers are reminded that 1,200 Pa is the yield stress manifested after deposition and after some time, as per Figure 2.

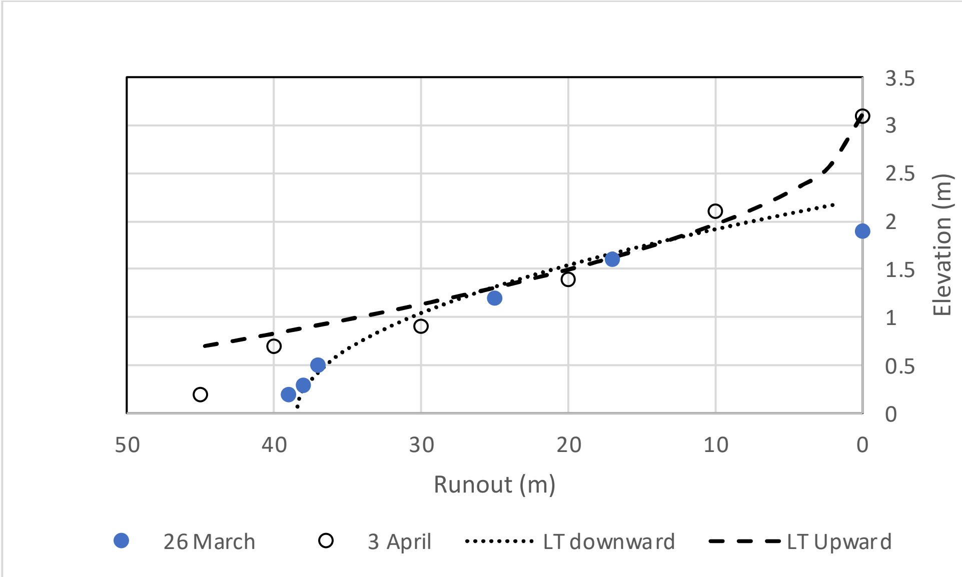
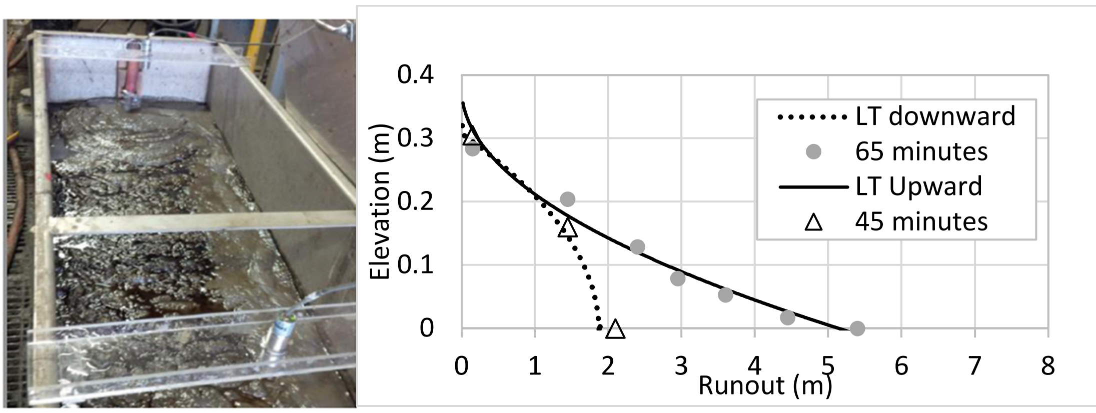


Figure 5 Early deposition at a tower at Bulyanhu fitted with Equation 2 using the same density and yield stress (1,200 Pa)

2.3 Oil sands tailings – 6 m-long flume

Mizani et al. (2017) reported on the thixotropic rheology of polymer flocculated fluid fine tailings, including a 6m-long flume test conducted at the Oil Sands Tailings Research Facility in Devon, Alberta. Figure 6 shows the slow deposition experiment at 10 L/m for 65 minutes in a 0.65 m-wide flume. Multiple rheometry measurements showed that these tailings were hysteretic: the yield stress required to initiate flow after short stoppage was 300 Pa while the yield stress characterising when the tailings came to a stop was 50–60 Pa). Figure 6a shows channel flow shortly after its initiation at 45 minutes. From 45 minutes to the end of the experiment at 65 minutes, the channel conveyed tailings to the base of the impoundment. For up to 45 minutes the profile could be fitted using the downward profile of Equation 2 and the higher measured yield stress of 300 Pa. The final profile, however, could only be fit using an upward profile, and the best fit yield stress for the final profile was 165 Pa. This is close to an average of the yield stresses for flow initiation and flow stoppage (which would be 175 Pa). It is noted that the behaviour of the material is complicated by the subsequent large release of water, and even during deposition.



(a) (b)

Figure 6 Flume experiment (0.65 m wide) at 10 L/min on oil sands tailings: (a) Initiation of channel flow observed at 45 minutes; (b) Fits of Equation 2 to profiles at 45 and 65 minutes

2.4 Gold tailings – fully developed field profile

Here Equation 2 is fit to the full-scale profile from the Bulyanhulu mine site reported by Addis & Cunningham (2010). The data presented up to this point in the paper suggests that the upward LT profile begins to better describe the overall shape of the tailings as deposits develop. Reflecting on the applicability of this equation to full-scale deposits, it seems likely that a frictional component of strength should become more important as tailings height increases, with the yield stress characterising the non-frictional component. Therefore, as a possible improvement of Equation 1, an additional term for the frictional component of strength is added: a shear strength/vertical effective stress ratio (Cu/σ'v). Further, assuming that the water table is at the surface, the effective stress is defined by the product of the height from the free surface and the difference between the bulk unit weight (γ) and the unit weight of water (γw). Equation 1 will then have the form of:

$$\frac{\partial h}{\partial x} = \frac{\tau_y}{\rho g H} + \frac{Cu}{\sigma_V'} \left(\frac{\gamma - \gamma_w}{\gamma}\right) \quad (3)$$

The predicted slope with be the sum of a constant value (the left-hand term) and the yield stress dependent term, the latter of which increases upwards towards the deposition point.

What is the appropriate value for the stress ratio? For argument's sake a value of 0.05 is suggested, which corresponds to the lower bound of liquefied shear strength suggested by Olson & Stark (2002). Then the last term, which is the minimum value of the slope, will vary in magnitude depending on the density: e.g. for a bulk densities of 1,200 kg/m^3 and 2,000 kg/m^3, the respective minimum slopes are 1 and 2.5%. Considering the range of real beach slopes, these estimates of the base slope seem plausible.

Equations 2 and 3 are applied to the full-scale Bulyanhulu data in Figure 7. The data is from Addis & Cunningham (2010) and is also reported in Simms et al. (2011). Equation 2 provides a best fit for a yield stress of 14 kPa, and Equation 3 for a yield stress of 4 kPa. While 14 kPa might be plausible as an average shear stress, given the potential for drying at the site, it does not seem very practical to require an estimate of the average single value of shear strength for the whole deposit. At least with Equation 3, if the extent of strength gain without desiccation is known, as per Figure 2 for gold tailings from the same mine, the parameters can be better defined.

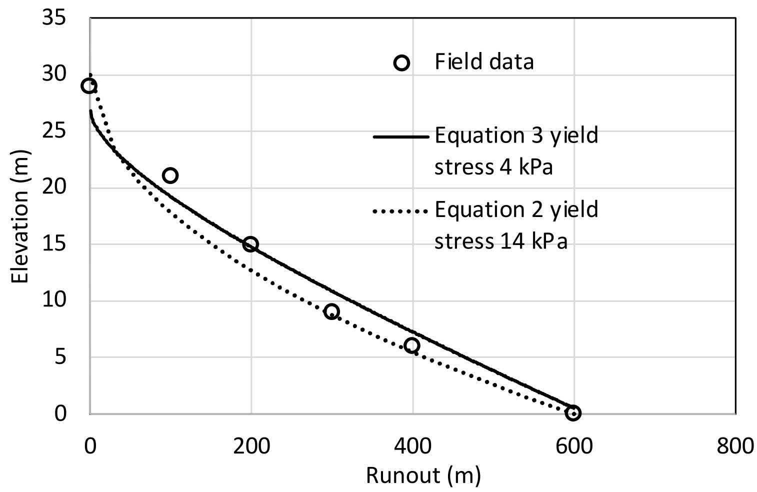


Figure 7 Bulyanhulu data from Addis & Cunningham (2010)

To round off this section, the equations arising from LT theory seem to have explanatory power up to full-scale deposits when assuming the conditions conforming to the upward profile generally dominate at full scale. More detailed full-scale data would be helpful to establish the predictive power of these equations. It is likely that the other phenomena on which other prediction methods are based (inertia of the flow, erosion by channel flow) could govern, depending on site-specific conditions, and are more likely as the deposition flowrate increases. The LT-based equations may serve as another tool to constrain beach slope estimates.

3 Rheometry for post-deposition applications

There are a range of methods for estimation of the yield stress which can generate a range of results for tailings (Mizani & Simms 2016, Mizani et al. 2017). As an example, a summary of different yield stress tests on two tailings, one hard rock and one oil sands, are shown in the following table. Most of these results are from the aforementioned references.

Table 1 Variation in yield stress estimated from thickened gold tailings and polymer-flocculated fluid fine tailings

Test	A hard rock tailings	A clayey tailings
Slump	30 Pa	50 Pa
Flume	30 Pa for deposition times < 30 s (increases with deposition time)	60 Pa (for short deposition time)
Stress growth	120 Pa	150 Pa
Controlled shear stress	100–120 Pa	300 Pa
Conventional flow curve	90 Pa	110 Pa

The variation in these results can be, in part, attributed to the thixotropic and/or hysteretic nature of the tailings. Put another way, the relevant yield stress depends on the stress history relevant to the application. The yield stress pertinent to calculating friction losses in a pipeline is from the test that simulates those conditions (e.g. a conventional flow curve), whereas the test pertinent to, say, the slowing of tailings to a stop should simulate those conditions as best as possible. One such test proposed by Mizani et al. (2017) is where the shear stress is controlled, but decreased in steps over time, starting from a fully sheared state. This test purports to simulate the slowing down of the tailings as they flow down the beach, or as they are slowing down subsequent to a dam breach. Figure 8 shows an example from an oil sands tailings where it is evident that the viscosity begins to increase once the imposed shear stress drops to 50 Pa. Our experience is that the shear stress from this test is generally fairly close to the yield stress from the slump test for hard rock tailings, though measurements are possible at a greater range of densities than for the slump test. For clayey tailings, the constant decreasing shear stress test predicts lower values than for the slump tests.

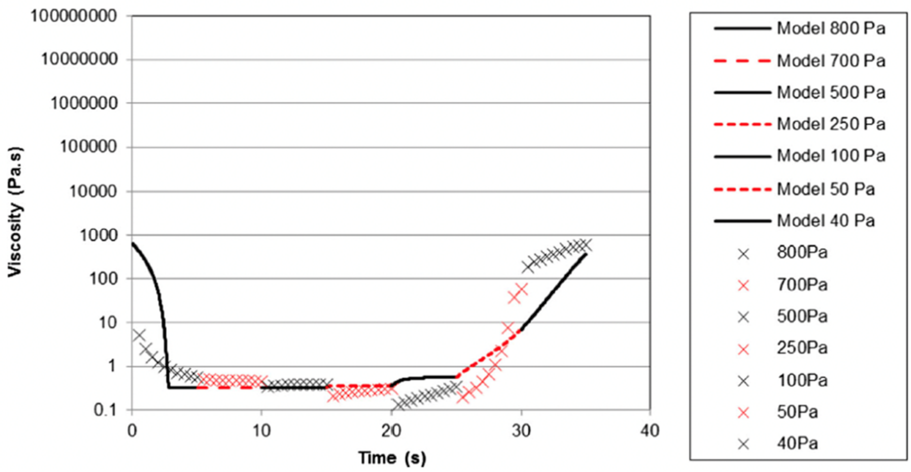


Figure 8 A controlled decreasing shear stress test fitted with a thixotropic rheology model (Mizani et al. 2017)

Mizani & Simms (2016) and Mizani et al. (2017) have shown that the variation in rheology with test type can be simulated using thixotropic rheology models of the type of Coussot et al. (2002) and Hewitt & Balmforth

(2013). These models predict viscosity using two simple terms: a shear stress dependent term that reduces the viscosity when the shear stress is above a certain value, and an 'ageing' term that increases the viscosity when shear stress gets low. The exact critical value that defines which behaviour dominates depends on the initial state of the simulated material.

As an example, the Coussot model (Coussot et al. 2002) is described by Equations 4 and 5:

$$\frac{d\lambda}{dt} = \frac{1}{T} - \alpha\gamma\lambda \quad (4)$$

$$\mu = \mu_0(1 + \lambda^n) \quad (5)$$

where:

α (dimensionless) and T (s)	=	material constants.
γ	=	strain rate (1/s).

The instantaneous viscosity is dependent on the state or 'structure' of the material (λ), where μ_0 is the fully sheared viscosity where structure is minimum (λ=1), and n is a parameter describing the rate of viscosity change over time. The critical shear stress, which depends on the ratio of the ageing and shearing parameters (T and α) in Equation 4, and also the initial structure of the material, which can be derived from Equations 4 and 5, is predicted in Equation 6. Setting $R = \alpha T$, the critical shear stress (τ) demarking either a decrease or increase in subsequent viscosity is (Coussot et al. 2002):

$$\tau = \mu_0/R\,(1+\lambda_0{}^n)/\,\lambda_0 \quad (6)$$

For a case where the slurry is fully sheared, such as that shown in Figure 8, and setting the minimum $\lambda_0 = 1$, Equation 6 becomes R = 2 μ_0/τ where τ is the estimated yield stress. The fully sheared minimum viscosity (about 0.2 PaS in Figure 8) would give 2 μ_0, as per Equation 5.

4 Application of thixotropic model to simulations of channel flow and an embankment failure

Parent & Simms (2019), Parent (2020), Xia & Simms (2021) and Saeed et al. (2022) have incorporated the Coussot model into material point method codes to simulate tailings deposition and tailings dam breach. Following are two examples: the first, from Parent (2020), shows a simulation of tailing deposition, and the second shows the simulation of a recent centrifuge test on an embankment failure at the GeoCerf facility at the University of Alberta.

The first simulation, pictured in Figure 9, shows the flow of tailings deposited at 0.1 m^3/s for three minutes on a plane sloping downward from the deposition point at 3%. The tailings have a fully sheared yield stress of 5.6 Pa and a minimum viscosity of 2 PaS. Tailings are discharged from a pipe at the origin, which is originally kept at a 0.3 m height but then raised to 1 m to avoid burial of the deposition point. The pipe needed to be initially placed at a low elevation to prevent 'splashing', which results in non-physical pressure oscillations. An artefact of raising the pipe, however, is the occurrence of some 'aged' tailings directly downstream of the pipe, which results in the formation of two channels instead of one.

The viscosity of the tailings is denoted by colour, the extremes of which are dark blue (the fully sheared lowest value) and red (high viscosity 'aged' tailings and a high but arbitrary value of 5,000 PaS). The tailings that move out of the way of the main flow age and increase rapidly in viscosity, becoming a relatively immobile bed for the conveyance of the fresh tailings by the channels. Once the pipe is turned off at three minutes the channels dry out from upslope to downslope. The maximum thickness of the deposit is 0.36 m.

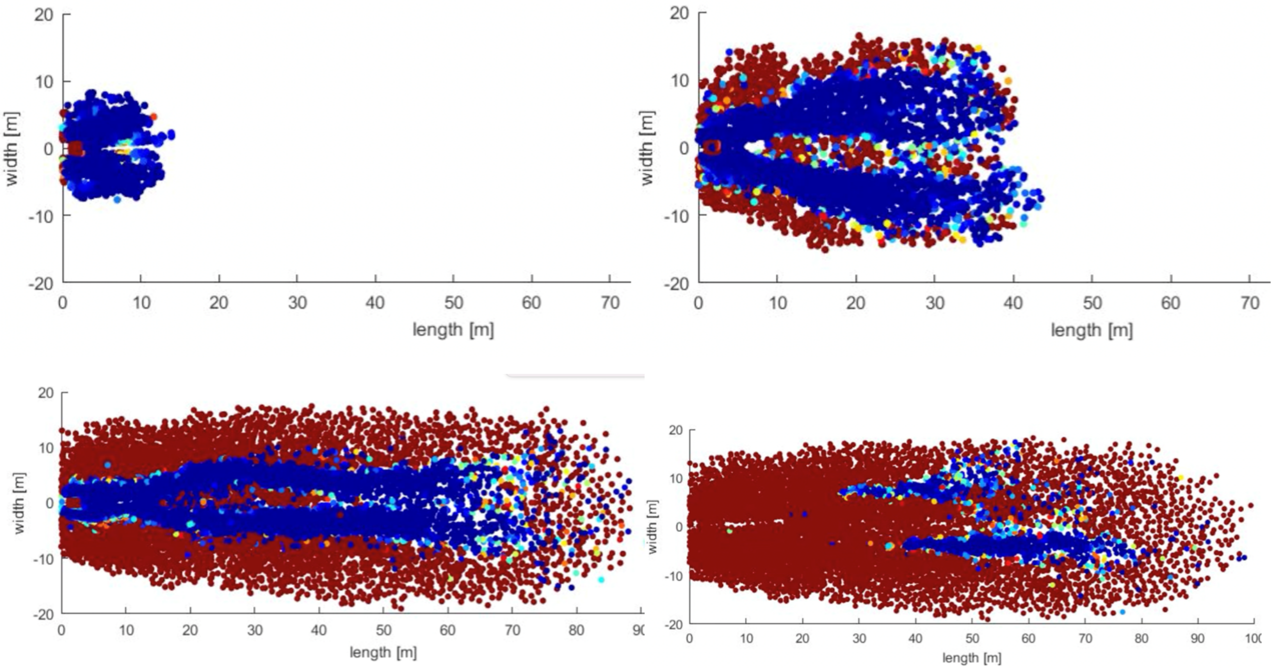


Figure 9 Material point method simulation of tailings deposition using Coussot rheology on a plane sloping downward 3%. Blue shows the fully sheared (lowest) viscosity (1 PaS) and red shows the maximum viscosity. Deposition occurs for three minutes at 100 L/s. The fully sheared yield stress is 5.6 Pa

From these simulations, it seems that thixotropic behaviour (which could be, in part, simply the settling/dewatering of tailings once they come to a stop) can explain channel formation. Therefore, models of this sort have the capacity to simulate realistic components of the deposition process, which may provide insights into deposition management.

Next, the Coussot model predictions are compared to quantitative data. Performed at the GeoCerf, the experiment presented in Figure 10 is a centrifuge test on a 0.3 m-high aged clay embankment spun up to a model prototype height of 3 m, where it subsequently failed. The sample, which was near its liquid limit, was shown to possess shear strengths of approximately 7 kPa in its unsheared region and about 2 kPa in its sheared regions, based on fall cone tests performed after the failure. Figure 11 compares the final elevation profile with estimates based on an LT equation for the intact and remoulded shear strength. The estimated profile using the Coussot model implemented in MPM is also shown, with the model parameters obtained using the two measured shear strengths and Equation 6 to find the R parameter and the initial λ_0. The fully sheared viscosity was obtained from rheology tests. The LT equations bracket the final runout, but readers should be cautioned that the LT equations do not consider inertia, nor 3D effects such as the boundary conditions. The Coussot simulation, which does account for those effects, gives a relatively close estimate of the measured profile and is between the LT estimated profiles. Detailed outputs from the Coussot model run are presented in Figure 12, which shows the sheared zone along one of the walls and along the bottom, the latter of which, at one time, was its greatest extent.

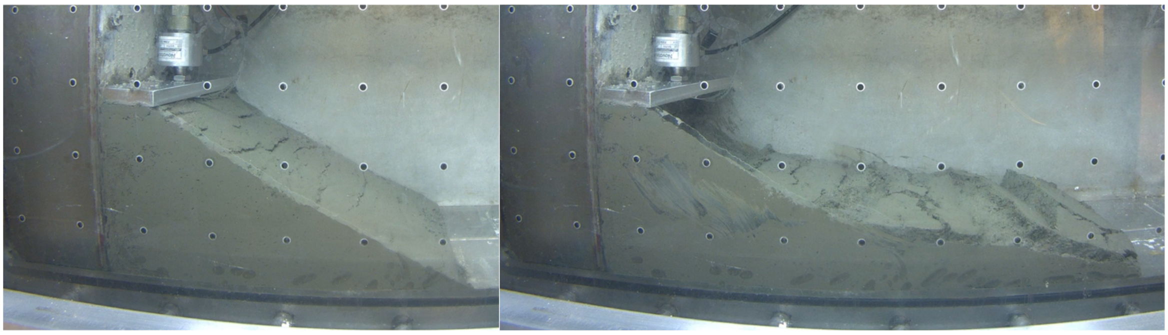


Figure 10 Centrifuge model test of aged clay at its liquid limit (0.3 m model height, 3 m high, 5 m long with 1 m bench in prototype), with an intact strength of 7 kPa and a remoulded strength 2 kPa

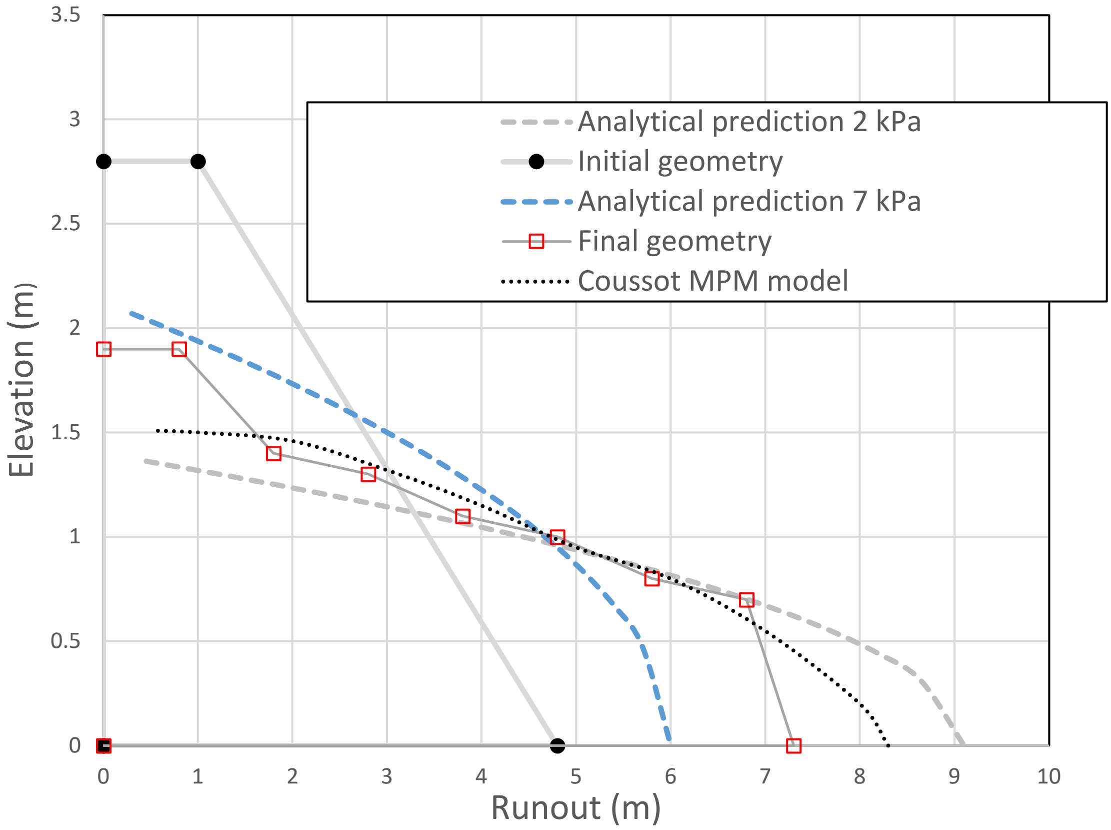


Figure 11 Runout elevation profile of GeoCerf experiment estimated by LT equation using either intact or remoulded strength, and the Coussot MPM model

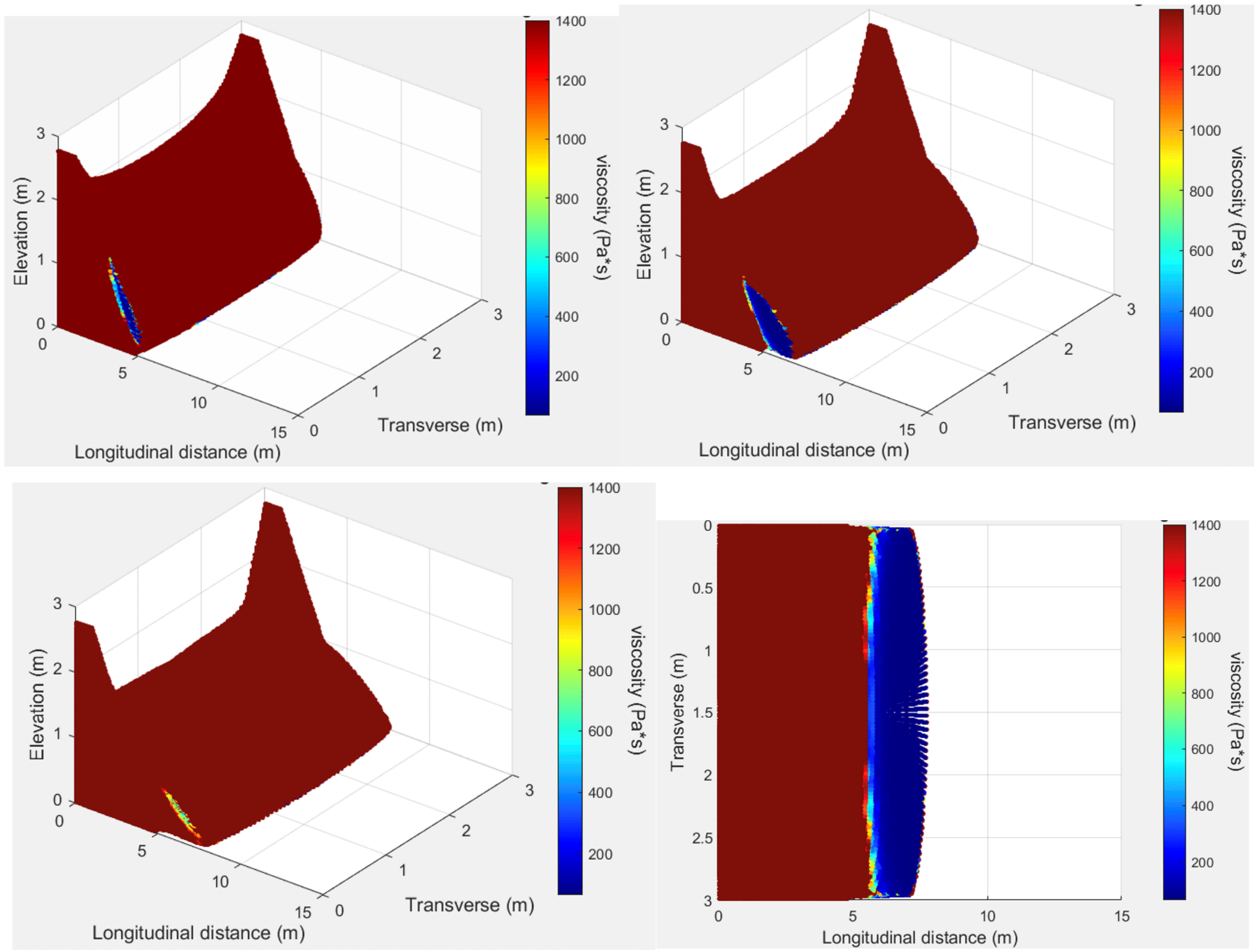


Figure 12 Simulation of GeoCerf experiment using Coussot model with initial and remoulded shear strengths of 7 and 2 kPa, counterclockwise from top left at 1 s, 2s and 3s stoppage imminent, and showing the bottom at 2.4 s (largest extent of bottom sheared zone)

5 Summary and conclusion

The paper reviews a body of work related to rheology and flow of tailings post-deposition. Novel contributions include showing how the LT equations can model deposit geometry from bench scale tests to early field deposition, to the geometry of a full site; at least if given some reasonable estimates of the yield stress/shear strength of the deposit as a whole. It is suggested that using the maximum yield stress that develops in a sample kept saturated provides a conservative estimate of concavity through Equation 3. The other term in Equation 3 gives a minimum angle and is based on the liquefied shear strength ratio. Using the minimum value suggested by Olsen & Stark (2002) seems to give reasonable estimates for the base slope of a subaerial tailings deposit. Equation 3 is suggested as a method to constrain estimates of beach slope. The reader is reminded that other methods consider the inertia of the flow and the eroding nature of the channels, which likely constrain the slope for certain conditions such as high flow rates, and have already been demonstrated to work for practice.

It is observed that in terms of layer-by-layer deposition, there is a point where the equation that describes the geometry switches from downward to upward profiles, with the upward profiles, if used alone, giving the best description of the shape of older field deposits.

The variation in rheology from test to test is discussed. The reader is reminded that the appropriate tests for a certain application are those tests that mimic the application in terms of the stress history of the sample. The controlled decreasing shear stress test is recommended to simulate the flow of tailings as they decelerate to a state of rest, as is pertinent to characterising deposition and runout post-breach.

Some of the variation in rheology from test to test can be explained, and even simulated, using rheological models that consider the thixotropic nature of the tailings. One of these models is briefly introduced. It is then applied to MPM simulations of channel formation during deposition and post-failure flows in an embankment. Hopefully it should be apparent to the reader that such analyses are sufficiently developed to study tailings flows with the aim of improving tailings management. While actual simulation of tailings deposition over the full lifetime of a site is not practical for CFD models, use of them to develop better empirical models now seems to be feasible.

Acknowledgements

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