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Estimating rheological properties of liquefied tailings for dam break simulation using site-specific parameters and laboratory testing

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Abstract

Tailings dam failures, claiming human lives and causing catastrophic environmental impact, are unfortunately still frequently reported around the world.

The tailings dam break simulation using site-specific parameters has now become an essential and critical part of the design, operation and closure cycle of every tailings storage facility (TSF), and is a requirement in many guidelines such as ANCOLD (2012), CDA (2021) and ICMM (2020).

Urging from the mining industry and regulatory authorities for the development of better and more comprehensive simulating techniques that can accurately predict the flow behaviour of liquefied tailings in the hypothetical scenario of a tailings dam breach has significantly increased in recent years.

The tailings deposited in a TSF often form a density profile with depth as the tailings consolidate and gain strength. This process increases the solids concentration and shear strength of the tailings within the TSF to a range that often makes direct measurement of the rheological properties of samples from the site using conventional bob and cup rotary viscometry impractical. Consequently, this imposes a challenge for obtaining reliable results from the tailings dam break simulation and needs to be overcome.

A methodology is proposed in this paper for estimating the rheological properties of liquefied tailings at high solids concentrations when the direct measurement technique is impractical. The method is based on combining site-specific parameters such as the in situ dry density with laboratory-measured parameters such as the residual shear strength of the tailings after failure, and the bob and cup rotary viscometry data at lower solids concentrations.

The method can be applied to establish a comprehensive understanding of the rheological behaviour of liquefied tailings at the wide range of solids concentrations required for dynamic tailings dam break modelling.

Keywords: *tailings dam break analysis, rheology, liquefied tailings, residual strength*

1 Introduction

Tailings storage facilities (TSFs) are widely used in the mining industry to store the process residue, i.e. tailings and supernatant water which is usually a mix of bleed water from the tailings and the surface runoff due to rainfall.

Safe operation and maintenance of the tailings dams are essential tasks for every mine. The dam owners should ensure that best practices and knowledge are applied in the design and operation of the TSF to minimise the risks to the downstream population, infrastructure and the environment. The operational condition of the TSF in any mine site can directly impact the mining permit.

Despite all the efforts that have been made around the world by regulatory authorities, design engineers and research institutions to improve the design and operation of the tailings dams, unfortunately several cases of tailings dams failure with catastrophic impact (and sometimes loss of human lives) are still reported every year around the world due to various reasons.

Tailings dam failure is defined by the Canadian Dam Association (CDA 2021) as “A physical breach of the dam followed by uncontrolled and typically sudden and catastrophic release of any or all stored materials (e.g. fluids, tailings, sludge, etc.)”.

Tailings dam breach analysis (TDBA) is often used to estimate the consequence category of a TSF and is defined based on potential loss of life, the population at risk, the environmental impact, and the potential direct and indirect losses to the owner in a hypothetical dam breach scenario. TDBA is also used to produce inundation mapping, typically in the form of flow depth and velocity for different failure scenarios which define the extent and severity of potential damages to the affected areas. Inundation mapping is the key input in the preparation of the TSF’s emergency response plan and failure mitigation plan.

Unlike water dam breach modelling, which simulates the outflow of water (i.e. a fluid with predefined and well-known properties regardless of the dam type and embankment height), obtaining realistic results from tailings dam breach simulation relies heavily on the correct and accurate estimation of both the in situ properties of the deposited tailings and the properties of the liquefied tailings when released from the dam.

Tailings properties can vary significantly from one mine site to another, and are dependent on numerous factors such as the mineralogy of the mine, clay content and the chemical composition of the ore, the process used in the extraction of the minerals, tailings particle size distribution (PSD) and fines content, the depth of the tailings deposit in the TSF, and consolidation, degree of saturation, etc.

Also, due to the non-Newtonian behaviour of liquefied tailings flow, one of the key parameters for tailings dam breach simulation is the rheological properties of the tailings slurry after it is released from the dam in a failure scenario.

Since tailings are man-made products with a very unique and uniform PSD, the rheological characteristics and flow behaviours of liquefied tailings can be very different from what is observed in the natural process, such as mud and debris flows which usually contain a wide range of solids from very fine clay to boulder-size particles. This prevents the mud and debris flow characteristics to be directly correlated for the estimation of tailings flow behaviour.

For the above reasons, the TDBA for any mine site should be undertaken based on site-specific parameters obtained from site investigation and field testing to evaluate the in situ conditions, and also laboratory testing on samples from the site (CDA 2021).

2 Tailings dam break modelling procedure

The detailed procedure and steps involved in performing a site-specific tailings dam break are described by Lu et al. (2022). The main steps that should usually be followed for a site-specific quantitative TDBA include:

1. Site investigation and collection of site-specific data from the deposited in situ tailings, embankment wall and foundation, downstream infrastructure, potential impact area, accurate 3D topographic model of the terrain, land cover, etc.
2. Hydrological study of the upstream and downstream catchments.
3. Assessment of credible failure modes for both sunny day and flood day failure scenarios.
4. Defining the potential breach location and dimensions (i.e. height and width).
5. Liquefaction assessment of the tailings.
6. Estimation of the potential released volume.

7. Defining the properties of tailings and flow characteristics by laboratory testing of the samples from the site.
8. Selecting the appropriate non-Newtonian flow model for tailings runout simulation (if the tailings are defined as liquefiable).
9. Running the non-Newtonian flow simulation.
10. Development of inundation mapping (flow depth, velocity, estimated flood wave arrival time and inundation peak time, etc).
11. Sensitivity analysis of the simulation outcome to input parameters.

The liquefaction assessment of the deposited tailings in the TSF is one of the key steps in the TDBA process which will influence the rest of the assessment. It should be emphasised here that all of the discussions presented in this paper are based on the assumption that the tailings released from the TSF in the hypothetical breach scenario are liquefiable and thus have the potential to flow over the terrain downstream of the breach as a non-Newtonian fluid.

The volume of the liquefied tailings released from the TSF in a dam break event should be estimated for each site using the site-specific properties of the in situ tailings and the TSF conditions rather than adopting the regression equations available in the technical literature (e.g. Piciullo et al. 2022), which correlates the expected released volume to embankment height or total storage volume regardless of the storage or embankment type.

The released volume can be estimated based on the difference between the original in situ tailings beach surface and the estimated post-failure tailings surface using the estimated post-failure slope (Lu et al. 2022).

The post-failure slope of tailings refers to the tailings residual and stable slope within the TSF after a dam break event. The post-failure slope angle is defined as a function of tailings consolidated density and shear strength profile within the TSF using infinite slope theory, as described by Seddon (2007).

The equations derived from the stability of long, shallow slopes (i.e. infinite slope) can be utilised to analyse the slope of the post-failure tailings surface. The theory assumes that after liquefaction of the tailings, the tailings strength would be greatly reduced, resulting in the slumping and mobilisation of the tailings until the tailings reach a stabilising slope where force equilibrium has been achieved. The in situ post-failure surface in the TSF can then be created based on the post-failure tailings slope and the breach size, and the released tailings volume can be estimated accordingly using geometric modelling.

One of the other key steps for the TDBA is the selection of the model for the liquefied tailings flow and runout analysis. The constitutive equations of the selected model for analysis of non-Newtonian open channel flow (i.e. liquefied tailings flow after embankment breach) must have the following properties as a minimum:

- Be capable of analysing both laminar and turbulent flow of the non-Newtonian fluids. The selected model and/or commercially available software packages developed based on non-Newtonian laminar flow equations only can significantly overpredict the flow velocity and underpredict the flow depth as they typically underestimate the energy loss in the tailings flow due to the sudden nature of the tailings dam break event and the rapid release of a significant volume of liquefied tailings in a relatively short period of time. To the authors' best knowledge, a comprehensive model for open channel flow of non-Newtonian fluid with solids particles is not currently available. However, there are published models for thickened tailings open channel flow such as Javadi et al. (2016) that can be utilised for this purpose. Some of the commercially available software packages such as FLO-2D also have an embedded approximation for the turbulent head loss term in the constitutive model used in the software (FLO-2D 2022).
- Be capable of considering the dynamic variation of rheological properties (i.e. yield stress and viscosity) of the tailings flow as the solids concentration changes due to further dilution or the thickening process of the flow after being released from the TSF. The liquefied tailings released

from the TSF are usually at high solids concentrations depending on the height of the dam, the age of the deposited tailings and the consolidation effect. However, dilution of the tailings flow can occur during the breach process (i.e. mixing of the tailings with a supernatant water pond) or downstream of the breach due to the existing flooding and temporary water pooling. The released tailings can also be trapped and settled in the local low points and depressions within the terrain and release the water which causes the solids concentration to increase locally. Therefore, it is essential that the modelling tools used for TDBA be capable of considering this effect.

3 Input parameters for dam break assessment and modelling

As previously stated, achieving realistic outcomes from a TDBA depends on reliable site-specific input parameters and assumptions. The input parameters should be obtained from site investigation and field testing, and also from laboratory testing of the representative samples taken from the site.

3.1 Data and information collected from field testing and site investigation

The site-specific parameters and inputs to TDBA that are usually defined through site investigation and field testing include the following:

- TSF embankment wall and foundation condition (visual inspection and review of historical site investigation data such as drilling, test pitting, etc.).
- In situ tailings density profile with depth (cone penetration testing [CPT] and undisturbed sampling).
- Degree of saturation, void ratio and phreatic surface estimation (CPT testing, undisturbed sampling, and review of site piezometers and monitoring bores data).
- Liquefaction potential assessment (CPT testing and cyclic triaxial testing).
- Post-liquefied shear strength ratio assessment (CPT testing and cyclic triaxial method).

One of the most important parameters that needs to be evaluated from field testing and analysis is the deposited tailings density profile with depth. Examples of recorded density and moisture content profiles with depth are presented in Figure 1. The measured specific gravity (SG) for this tailings sample was 2.89.

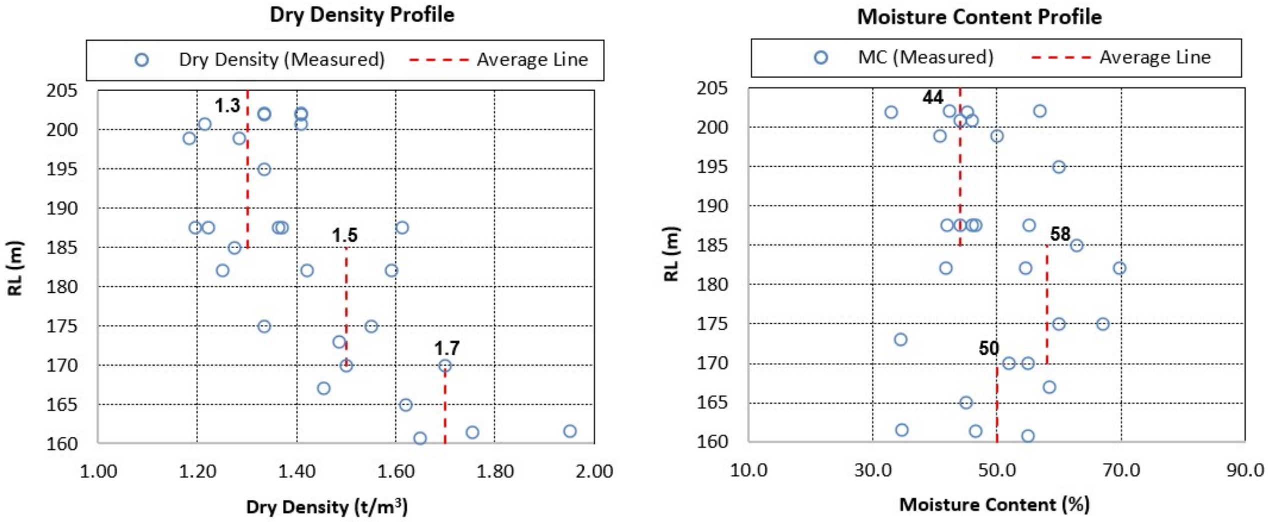

Figure 1 Example of density and moisture content profiles measurement by site investigation and in situ testing and sampling

The density and moisture content profiles indicate the in situ condition of the deposited tailings and the level of consolidation achieved over the life of the TSF. The information and data are also used to define the starting density and solids concentration for other laboratory testing such as triaxial and rheology testing.

3.2 Parameters defined by laboratory testing

The samples taken from the site investigation and field testing (undisturbed and disturbed) are sent to the laboratory for further testing. Some of the tests such as cyclic triaxial and direct shear tests are ideally performed on undisturbed samples, but other laboratory tests such as SG, PSD and rheological testing to define the flow characteristics of the liquefied tailings can be undertaken on the disturbed samples.

The rheological testing aims to estimate the flow properties of the liquefied tailings after the failure of the tailings dam. Therefore tests can be done on the disturbed samples collected from the site and still be representative of the flow behaviour of the site material.

The rheological testing is usually undertaken for a range of tailings solids concentrations to define the variation of rheological properties of the tailings (i.e. yield stress and viscosity) with solids concentration, which is an important input to the TDBA (as discussed in Section 2).

4 Rheological testing to estimate properties of liquefied tailings

Rheological properties of the tailings samples from the mine site are usually measured in the laboratory using a rheometer equipped with bob and cup sensor. The solids concentration of the tailings sample is adjusted in the laboratory via dilution or thickening process to achieve the desired solids concentrations representative of the tailings in situ density within the TSF prior to the dam break event.

A shear vane sensor can also be used for the measurement of the flow curve, static peak shear stress and the residual shear stress of the tailings at different solids concentrations.

Figure 2 presents the rheology curves for a mine tailings sample measured by a Thermo Haake VT550 Viscotester with an MV2P Couette flow (bob in cup) sensor system. As seen in Figure 2, in addition to the rheograms measured by bob and cup sensor, the direct measurement of the flow curves and the static peak shear stress for each sample have also been recorded using the FL10 and FL100 shear vane sensor systems.

The testing results presented in Figure 2 are for the tailings samples from the same mine for which the density and moisture content profiles are plotted in Figure 1.

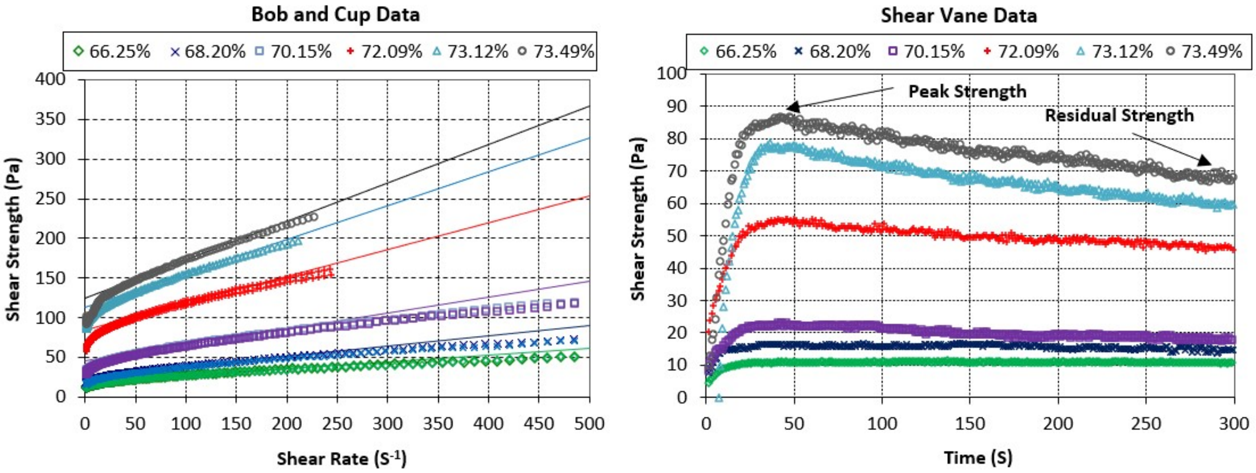

Figure 2 Example of rheological test plots for mine tailings using bob and cap, and shear vane arrangements (solids concentration by weight)

The rheological properties of mine tailings are usually best represented by either the Herschel–Bulkley or Bingham plastic models. The Herschel–Bulkley model describes the flow behaviour of yield pseudo-plastic fluids with the following equation:

$$\tau = \tau_y + K\dot{\gamma}^n \tag{1}$$

where:

τ = shear stress (Pa).

τ_y = yield stress (Pa).

K = flow consistency factor.

N = flow behaviour index.

$\dot{\gamma}$ = strain rate (s^{-1}).

For n = 1, the Herschel–Bulkley model converts to Bingham plastic model which is used to describe the viscoplastic material with the following equation:

$$\tau = \tau_y + \eta\dot{\gamma} \tag{2}$$

where:

τ = shear stress (Pa).

τ_y = yield stress (Pa).

η = Bingham plastic viscosity (Pa.s).

$\dot{\gamma}$ = strain rate (s^{-1}).

Most of the flow and head loss models developed for non-Newtonian fluid are developed and calibrated based on either the Herschel–Bulkley model (Javadi et al. 2016) or Bingham plastic models (FLO-2D 2022).

The Bingham plastic model is a simpler model which represents the mine tailings flow behaviour very well given that, in a lot of cases and conditions, the tailings flow from a dam breach occurs at relatively high shear rates (i.e. the linear part of the rheology curve). Other research work has also shown that the Bingham rheological model is applicable for debris and mud flow motion (Jeong 2019).

For simplicity, the discussion in this paper has focused on defining the Bingham plastic model parameters as a function of tailings solids concentration to provide input for TDBA just to demonstrate the proposed procedure and technique. A similar approach can be implemented to obtain the Herschel–Bulkley model parameters if needed. Using the Herschel–Bulkley model for TDBA has the advantage of enabling prediction of the true rheological behaviour of the material at low shear rates (e.g. the curved part of the rheograms in Figure 2), which can be the case for the flow of very thick slurries at relatively low velocities. Provided that the selected head loss model for TDMA is also capable of using the Herschel–Bulkley model parameters, adopting this rheological model will provide more realistic and accurate results.

Table 1 presents the Bingham plastic model parameters (i.e. Bingham yield stress and viscosity) for the range of solids concentrations which was practical to directly measure using a rheometer with bob and cap arrangement for the same tailings sample (i.e. the respective rheograms presented in Figure 2).

As presented in Table 1, the maximum solids concentration for which direct measurement of rheology with bob and cup arrangement was practical is 73.5% (by weight). However, the density profile presented in Figure 1 shows that the average in situ dry densities of the tailings at different depths in the TSF are 1.3 t/m^3, 1.5 t/m^3 and 1.7 t/m^3. These values are equivalent to 70.3%, 75.8% and 80.5% solids concentrations by weight, respectively.

The challenge that arises here is that for TDBA, it is often necessary that the rheological properties of the liquefied tailings (i.e. Bingham yield stress and viscosity) be estimated for tailings solids concentrations higher than the range that conventional rotary rheometers with bob and cup sensor can measure.

Table 1 Bingham plastic model parameters for the tailings sample at a low solids concentrations range

Solids (%)	Yield stress (Pa)	Bingham plastic (mPa.s)	Shear vane peak stress (Pa)	Residual shear stress (Pa)
66.3	18.7	84.7	11.3	10.0
68.2	25.7	127.6	16.9	15.0
70.2	45.0	201.4	23.1	20.0
72.1	84.0	338.2	55.3	47.0
73.1	113.0	428.0	78.5	60.0
73.5	125.0	484.0	86.9	67.0

To overcome this challenge, the bob and cup and shear vane data (for which the range of solids concentrations measurement with both sensors is practical) are used to develop a correlation between the Bingham plastic model parameters and the residual shear stress estimate from the flow curves measured by shear vane sensor. Figure 3 presents examples of such correlations.

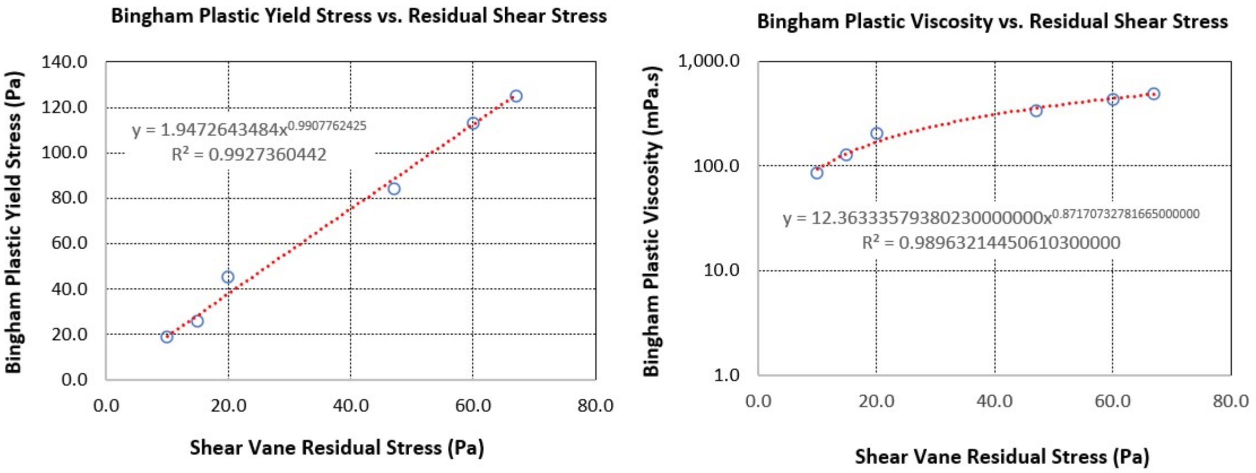

Figure 3 Correlation between residual shear stress and Bigham plastic yield stress and viscosity

Figure 4 shows the flow curves, the peak shear stress and the residual shear stress for tailings at a high solids concentration range (75.3 to 81.9%) measured by FL10 and FL100 shear vane sensors.

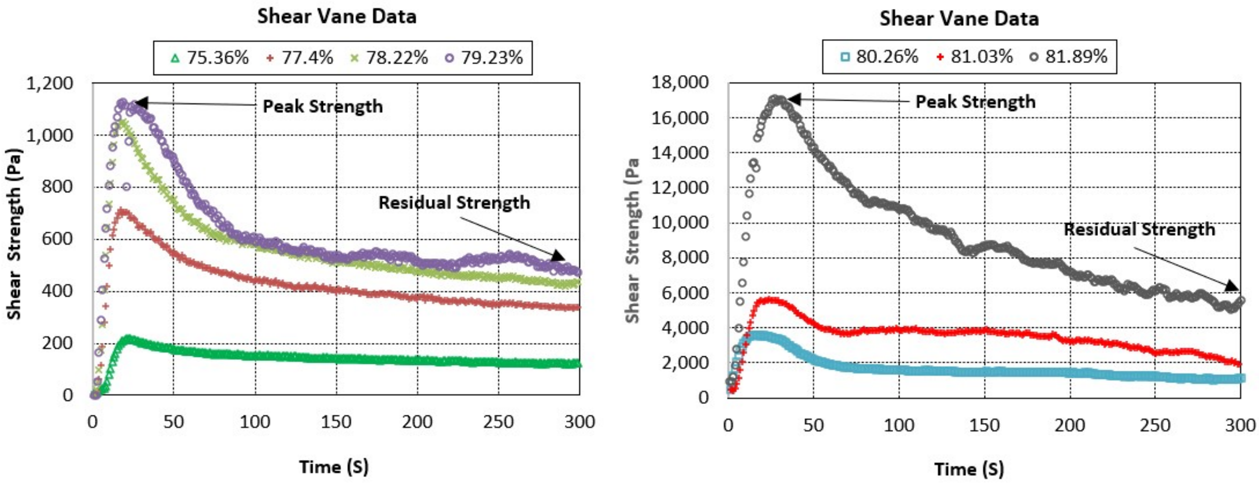

Figure 4 Flow curves presenting the peak and residual shear stress for tailings samples at a high solids concentrations range

The measured values of peak shear stress and residual shear stress for the flow curves in Figure 4 are tabulated in Table 2.

Table 2 Peak and residual shear stress for tailings samples at a high solids concentrations range

Solids (%)	Peak shear stress (Pa)	Residual shear stress (Pa)
75.4	220	120
77.4	710	300
78.2	1,050	420
79.2	1,500	500
80.3	3,600	1,000
81.0	5,600	2,000
81.9	17,000	5,000

The residual shear stresses measured by the shear vane sensor are indicative values which represent the material strength after failure (i.e. after liquefaction). The measured residual shear stress values at higher solids concentrations (i.e. values in Table 2) can be used in the correlations developed at lower solids concentrations (i.e. correlations presented in Figure 3) to estimate the Bingham plastic model parameters at higher solids concentrations where direct measurement of rheology with bob and cup is not possible.

5 Rheological properties as a function of solids concentration

The correlations developed in Figure 3 between the residual shear stress of the tailings and the Bingham plastic model parameters are used to extrapolate the Bingham yield stress and viscosity at higher solids concentrations. The estimated Bingham plastic model parameters for the entire range of tailings solids concentrations from 66.3% to 81.9% (by weight) are presented in Table 3.

Table 3 Estimated Bingham plastic model parameters for the full range of tailings solids concentrations

	Solids (%)	Peak shear vane stress (Pa)	Residual shear stress (Pa)	Bingham plastic yield stress (Pa)	Bingham plastic (mPa.S)
Measured by bob and cup	66.3	11.3	10.0	18.7	84.7
	68.2	16.9	15.0	25.7	127.6
	70.2	23.1	20.0	45.0	201.4
	72.1	55.3	47.0	84.0	338.2
	73.1	78.5	60.0	113.0	428.0
	73.5	86.9	67.0	125.0	484.0
Extrapolated from residual stress	75.4	219.4	120.0	223.6	802.7
	75.6	236.9	186.0	345.1	1,176.2
	77.4	711.8	300.0	554.2	1,784.3
	77.4	612.0	370.0	682.2	2,142.2
	78.2	1,052.0	420.0	773.5	2,392.4
	79.2	1,509.0	500.0	919.4	2,785.1
	80.3	3,607.0	1,000.0	1,827.1	5,096.3
	81.0	5,614.0	2,000.0	3,630.8	9,325.4
	81.9	17,070.0	5,000.0	9,000.7	20,727.9

The Bingham plastic model parameters presented in Table 3 can be redefined as a function of tailings volumetric solids concentration using an SG value of 2.89 for the solids particles.

Figure 5 below plots the variations of Bingham plastic yield stress and viscosity as a function of tailings volumetric solids concentrations. These two curves can then be used as the main inputs to the tailings dam break simulation.

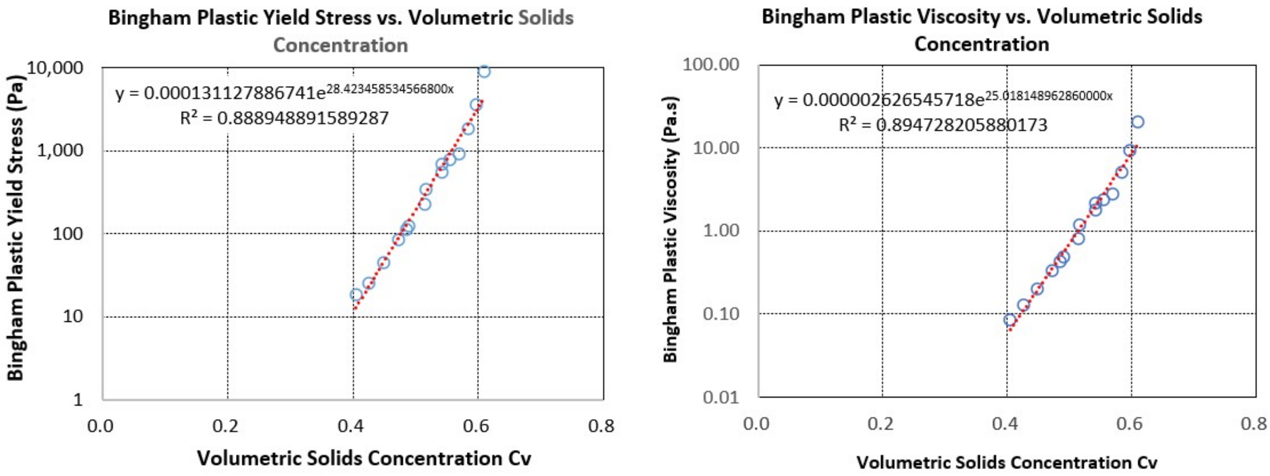

Figure 5 Rheological properties of liquefied tailings as a function of tailings solids concentrations

6 Conclusion

Rheological properties of the liquefied tailings are key input parameters to the TDBA.

Both Herschel–Bulkley and Bingham plastic models are well-accepted in the industry for estimation of the rheological behaviour of mine tailings. However, measurement of the rheological properties of tailings at high solids concentrations (i.e. solids concentrations that the stored tailings at the TSF have rather than the discharge solids concentrations) is often a challenge as the conventional rotary viscometry technique with bob and cup sensor cannot be directly employed for this purpose.

A practical technique to overcome this issue is presented in this paper. The technique is based on the development of correlations between the Bingham model yield stress and viscosity (obtained from the bob and cup rotary viscometry) and the residual shear stress value (obtained from the shear vane flow curve).

The technique enables the modeller to use the residual shear stress measured by the shear vane at high solids concentrations for the estimation of the rheological properties of the liquefied tailings for the entire range of solids concentrations.

The variation of rheological properties of liquefied tailings is defined as a function of tailings volumetric solids concentration, which can then be used as a direct input to tailings dam break simulation.

The technique can also be applied to estimate the Herschel–Bulkley model parameters at high solids concentrations where direct measurement with rotary viscometry is not practical. Using the Herschel–Bulkley model for TDBA has an advantage over the Bingham plastic model as the former can predict the rheological behaviour of the tailings at low shear rates as well as high shear rates (both cases can occur during the TDBA).

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