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Single-phase or two-phase? The impact on tailings dam breach modelling and impact assessment

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Abstract

Historically, dam breach analysis for tailings dams with supernatant ponds has used a single-phase approach, considering the breach flow as a mix of supernatant water and tailings, both eroded and liquefied due to lateral unloading. This flow mixture is typically modelled as a non-Newtonian fluid. The rheological properties are usually defined by the average solid concentration calculated using the estimated pond and tailings discharge volumes. In contrast, the two-phase modelling approach is a newer method that treats the breach in two separate stages: the initial release of supernatant water with eroded materials forming an initial flood wave, followed by the discharge of flowable tailings from liquefaction or slumping. The latter tends to have higher solid content and consequently deposits closer to the facility.

Although high density thickened tailings facilities operate with minimal supernatant water, they are usually designed with a storm storage allowance mandated by design codes. Therefore, it is necessary to assume a significant supernatant pond volume when considering flood-induced failure for this type of facility when doing dam breach analysis. For modelling assessment of the flood-induced breach, the choice between single-phase and two-phase approaches would significantly affect the modelling outcomes, as the solid content approaches that of high density thickened tailings, slight variations in solid content can lead to significant changes in the rheological properties.

This paper presents a case study where both single-phase and two-phase approaches were applied to a hypothetical high density thickened tailings storage facility. The study aims to investigate the differences in modelling outcomes and their implications on the dam breach impact assessment and highlight the importance of selecting appropriate modelling approaches for this type of facility.

Keywords: *tailings dam breach analysis, high density thickened tailings, two-phase, rheology, impact assessment, non-Newtonian fluid*

1 Introduction

A tailings dam breach analysis (TDBA) is used to predict the potential impact of a tailings storage facility (TSF) failure. For this purpose, the TDBA often covers various credible failure modes and both fair weather (sunny day) and flood-induced (rainy day) scenarios to identify the representative or critical scenario that would result in the highest consequences (Canadian Dam Association [CDA] 2021). Although high density thickened tailings (HDTT) storage facilities normally operate with no or minimal supernatant water, they may be designed with a significant storm storage allowance mandated by design codes. Therefore, TDBA for this type of facility still needs to consider the flood-induced failure scenarios, where the TSF retains a significant amount of supernatant water due to extreme precipitation, snow melt or flooding at the time of the breach.

Unlike a water-retaining dam breach which releases only water, a breach of a TSF with a supernatant pond involves releasing both water and solids. The runout process typically starts with a rapid release of supernatant water and eroded tailings solids, forming a flood wave, followed by the runout of liquefied or slumped tailings. Depending on the solids concentration, the breach outflow can be categorised as either Newtonian (water flooding) or non-Newtonian (mud floods, mudflow, flow slide, flow slumping, or debris flow). For non-Newtonian outflows, practitioners often simulate the downstream impact using a non-Newtonian hydraulic model, and the flow behaviour is defined by the estimated solid concentration and the rheological characteristics–solids concentration relationship derived from rheology tests. This paper focuses on comparing two different breach runout modelling approaches and their implications on assessing dam failure, especially for HDTT storage facilities.

2 Influence of solid concentration on rheology

In a TDBA, the solids concentration in the outflow is normally considered the dominant factor that defines the rheological characteristics and flowability of a non-Newtonian breach outflow. The influence of solids concentration on rheology is generally well understood from historical studies. Figure 1 shows the relationship between solids concentration and yield stress for several different mineral tailings samples as presented in Boger et al. (2006). Although the relationship between yield stress and solids concentration is quite unique for each tailings sample, all these materials exhibit an exponential rise in yield stress as solids concentration increases. Another common feature for all the tailings samples in Figure 1 is that the yield stress starts to rise rapidly once it past the 'elbow' of the curve, typically at around 100 to 200 Pa.

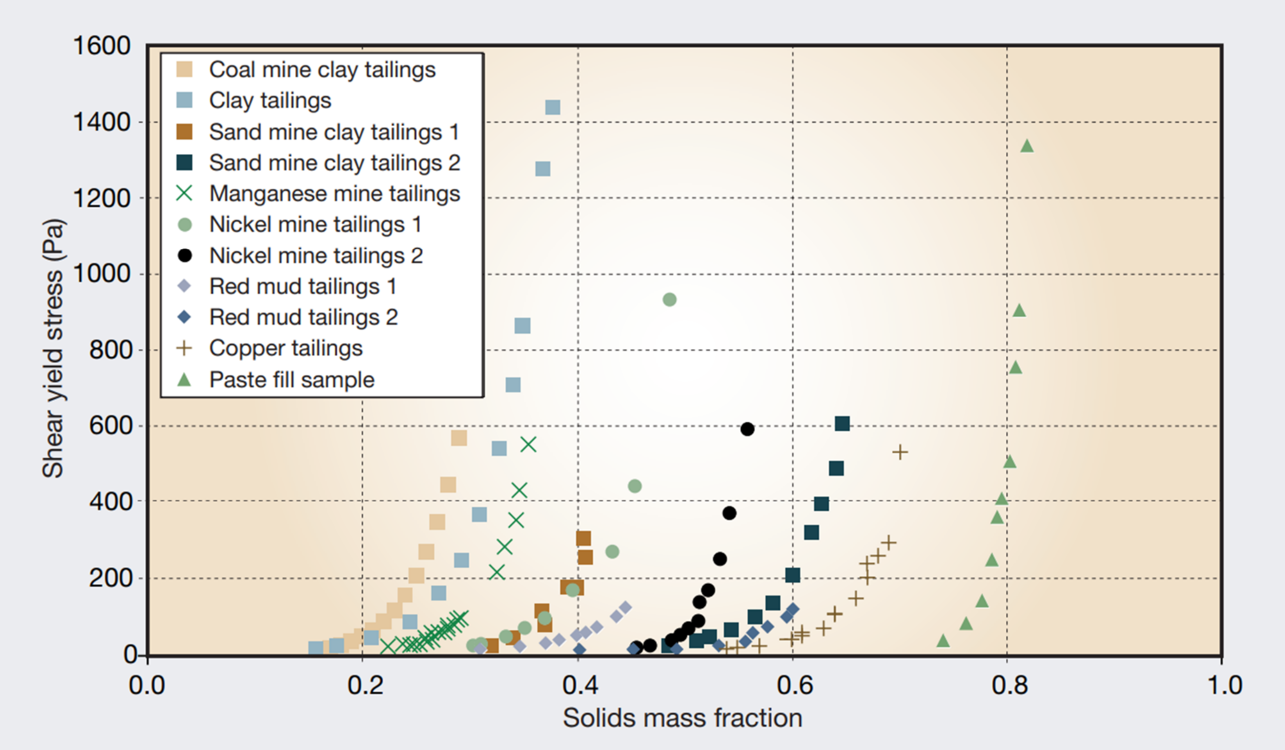


Figure 1 Yield stress versus solids concentration relationships for different mineral tailings from Boger et al. (2006)

HDTT is typically handled at yield stress ranging from 20 to 100 Pa, positioned before the 'elbow' in the yield stress–solids concentration curve. However, once placed in a TSF, this yield stress is expected to surpass the 'elbow' and enter the rapid rise zone. This change is due to an increase in solids concentration over time, resulting from the densification process by consolidation, bleeding, seepage, and evaporation. While similar changes occur in conventional tailings, they take longer to reach the rapid increase zone compared to HDTT, which is deposited into a TSF with a solids concentration near the 'elbow'. Therefore, breach outflows from HDTT storage facilities are likely more sensitive to changes in solid concentration. This emphasises the importance of carefully choosing modelling approaches and assumptions for evaluating the solids concentration of the breach outflow from such facilities.

3 Runout process and modelling approach

For TSF with a supernatant pond, the runout process following a tailings dam breach is complex and not yet fully understood. However, for TDBA the runout process can be considered as two distinct processes which can occur individually, simultaneously or sequentially (CDA 2021; Martin et al. 2015):

Process I involves the rapid release of supernatant pond carrying eroded tailings and dam fill materials. Depending on the pond's location, this process can either trigger the dam's failure or occur after the dam has already failed due to another cause, resulting in the discharge of tailings first. This flood wave travels downstream causing erosion and flooding in the receiving environment. Some of the coarse particles carried by the flood may settle along the way, while the finer tailings remain suspended until the flow velocity decreases enough for them to settle, typically in a lake or the ocean.

Process II represents the discharge of tailings that have become flowable due to tailings liquefaction or progressive slumping of unsupported tailings. Process II can occur either at the beginning of a breach if the pond is further from the dam or after the pond discharge. It may also be the sole process if the pond is located far enough from the dam to not participate in the breach. The outflow from this process typically would have a much higher solids concentration compared to Process I, containing only the tailings solids with interstitial water and would likely behave as a mudflow, flow slide or slumping. The runout distance and impact extent in this process are likely less than in Process I due to the lower flowability of the runout flow.

However, many TDBA completed in the past did not differentiate between the two physical processes involved in a dam breach. Runout modelling, based on how it aligns with these two processes, can be classified as either single-phase or two-phase approaches.

3.1 Single-phase runout modelling approach

In the past, dam break studies usually used a single-phase modelling approach for tailings runout simulation. This approach is still often used by practitioners and is considered acceptable by CDA (2021). This approach simplifies the runout process by considering the breach outflow as a single homogeneous mixture of released supernatant water and solids, overlooking the two distinct processes potentially involved. Generally, this mixture is modelled as a non-Newtonian fluid, with its rheological characteristics determined based on the average solid concentration. This concentration is typically determined based on estimates of pond and tailings discharge volumes.

3.2 Two-phase runout modelling approach

The two-phase modelling approach suggested by CDA (2021) provides an improved representation of the two distinct physical processes involved in tailings runout. In this approach, the breach flow from Processes I and II are assessed separately based on associated solids concentration. Typically, the breach flow in Process I has a low solids concentration and may behave like a water flood or mud flood. These can be simulated as Newtonian or non-Newtonian fluids using a hydrodynamic modelling package. The breach flow from Process II would contain only tailings and interstitial water, so the solid concentration is likely consistent with the in situ condition of the stored tailings. This breach outflow would behave as a non-Newtonian fluid that can be assessed using a hydrodynamic modelling package with non-Newtonian capabilities or geomechanical dynamic modelling tools based on mass and momentum conservation of the flow.

4 Case study on a hypothetical HDTT storage facility

The case study evaluated the flood-induced failure of a hypothetical HDTT storage facility using both single-phase and two-phase runout modelling approaches. The facility was created within a digital elevation model, and potential downstream receptors were positioned in the estimated path of the breach outflow. This arrangement allowed for an evaluation of the impact on these receptors from both runout modelling methods. To compare the impact of adopting different runout modelling approaches, consistent methods and assumptions were applied across other breach inputs and parameters. The key assumptions, methodology, and results of the TDBAs are detailed in the subsequent sections.

4.1 Site description

TSF 1 is a Turkey Nest HDTT storage facility located approximately 1.5 km south of a natural creek flowing east to west. A community of 700 residents lies northeast of TSF 1 and south of the creek. To protect the community from potential flooding due to a dam breach, a 3 m-high levee has been constructed along its southern and western boundaries. Figure 2 shows the site's layout and the assumed breach location that is expected to result in the worst impact on the community and the natural creek.

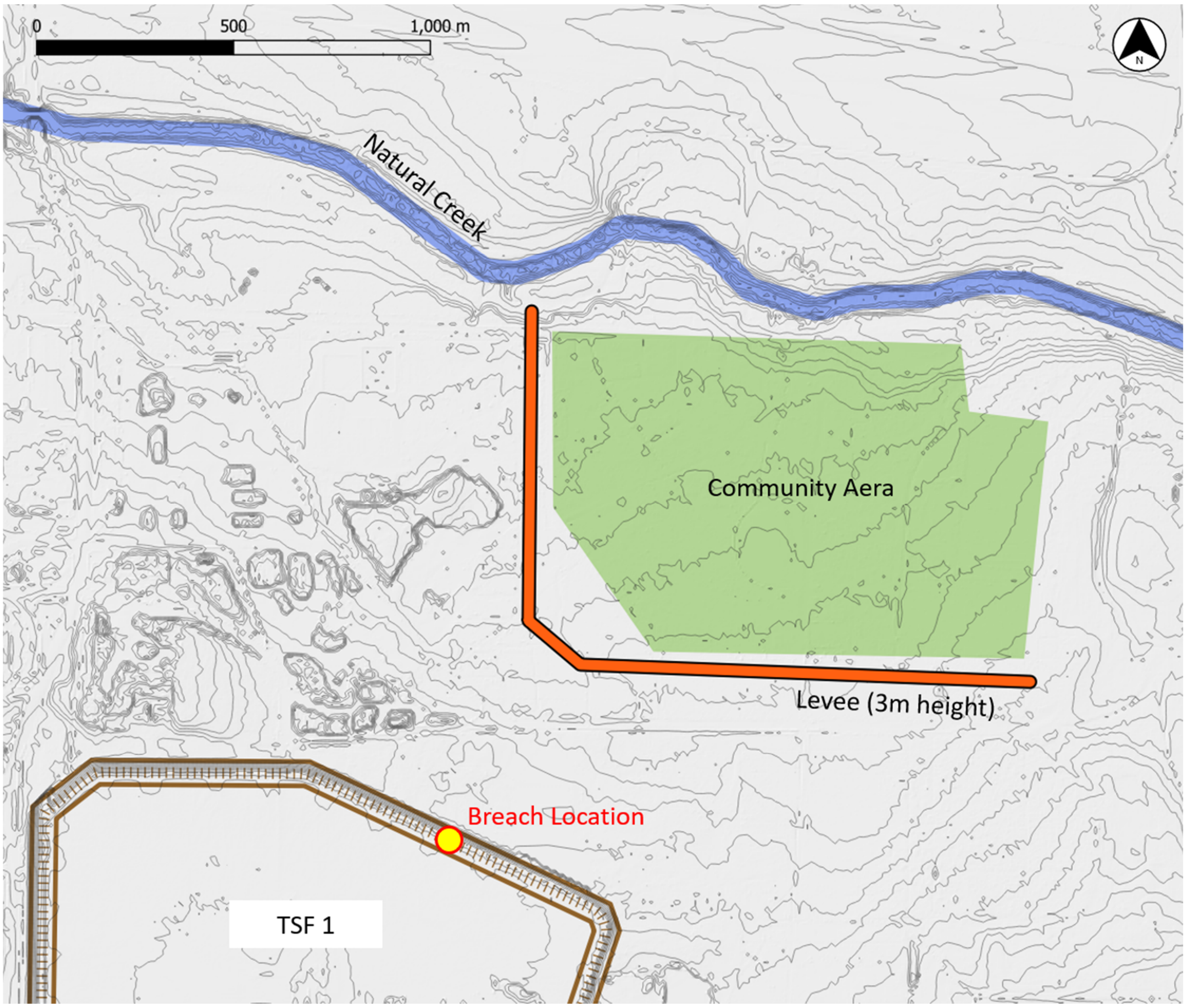


Figure 2 Site layout and the assumed breach location

4.2 Tailings storage facility conditions

To ensure a realistic assessment, key features of the hypothetical TSF were derived and adapted from an existing HDTT storage facility. In the scenario of a flood-induced failure, it was assumed that the TSF's supernatant pond would be filled to the embankment crest level due to an extreme storm event. Table 1 summarises the assumed conditions of TSF 1.

Table 1 **Key features of TSF 1**

Feature	Assumed values
Dam embankment height at breach location	15.0 m
Average tailings height	14.0 m (1.0 m below embankment crest)
Supernatant pond volume	1.0 Mm^3 (pond level at embankment crest)
Total volume of stored tailings	11.0 Mm^3
Average dry density of stored tailings	1.3 t/m^3
Tailings solids density	2.6 t/m^3
Tailings saturation	100%

Additionally, the rheological test results for that existing HDTT storage facility are also applied to the TSF 1. Figure 3 shows the yield stress–solids concentration relationship developed from the available rheology test.

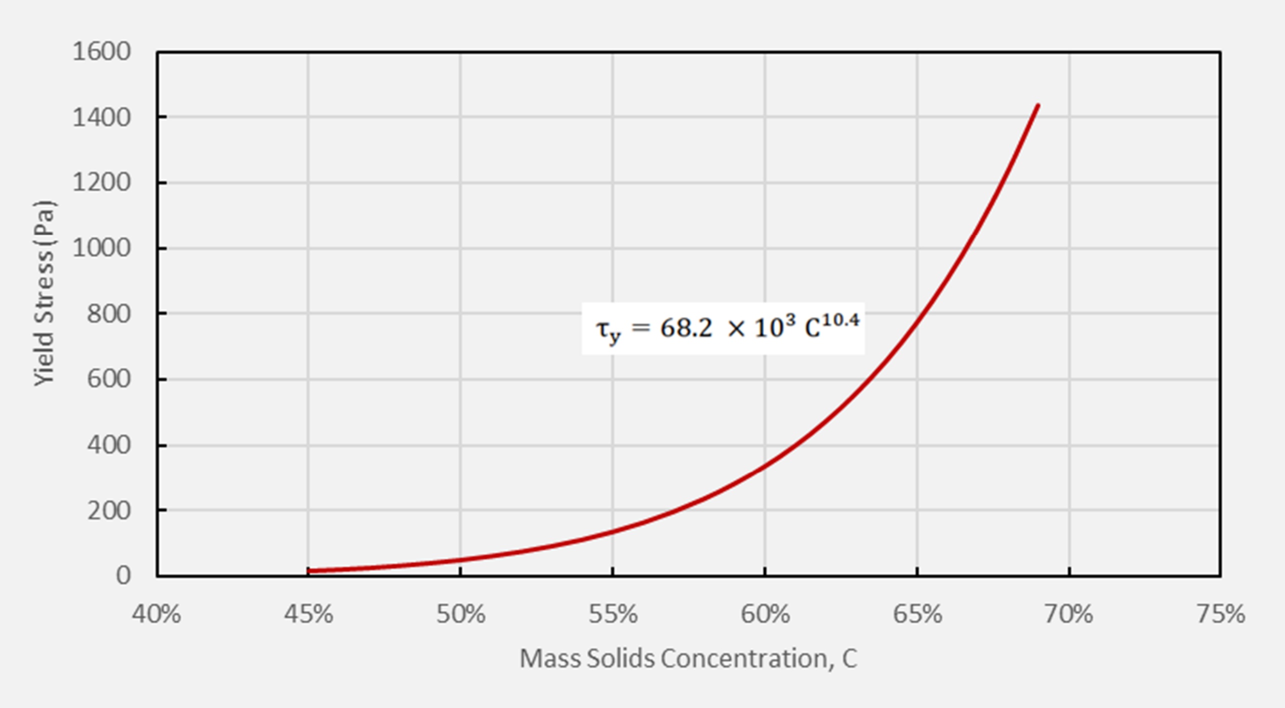


Figure 3 **Assumed yield stress–solids concentration relation for TSF 1**

4.3 Breach volume estimation

The breach volume from a tailings dam breach comprises the volume of the released supernatant pond and the volume of released tailings. This case study assumes all of the 1.0 Mm^3 supernatant water would be released from TSF.

The volume of released tailings was estimated using the method suggested by the CDA (2021) dam break bulletin. The released volume was estimated based on the cone of depression formed after the release of tailings, as shown in Figure 4. The volume of released tailings was estimated to be 0.8 Mm^3 based on an arbitrary post-failure slope of 4% selected from the range (3.5 to 9%) of past failures (Lucia et al. 1981; Blight & Fourie 2003).

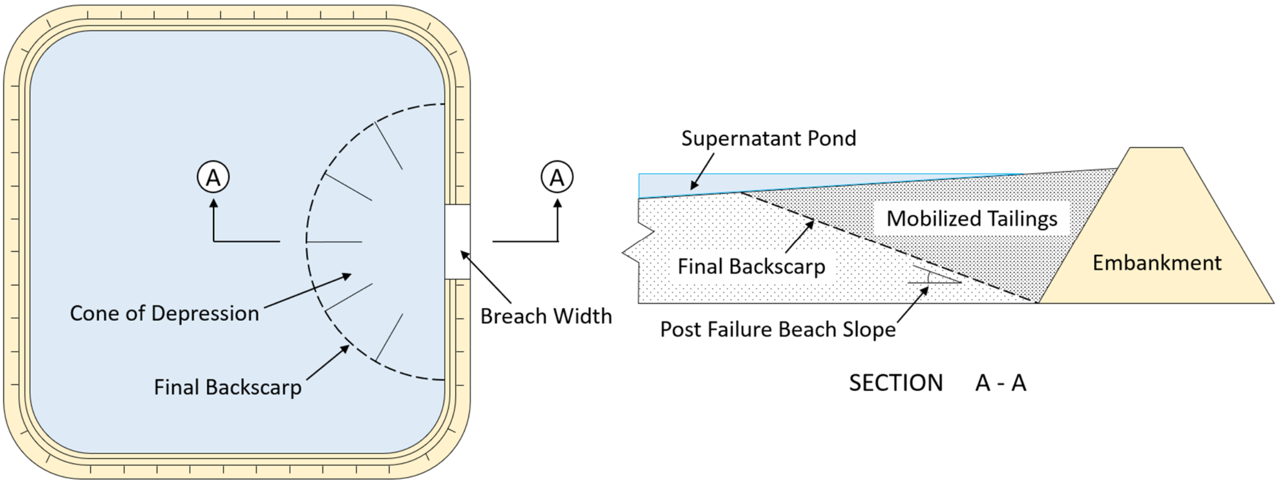


Figure 4 Post-failure cone of depression for breach volume estimation

4.4 Breach parameters and breach hydrograph

The breach parameters for the TDBA were estimated using the empirical equations developed by Froehlich (2008). The values of these estimated parameters are summarised in Table 2. This table also includes a comparison between the estimated values and the typical parameter ranges found in various guidelines. This comparison indicates that the estimated breach parameters fall within the commonly accepted range.

Table 2 Estimated breach parameter values

Breach parameters	Estimated values by Froehlich (2008)	Common guideline values
Breach height	15 m	Based on the breach developed to ground level
Average breach width	30 m	7.5 to 75 m 1 to 5 times the height of the dam (Federal Energy Regulatory Commission [FERC] 1993) 0.5 to 5 times the height of the dam (USACE 2007)
Breach Side Slope	1 H:1 V	0.25 horizontal to 1 vertical (FERC 1993) 0 horizontal to 1 vertical (US Army Corps of Engineers [USACE] 2007)
Breach formation time	0.37 hour	0.1 to 1 hour (FERC 1993) 0.1 to 4 hours (USACE 2007)

The breach hydrograph was calculated using the HEC-HMS software based on the estimated breach parameters and the storage character of the supernatant pond. Figure 5 presents the breach hydrograph estimated by HEC-HMS.

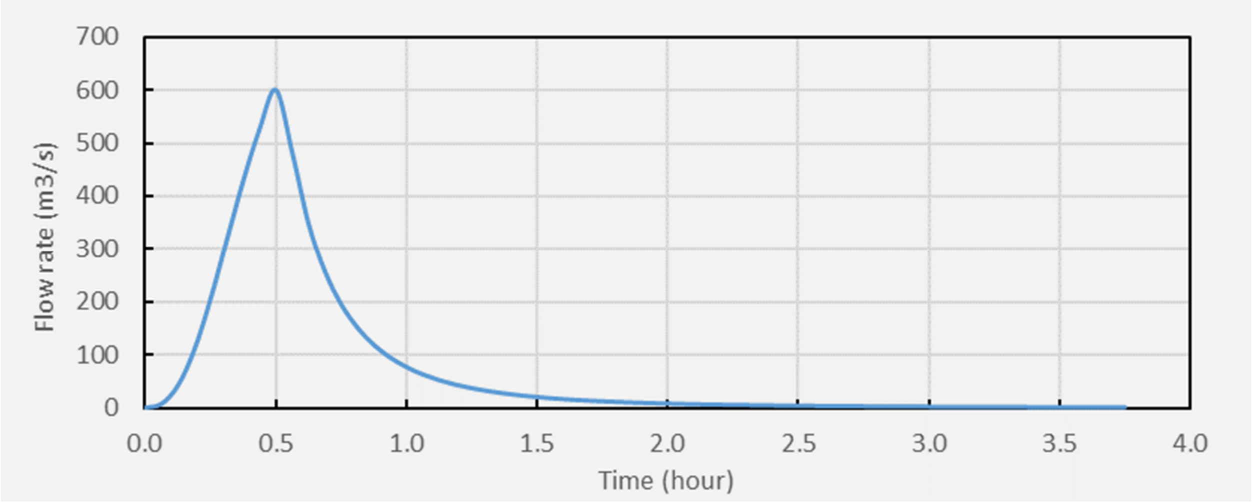


Figure 5 **Estimated breach hydrograph**

4.5 Runout modelling

Runout modelling in this study was performed using both single-phase and two-phase approaches to compare the differences in their results. To simulate different flow types involved in the single-phase and two-phase modelling approaches two different hydrodynamic models were used in this case study:

- **MADflow:** Developed originally by Chen & Lee (2000) for academic research, MADflow is a light-weight and accurate numerical simulation tool for mobility analysis of gravity-driven flows of tailings, soil, rock and/or water mixtures (such as debris flow, tailings flow, mudflow, mud flood, flowslide and avalanche). Non-Newtonian flows in this case study were simulated using this model with its quadratic rheology option, which requires inputs of Bingham yield stress and Bingham viscosity to define the flow's rheology.
- **TUFLOW:** TUFLOW is a hydrodynamic model developed by the British Maritime Technology Group. It simulates flood wave propagation processes by solving the full shallow-water equation using the finite volume approximation numerical scheme. TUFLOW is used widely for modelling water floods. In this case study, TUFLOW was applied to simulate Newtonian flows.

To decide whether to simulate the breach flow as Newtonian or non-Newtonian, the solid concentration and corresponding flow type were determined for the hydrodynamic modelling simulations in each approach:

- **Single-phase modelling approach:** This considers the breach outflow as a single mixture of supernatant pond volume and released tailings. The solid concentration for the breach flow is calculated by the total tailings release volume, determined from the cone of depression, and the total supernatant pond volume.
- **Two-phase modelling approach:** This separates the runout process mechanisms into two distinct model runs. Model Run 1 (Process I) simulates the initial rapid release of supernatant water, while Model Run 2 (Process II) models the subsequent release of liquefied or slumped tailings after the supernatant pond's discharge in Model Run 1 (Process I). The assumption is that the total supernatant pond volume is released in Model Run 1, and the total tailings release volume, determined from the cone of depression, is divided between the two model runs. About 20% of the total tailings volume is assumed to be released during Model Run 1 (Process I) due to erosion, with the remaining 80% released in Model Run 2 (Process II).

The solids concentrations for these model runs are calculated using the volumes of supernatant water and tailings, along with the assumed in situ geotechnical characteristics outlined in Table 1. Flow types for each model run are determined using the chart of flow types as a function of solids concentration, presented in Figure 6. Then the choice of Newtonian or non-Newtonian flows and corresponding hydrodynamic modelling software for each model run is based on these flow types. For the simulation of non-Newtonian flow in Moldflow, rheology parameters are specified based on the estimated solids concentration.

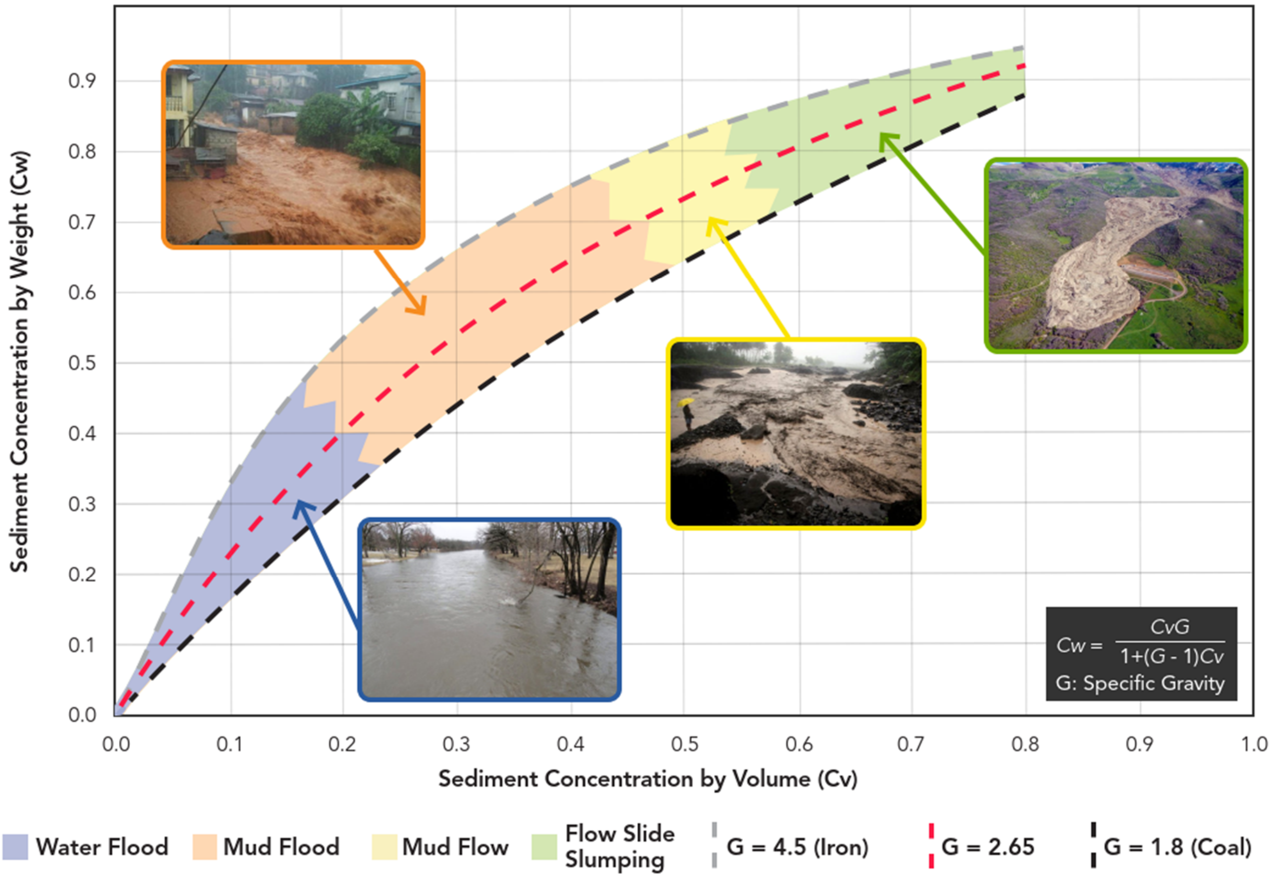


Figure 6 Chart of flow types as a function of solids concentration (CDA 2021)

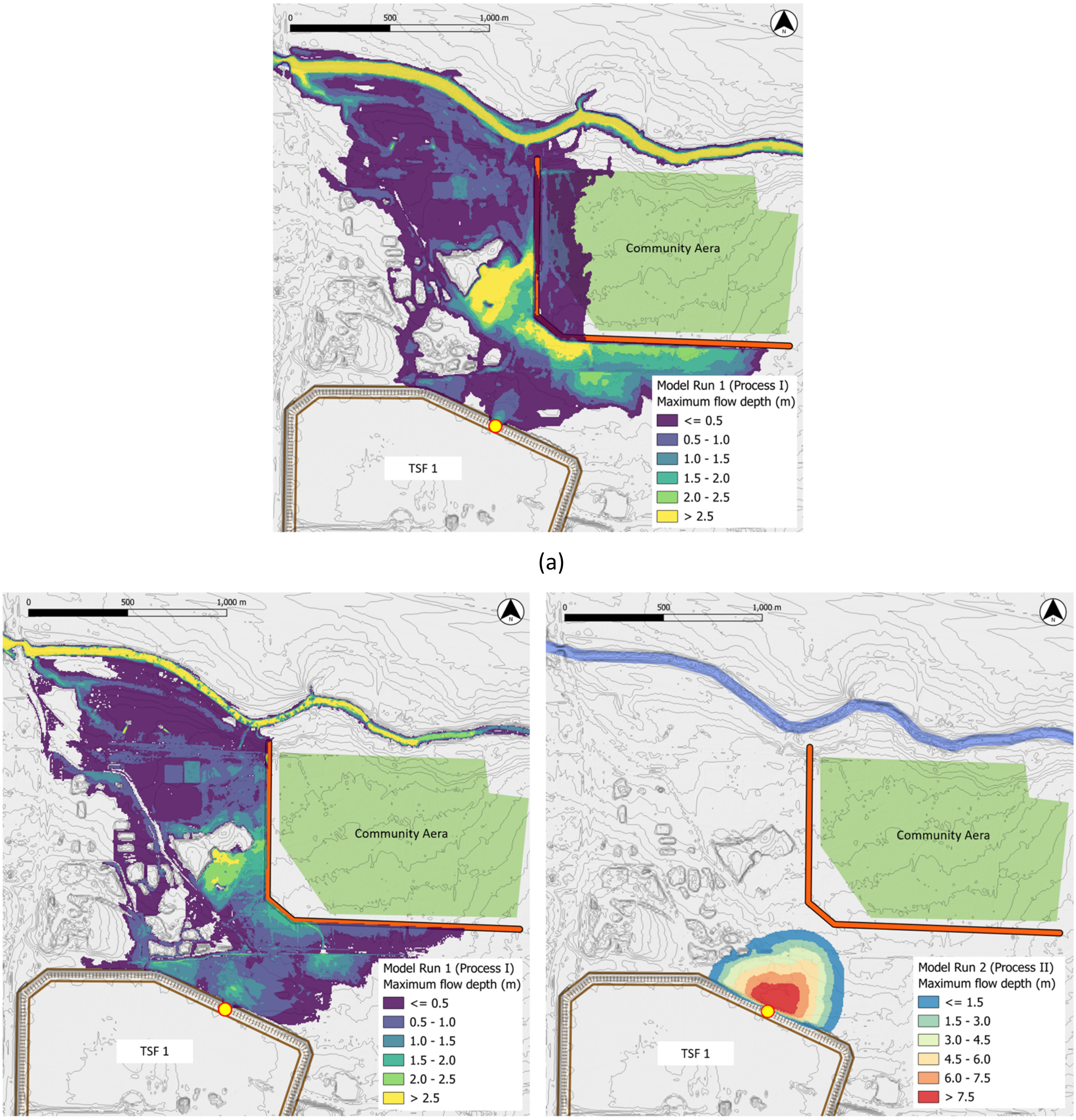
Additionally, it should be noted that the breach hydrograph shown in Figure 5 was calculated based on the release of 1 Mm^3 of the supernatant pond. For each model run, a bulk factor will be applied to the hydrograph to match the hydrograph volume with the breach flow volume. Table 3 presents a summary of the key parameters applied to each runout model run.

Table 3 Runout model run parameters

Parameter	Single-phase	Two-phase (Model Run 1)	Two-phase (Model Run 2)
Released supernatant water	1.0 Mm^3	1.0 Mm^3	0
Released tailings	0.8 Mm^3	0.16 Mm^3	0.64 Mm^3
Total breach flow volume	1.8 Mm^3	1.16 Mm^3	0.64 Mm^3
Mass solids concentration (flow type)	47% (mud flood)	17% (water flood)	72% (mud flow)
Flow type in hydrodynamic modelling	Non-Newtonian	Newtonian	Non-Newtonian
Adopted modelling software	MADflow	TUFLOW	MADflow
Bingham Yield stress	28 Pa	N/A	2,238 Pa
Bingham Viscosity	0.002 Pa.S	N/A	0.024 Pa.S

4.6 Modelling results

Hydrodynamic modelling was conducted for the three model runs summarised in Table 3. The modelling was run until the maximum inundation area was reached to ensure the maximum dam breach impact was captured. Figure 7 shows the simulated maximum flow depth results of the single-phase and two-phase model runs. Generally, the overall inundation area from the two approaches is similar, but their failure impact is dramatically different. The failure impact implied by each modelling approach is discussed in subsequent sections.



(a)

(b) (c)

Figure 7 **Maximum flow depth results from MADflow hydrodynamic modelling (a) Single-phase; (b) Two-phase, Model Run 1 (Process I); (c) Two-phase, Model Run 2 (Process II)**

4.6.1 Breach impact on people

As shown in Figure 7a, the hydrodynamic modelling results indicate that the single-phase model run leads to the overtopping of the 3 m-high flood levee, resulting in the inundation of a small part of the community area. In contrast, the two-phase model runs do not result in levee overtopping (Figures 7b and c). In the two-phase Model Run 1 (Process I), the peak flow depth between the TSF and the levee is generally much smaller than the single-phase run. However, it causes a larger inundation in the downstream areas near the natural creek. The outflow from the two-phase Model Run 2 (Process II) stops at a maximum distance of 440 m from the TSF.

The observed differences in inundation patterns between the models are attributed to several factors:

- The single-phase model uses a single hydrograph with a total flow volume equal to the combined volume of the supernatant pond and released tailings. Despite being mixed with tailings, the solid concentration remains relatively low, facilitating a rapid release of breach flow and creating a flood wave that travels a significant distance downstream. Conversely, in the two-phase model, the tailings volume released through Process II does not contribute to the flood wave produced from Process I. As a result, the flood wave in the single-phase approach was generated from a larger outflow volume and consequently a higher peak flow rate compared to the two-phase approach.
- The breach flow from the single-phase approach has a higher yield stress than the Model Run 1 (Process I) of the two-phase approach due to the higher solid concentration. Due to the impact of the yield stress, the downstream flows tend to have a higher water depth along the flow path and lower flow depth for flow directions away from the flow path. This results in less spreading of the breach flood than the two-phase approach.

4.6.2 Breach impact on environment

To determine the environmental impact of the dam breach, the modelling results were analysed to count the volumes of supernatant water and tailings solids that travel into the natural creek. Table 4 provides statistics on the volumes of supernatant water and tailings entering the natural creek for each runout modelling approach.

Table 4 Statistics on the volumes of supernatant water and tailings entering the natural creek

Parameter	Single-phase	Two-phase
Total flow volume into creek	1.47 Mm^3	0.99 Mm^3
Breach flow mass solid concentration	47%	17%
Supernatant water volume into creek	1.09 Mm^3	0.92 Mm^3
Solids volume into creek	0.38 Mm^3	0.07 Mm^3

Generally, the single-phase approach results in a significantly higher impact on the downstream environment by releasing four times more tailings solids and slightly more supernatant water into the natural creek.

5 Conclusion

The case study on the hypothetical HDTT storage facility demonstrates that the single-phase and two-phase runout modelling approaches can yield significantly different impacts due to variations in estimated flood wave volume, solids concentration, and rheological characteristics. In this study, the single-phase approach resulted in a considerably greater impact on both the community and the environment downstream of the TSF. However, the outcomes may vary under different site conditions and tailings rheological characteristics, potentially leading to the opposite result. Despite these uncertainties, the two-phase modelling approach, which offers a more accurate representation of the runout process, is recommended for any comprehensive TDBA.

It is important to acknowledge that tailings runout is a complex process influenced by numerous factors. For instance, if tailings liquefaction coincides with the release of supernatant water, the resulting mixture in Process I could have an unusually high solids concentration. Similarly, the sediment concentration in the tailings flow from Process II may mix with downstream water, reducing the solid concentration of the flow.

Consequently, practitioners must base their judgments on site-specific information. Conducting a sensitivity analysis for the parameters and assumptions identified as the primary sources of uncertainty is essential to ensure a thorough and reliable assessment.

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References

Blight, GE & Fourie, AB 2003, ‘A review of catastrophic flow failures of deposits of mine waste and municipal refuse’, *Proceedings of the international conference FSM2003*, Naples, pp. 1–17.

Boger, DV, Scales, PJ & Sofra, F 2006, ‘Rheological concepts’, in RJ Jewell & AB Fourie (eds), *Paste and Thickened Tailings – A Guide*, 2nd edn, Australian Centre for Geomechanics, Perth.

Canadian Dam Association 2021, *Technical Bulletin: Tailings Dam Breach Analysis*.

Chen, H & Lee, CF 2000, ‘Numerical simulation of debris flows’, *Canadian Geotechnical Journal*, vol. 37, no. 1, pp. 146–160, https://doi.org/10.1139/t99-089

Federal Energy Regulatory Commission 1993, ‘Selecting and accommodating inflow design floods for dams’, *Engineering Guidelines for the Evaluation of Hydropower Projects*, Office of Hydropower Licensing, Duluth.

Froehlich, DC 2008, ‘Embankment dam breach parameters and their uncertainties’, *Journal of Hydraulic Engineering*, vol. 134, no. 12, pp. 1708–1721, https://doi.org/10.1061/(ASCE)0733-9429(2008)134:12(1708)

Lucia, PC, Duncan, JM & Seed, HB 1981, ‘Summary of research on case histories of flow failures of mine tailings impoundments’, *Proceedings Mine Waste Disposal Technology: Technology Transfer Workshop*, US Environmental Protection Agency and US Department of the Interior, Washington, pp. 46–53.

Martin, V, Fontaine, D & Cathcart, J 2015, ‘Challenges with conducting tailings dam breach studies’, *Proceedings Tailings and Mine Waste 2015*, Vancouver, pp. 46–53.

US Army Corps of Engineers 2007, *Dam Failure Analysis Toolbox*, computer software.