Tailings2022 | July 6 - 8, 2022 · Online Conference
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Non-Newtonian Tailings Dam Break Analysis and Released Volume Estimation Using Site-Specific Parameters

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ABSTRACT

A series of major tailings dam break events have been recorded across the world in recent years. A breach in the impounding structure of a Tailings Storage Facilities (TSF) can lead to catastrophic environmental, social and economic impacts and potentially result in the loss of human lives.

Unlike a water dam break, the flow of the released tailings from a TSF will be mostly dominated by the non-Newtonian behaviors of the tailings slurry that is determined by the hyper-concentrated solids effect and rheological characteristics of the material. Modelling tailings flow as water (Newtonian flow) would lead to both unrealistically larger inundation areas, shallower depth of flow and higher velocities which may consequently result in unrealistic consequence category assessments.

In addition to the rheological parameters, the estimation of released tailings volume is another crucial component of the tailings dam break analysis. Most of the existing methods currently used for the estimation of the tailings released volume are based on empirical correlations which do not take into account the important site-specific parameters such as embankment type, deposited tailings in-situ density, liquefaction potential and post-liquified residual strength.

In the methodology proposed in this paper, the tailings released volume is estimated by utilizing the site-specific parameters such as deposited tailings in-situ density and post-liquefied shear strength ratio. The tailings solids effect and rheological properties have also been applied to the dam break analysis to create a comprehensive numerical model that integrates the non-Newtonian properties of the tailings along with the Newtonian behavior of water release from a TSF in a hypothetical failure scenario. A case study is then presented to illustrate the difference between the results from a Newtonian-only flow simulation, an empirical tailing released volume estimation, and the simulation undertaken based on the non-Newtonian flow behavior using site-specific parameters for the given scenario.

INTRODUCTION

Background

A series of major tailings dam break events across the world have been recorded in the recent years, including the failure of Mount Polley TSF in Canada, 2014 (IEEIRP, 2015), Fundão TSF in Brazil, 2015 (Carmo et al., 2017) and Feijão TSF in Brazil, 2019 (Rotta et al., 2020, and Rana et al., 2021).

It is well-understood that the breach in the impounding structure of the Tailings Storage Facilities (TSF) can lead to catastrophic environmental, social and economic impacts and can potentially result in the loss of human lives. To quantify the risk of a dam break, understanding the potential failure impact on the downstream area is critical. Therefore, predictive modelling techniques of tailings dam breaches have been developed and gradually improved over the recent decades to facilitate the understanding of the dynamics of the breach flow behaviors.

The predictive hydraulic modelling of tailings dam break events normally involves the release of mobilized tailings from the storage, as well as any supernatant pond within the TSF, via the potential embankment breach opening, which are routed within the downstream receiving area to assess the inundation propagation and impact.

Comprehensive numerical modelling of the dam break and flood routing can provide a reference for the designers and dam operators to visualize and assess the potential impact on the downstream area should a dam break event occur. The mitigation strategies, including flood protection levees, diversion channels and Emergency Preparedness and Response Plan (EPRP), can then be developed and implemented accordingly. The inundation mapping and failure impact assessment based on the dam break modelling also provide direct input towards detailed hazard analysis and consequence assessment.

Objectives

The recent Global Industry Standard on Tailings Management (GISTM) (ICMM, 2020) was put forward to provide a guideline for tailings management across the world. As specified in the Requirement 2.3 of the GISTM Guidelines, "*breach analysis needs to consider the credible failure modes, site conditions and the properties of the slurry*".

To ensure a credible failure mode, realistic causes to induce dam failure (e.g., excessive seepage, cyclic/static liquefaction, extreme storm storage, etc.) shall be examined to identify possible failure scenarios and to eliminate unrealistic conditions.

For the credible failure assessment, the modelling methodology is a critical component in tailings dam break assessment. Should the tailings be identified as potentially liquefiable and thus subject to mobilization, the run-out of the tailings needs to be modelled as a slurry or mudflow (i.e., solid-water mixture), which are generally considered a non-Newtonian fluid (CDA, 2020). Non-Newtonian fluid properties differ from water flow, which is the Newtonian fluid, in that it has a shear rate-dependent viscosity (i.e., non-constant viscosity). Consequently, the flow behavior of non-Newtonian fluid is governed by its rheological properties including viscosity and yield stresses, which can be significantly different from water flow. The viscosity controls the tailings flow speed which affects the arrival time for the inundation propagation to reach certain areas-of-interest, and the yield stress governs the final tailings inundation footprint which affects the consequence category assessment of the dam.

Therefore, for tailings run-out modelling, rheological models should be incorporated into the modelling to reflect the true properties and behavior of the slurry. With the commonly adopted rheological models such as Bingham Plastic and Herschel-Bulkley models, the effect of both yield stress and viscosity are directly correlated to and vary with the solids concentration of the tailings slurry, which reflects the in-situ properties of the deposited tailings as a crucial component of the overall dam break modelling setup.

In addition to the rheological parameters, the released volume of stored tailings, should they liquefy and mobilize during a dam break event, shall be realistically analyzed as it can be one of the main high-influence parameters that affect the dam break simulation outcome (Ghahramani et al., 2022). The released volume of tailings is a controlling factor and often gets overlooked for a dam break analysis as recognized by Gildeh et al. (2020). The modelling of conventional water outflows from a dam break is generally well-understood and utilizes well-established methodologies. However, the modelling and estimation of tailings run-out volume and distance are more complex due to the variables involved and hence requires greater qualitative engineering assessment to adopt valid modelling techniques and representative input parameters. Some of the more commonly used methods include "rule-of-thumb" approaches, assumed post-failure slopes, and empirically derived storage-height relationships.

Estimating the tailings released volume as the input for dam break modelling based on empirical relationships has been commonly practiced in the industry. However, these empirically derived approaches are considered to be highly variable with no broad consensus. For instance, ICOLD (2001) presented statistics from 40 historical failures where the proportion of released tailings ranged from 1% to 100% of the stored volume, with an average of 37%. Rico, Benito & Díez-Herero (2008) and Larrauri & Lall (2018) summarized the historical tailings dam breaches and correlated the released volumes with the total impounded volumes. As a result, a regression equation for the prediction of the released volume of tailings has been developed by Larrauri & Lall (2018) as shown below.

$$\log(V_F) = -0.477 + 0.954\log(V_T) \tag{1}$$

where

V_F	TSF failure released volume, m^3
V_T	TSF total storage volume, m^3

However, this regression equation takes no account of the TSF storage configuration, tailings types and properties such as in-situ density and strength characteristics, or historical water management practices, all of which are significant contributors to the potential quantity of released tailings in a dam break scenario.

To summarize, in correspondence with the GISTM Requirement 2.3, to achieve a realistic and credible failure assessment of tailings dam breach, it is crucial to assess and incorporate the actual site conditions and in-situ tailings characteristics, as every TSF has its site-specific properties which define the input parameters for the dam break modelling.

A methodology is therefore discussed in this paper to present a systematic workflow for the tailings dam break analysis. In the proposed method, the tailings released volume is estimated based on the geometric modelling that incorporates the in-situ tailings post-liquefied shear strength profile and actual site conditions. The site-specific tailings properties and rheological characteristics are applied in the run-out modelling to establish a hydraulic model that integrates both tailings (non-Newtonian) and water (Newtonian) releases from a breached TSF.

PROPOSED METHODOLOGY FOR DAM BREAK ANALYSIS

Released Volume Assessment

The failure released volume is a dominating factor for the tailings dam breach modelling. As discussed in the previous section, empirical methods do not incorporate the actual site conditions or the in-situ tailing properties, and can consequently generate unrealistic results. To estimate the tailings released volume, the liquefaction potential of the tailings shall be assessed prior to any dam break analysis. Tailings with no liquefaction potential would have a significantly less released volume compared to the liquefied tailings, and may result in a slumping failure only. Also, the type of TSF embankment construction should be considered in the failure released volume estimation. For instance, an upstream-raised TSF embankment is more likely to show a failure to a significant depth compared with a downstream-raised embankment, considering the base width of the embankment.

Two main parameters that shall be considered when assessing the tailings released volume include the breach size and the post-failure slope. Both parameters are discussed in more details in the following sections.

Breach Size

The breach size refers to the physical opening size of the embankment in a dam break event. The failure mechanism shall be incorporated to assess the breach size. ANCOLD (2012) specified two types of failure mechanisms for the consequence category assessment, i.e., Sunny Day Failure (SDF) and Flood Day Failure (FDF).

For the SDF scenario, seismic activity can generally induce instantaneous failure and slumping of the tailings. It is therefore commonly assumed that the breach happens instantly with almost no breach development time for a conservative assessment. The breach size is generally estimated based on the natural terrain profile, construction history and the dam height. SDF can also be triggered by excessive seepage (piping) or static liquefaction.

For the FDF scenario, it is often assumed that the TSF embankment failure would happen due to extreme storm events, where the surface runoff water resultant from such storm events would trigger either a piping or overtopping failure which gradually erodes the embankment. The characteristics of the embankment breach, through which release would occur, would be determined using empirical equations (Froehlich, 2008) or erosion-based embankment scouring modelling.

Froehlich's empirical breach equations, developed from historical dam failure case studies, can determine the breach width, breach development time and breach geometry side slopes based on the failure mode (i.e., piping or overtopping), breach released volume and breach height. These equations are:

$$B_{AVE} = 0.27\, K_0 V_W^{0.32} h_b^{0.04} \tag{2}$$

$$t_f = 63.2\sqrt{\frac{V_W}{g h_b^2}} \tag{3}$$

where

B_{AVE}	Average breach width, $(B_{TOP} + B_{Bottom})/2$, m
K_0	Failure mode coefficient ($K_{Piping} = 1.0$, $K_{Overtopping} = 1.3$)
V_W	Volume above breach level, m^3
h_b	Depth of breach measured from embankment crest level, m
t_f	Breach progression time, second

In-situ Post-Failure Slope

In-situ post-failure slope of tailings refers to the tailings residual slope within the TSF after a dam break event. The tailings released volume can then be assessed based on the difference between the original tailings beach surface, and the post-failure tailings surface using the estimated slope. The post-failure slope is estimated with its gradient being a function of the tailings consolidation 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) have been used to analyze 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 mobilization of the tailings until the tailings reach a stabilizing slope where force balance has been achieved. At this condition, it is identified that the shear strength of the tailings will be the same as the gravity component that drives the failure of the potential tailings. The equation is given by:

$$S_u = \gamma h \sin\beta \cos\beta \tag{4}$$

where

S_u Undrained, post-liquefaction shear strength, $S_{u,res}$, kPa
γ Total unit weight of tailings, kN/m^3
h Depth of tailings, m
β Post-failure slope angle, degree

Hydrograph of Released Volume from the TSF

The hydrograph of released volume from a dam break scenario controls the rate of tailings discharge from the embankment breach. The released volume of the tailings is used to estimate the shape of the outflow hydrograph from the TSF in a dam break scenario. It can be conservatively assumed that the shape of the hydrograph would be similar to that of a water flow. Hence, the two-dimensional unsteady flow simulation software HEC-RAS (USACE, 2022) is used to establish the breach flow hydrographs for the failure scenario.

In HEC-RAS, the TSF is defined as a storage area with stage-volume information for the mixture of tailings and water. The TSF is then connected to the downstream floodplain as a 2D computational mesh via an embankment connection with the breach formation parameters estimated using the aforementioned method. The simulations are then run, during which the breach volume is released from the TSF storage into the 2D mesh floodplain, to extract the outflow hydrographs at the connection.

The hydrograph of the SDF scenario typically shows a higher peak flow rate and shorter duration compared with the FDF scenario. This is due to the difference in breach size and in breach development time between the SDF and FDF scenarios.

Rheological Properties of Tailings

The rheological properties of the deposited tailings after failure, are measured in the laboratory by undertaking rheological testing on tailings samples taken from site. The rheological testing is often repeated for a range of slurry solids concentrations to define the Bingham Plastic or Herschel–Bulkley models parameters (i.e., yield stress and viscosity) as a function of slurry solids concentrations.

Non-Newtonian Fluid Modelling

Most dam break numerical models have traditionally been developed for water dams and Newtonian fluids (i.e., water). These models intend to predict conventional flood characteristics depending on dam types, failure mechanisms and breach size. For tailings dam break predictive modelling, the adopted model needs to account for hyper-concentrated flow properties (i.e., non-Newtonian fluids).

For this paper, the predictive simulation of a tailings dam break event has been conducted using the FLO-2D volume conservation flood routing program (FLO-2D, 2022). This commercial program can simulate both Newtonian and non-Newtonian flows and can be used for modelling unconventional flood routing problems such as mine tailings, and mud and debris flows. The program models non-Newtonian flows by allowing its user to assign dynamic viscosity and yield stress parameters for the built-in Bingham Plastic rheological model. The Bingham Plastic model parameters for the deposited tailings after failure are defined as a function of tailings solids concentration using a quadratic equation.

FLO-2D routes tailings dam break flows as a fluid continuum by predicting viscous fluid motion. The sediment continuity is observed during the run, which provides FLO-2D with the advantage over other programs in the capability of modelling tailings flow discharged into water and getting diluted. As sediment concentration changes for a given grid element, dilution effects, tailings flow cessation and the re-mobilization of deposits are simulated.

CASE STUDY

A case study is presented in the following section of the paper to demonstrate the simulation process of a hypothetical TSF dam break event and to compare the results from different simulation approaches. A cross-valley starter embankment has been constructed to store tailings with a maximum height of 32m at RL165m, followed by five consecutive upstream raises with 3m high embankments, forming a final crest level at RL180m. The tailings are discharged from the embankment crest, with a beach slope of 1% transitioning to 0.5% towards the valley. The final total tailings storage volume is approximately 1.64Mm^3 at the maximum discharge level at RL179.5m. Decant pond is formed above the tailings beach away from the embankment, with a maximum storage capacity of 187,800m^3 up to the embankment crest level. The natural topography of the valley is sloping at approximately 10% towards the east and reduces in gradient to 5% upon reaching the eastern open residential area. All the downstream residential buildings have been modelled with a nominal height of 3m for the assessment of flood inundation.

This case study aims to demonstrate the result difference between non-Newtonian and Newtonian modelling approaches, as well as the importance of applying site-specific input parameters. The analyzed dam break scenario is assumed to be a Flood Day Failure, where the extreme storm storage exceeds the flood storage capacity of the TSF, consequently triggering an overtopping, erosion-based breach opening through all the upstream-raised embankments, releasing both the decant pond and tailings storage. Natural flooding in the downstream receiving environment is assumed to be subsided at the time of the TSF breach, due to the size difference of its catchment compared with that of the TSF. It is also assumed that all the stored tailings in the TSF are fully saturated prior to the breach and are potentially liquefiable.

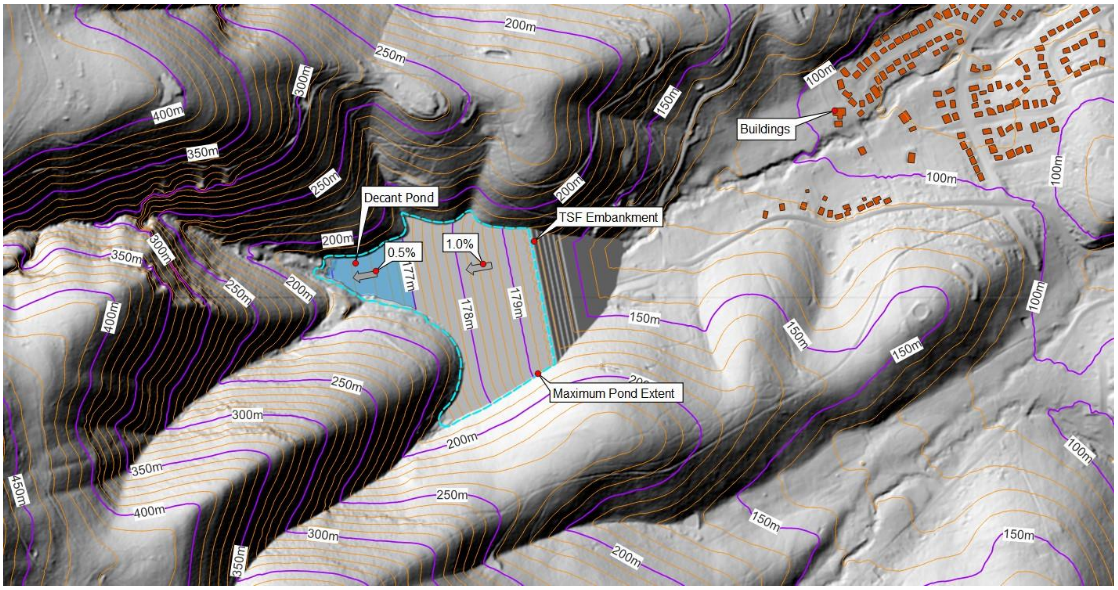
The tailings parameters adopted for the case study are summarized in **Table 1** below.

Table 1 Tailings parameters summary

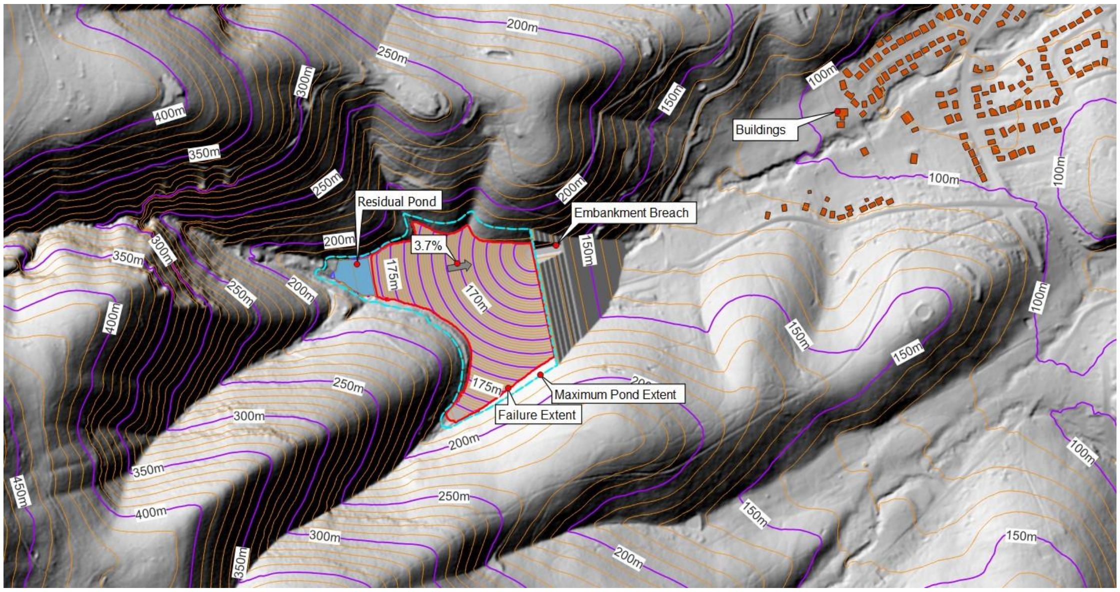
Tailings Basic Parameters	**Source**	**Value**
Specific gravity (SG)	From laboratory test	2.84
In-situ dry density	From site operation	1.3 t/m^3
Post-liquefaction shear strength ratio	From in-situ/laboratory test	0.08
Post-failure residual slope	Calculated from other parameters	3.7%
In-situ solids concentration (by volume)	Calculated from other parameters	45.8%
Tailings Rheological Parameters	**Source**	**Value**
Yield stress (at 45.8% solids)	From laboratory test	1,000 Pa
Viscosity (at 45.8% solids)	From laboratory test	2.5 Pa·s

It should be noted that the yield stress and viscosity of the tailings are directly related to the solids concentration, which may change during the dynamic modelling process when water interactions are encountered. Hence, these rheological parameters listed in **Table 1** are only representative of the in-situ condition of the tailings (i.e., at 45.8% solids concentration), and correlations between rheological parameters and solids concentration have been defined in FLO-2D based on actual laboratory test results.

The site layout and the hypothetical TSF is shown in **Figure 1a**. The layout for the post-failure surface with embankment breach modelled using the methodology described herein is shown in **Figure 1b**.



(a)



(b)

Figure 1 (a) Site layout with TSF; (b) Dam break post-failure layout

Comparison of Modelling Approaches

To compare the results from dam break simulation based on the proposed methodology in this paper with other approaches, the modelling technique and released volume have been selected as the variables. The base case modelling is carried out using the non-Newtonian flow model and site-specific parameters for the released volume estimation. The results are compared to simulation outcomes from Newtonian flow modelling and the empirical released volume. The Newtonian modelling simply assumes that all released volume from the TSF is considered as a water flow. The estimated tailings released volume using the methodology proposed in this paper is 547,610m^3, whereas the empirical failure released volume (V_F) is calculated to be 314,560m^3 using **Equation 1** proposed by Larrauri & Lall (2018), based on a total impoundment volume (V_T) of 1.83Mm^3.

The input parameters for different models runs are summarized in **Table 2**.

Table 2 Dam break model input parameters

Breach Parameters	**Non-Newtonian Flow**	**Newtonian Flow**	**Non-Newtonian Flow with Reduced Released Volume**
Total Released Volume	547,610m^3 (Tailings) 187,110m^3 (Pond*)	734,720m^3 (Water)	314,560m^3 (Tailings & Water)
Breach Base Width	14m	14m	7m
Breach Development Time	0.32hr	0.32hr	0.21hr

*This represents the released decant pond volume, as a small amount of pond water is expected to remain over the tailings beach after the breach due to the geometry of the post-failure surface, as shown in **Figure 1b**.

All models have been defined in FLO-2D with a computational grid using 5m×5m cells, and a total model run-time of 2 hours. The developed breach hydrographs for the non-Newtonian and Newtonian models have been mostly the same, apart from solids being loaded into the non-Newtonian hydrograph based on the defined solids concentration. The breach hydrograph for the model run with empirical released volume is estimated based on a proportionated reduction from the original hydrograph. These adopted hydrographs are plotted in **Figure 2** below.

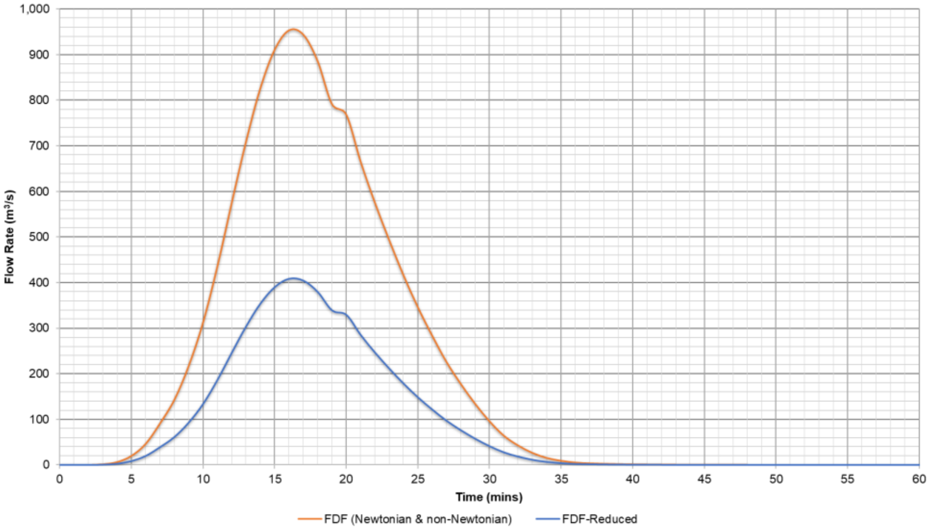
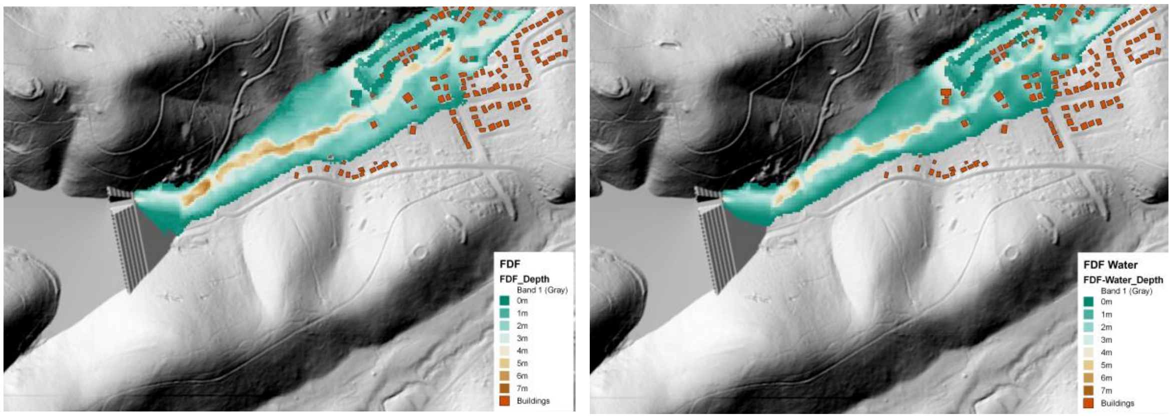


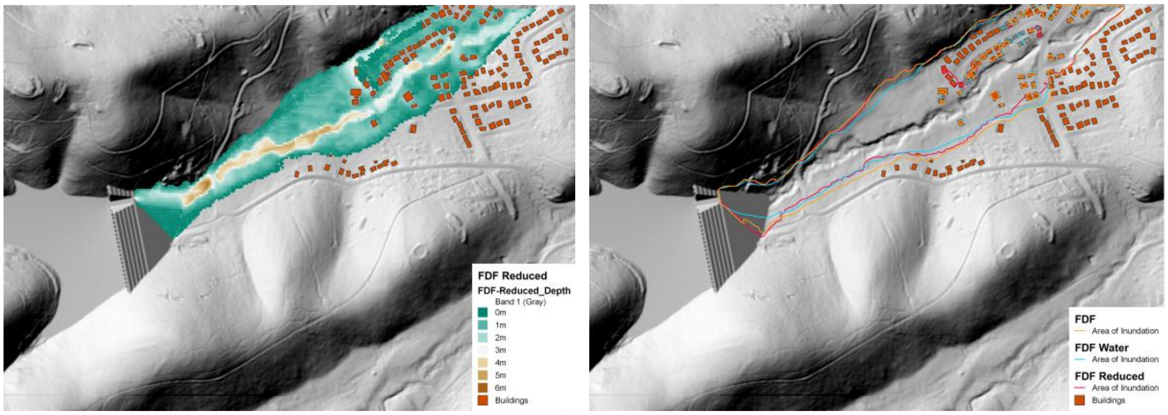
Figure 2 Breach hydrographs of released tailings for different model runs

Results Discussion

Using the model outputs, the maximum inundation boundaries and maximum inundation depths from these different models are presented and compared in **Figure 3**, whilst the maximum inundation velocities are presented and compared in **Figure 4**.

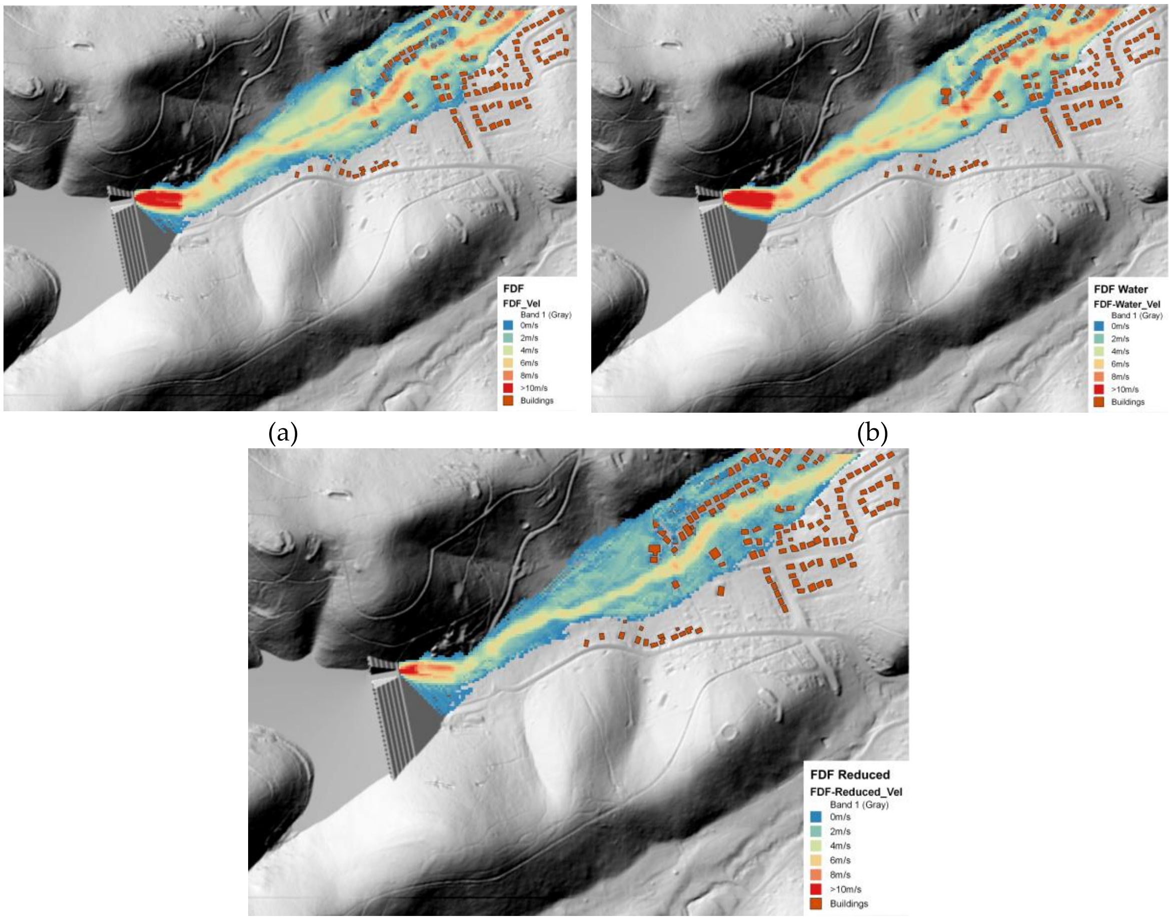


(a) (b)



(c) (d)

Figure 3 Inundation maximum depth map for (a) non-Newtonian modelling, (b) Newtonian modelling, (c) empirical tailings released volume; and (d) inundation boundary comparison



(a) (b)

(c)

Figure 4 Maximum inundation velocity map for (a) non-Newtonian modelling, (b) Newtonian modelling, (c) empirical tailings released volume

These inundation maps indicate that the inundation footprint for the non-Newtonian modelling is generally larger than the Newtonian modelling, due to its additional flow resistance which resulted in a slower velocity, deeper flow depth and more deposition along the flow path. The slowdown of the tailings flow also resulted in a deeper inundation at the downstream residential houses compared with the water flow results, as the tailings run-out does not bypass buildings as fast as water. Also, comparing with the modelling outcomes from the empirical released volume case, it is evident that the reduction in released volume has resulted in a shallower flow depth and a less severe inundation.

Using the inundation depth, velocity time series recorded during each model run, the depth times velocity (D×V, in m^2/s) values achieved throughout the model duration can also be extracted, which are typically used to quantify the flood impact hazard. The flood hazard can help with the emergency response and flood risk management plan for the existing infrastructure, or can be used for strategic planning purposes (Australian Institute for Disaster Resilience, 2014). Based on the hazard vulnerability index curves proposed by Smith, Davey & Cox (2014), which is adapted in **Figure 5** below, the hazard levels can be mapped for these model runs. The results are shown in **Figure 6**.

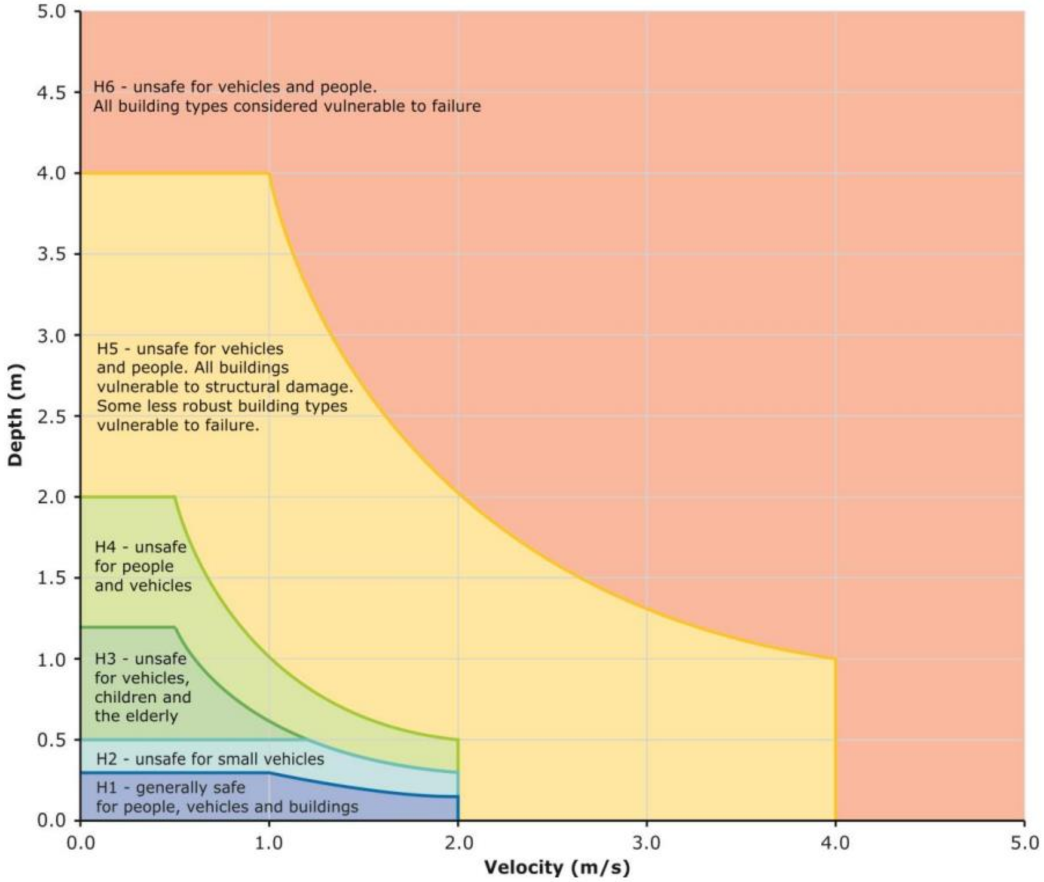
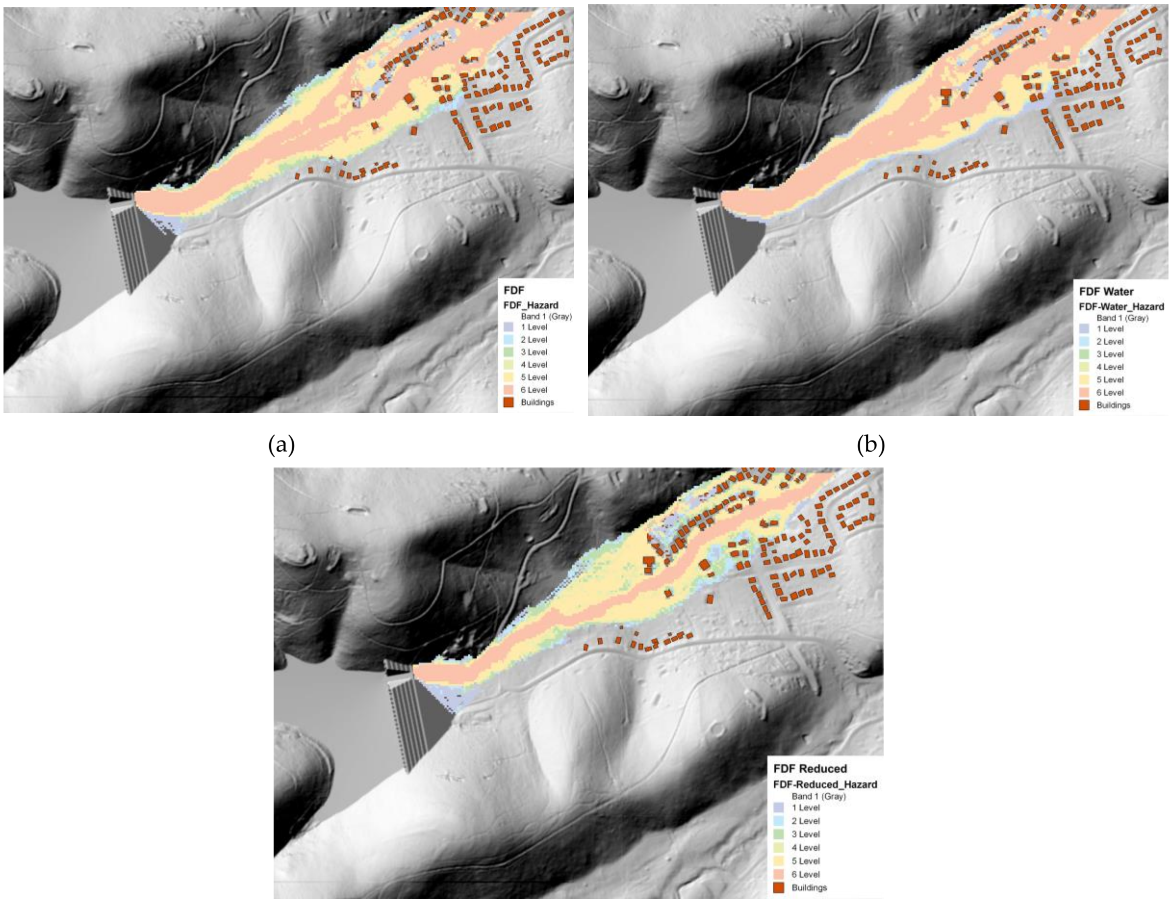


Figure 5 General flood hazard vulnerability curve (adapted from Smith, Davey & Cox, 2014)



(a) (b)

(c)

Figure 6 Inundation hazard level map for (a) non-Newtonian modelling, (b) Newtonian modelling, (c) empirical tailings released volume

From these hazard assessment maps, it is evident that due to the over-estimated inundation velocities along the main flow path in the Newtonian modelling, the majority of the residential area has been assessed to be at a level of H6, while the rest of the downstream area has been mostly assessed at H5. In comparison, the non-Newtonian modelling demonstrated a more realistic outcome, where obstruction of flow between buildings reduces the hazard level. Furthermore, due to the reduced inundation extent, the model run with the empirical released volume estimation has been less conservative and may under-estimate the potential hazards to certain residential buildings.

CONCLUSION

Dam break study is critical for the consequence category assessment and emergency response plan development for every TSF. A workflow has been presented in this paper for non-Newtonian tailings dam break modelling, summarized as follows.

- Assessment of tailings physical parameters – from site data and laboratory test
- Estimation of tailing released volume using site-specific parameters
- Assessment of breach hydrograph of released tailings and water
- Assembly of non-Newtonian flow routing model based on tailings rheological parameters

Liquefied tailings released from a TSF breach exhibit non-Newtonian flow behaviors. The non-Newtonian flow differs from the Newtonian flow, as the non-Newtonian nature generates greater energy loss along the flow path and the yield stress of the material will eventually cease the motion.

The realistic approach to the simulation of tailings dam break requires a comprehensive understanding of the site-specific conditions and definition of the tailings rheological characteristics as inputs to the dynamic hydraulic model. The properties of the deposited tailings in the TSF, including yield stress and viscosity at different solids concentrations, can be obtained via specialized laboratory testing.

As presented in this paper, another important consideration in tailings dam break simulation is that the in-situ tailings properties and actual site conditions are incorporated into the adopted method for the assessment of the released volume. The parameters required for the released volume estimation generally include tailings SG, in-situ dry density and post-liquefied undrained shear strength ratio.

The case study presented in this paper assessed the difference between non-Newtonian and Newtonian modelling approaches, as well as the difference in results by adopting site-specific parameters rather than empirical equations. The outcomes from the case study indicate that the Newtonian modelling approach will generally generate faster flood propagation velocity but shallower flow depth, which may result in unrealistic arrival times, run-out extents or flood impact. On the other hand, as the empirical released volume estimation does not consider the site conditions or site-specific tailings parameters, it can result in values with great uncertainties which will not be beneficial for predictive modelling.

It is therefore concluded that the Newtonian modelling is not suitable for a tailings dam break analysis and that empirical correlations for released volume assessment can be unreliable. To improve the credibility of dynamic hydraulic modelling of dam break events, and to conform to the requirements from the GISTM guidelines, it is suggested that non-Newtonian modelling methodology with tailings rheological models and site-specific tailings parameters should be adopted for the modelling of TSF dam breaks.

Nevertheless, it should be emphasized that the dam break modelling methodology provided herein is never the "one-and-only" or "silver bullet" approach towards the ever-evolving, technology-driven topic of dam break simulation and relevant engineering analysis, but the authors sincerely wish that this study will spark innovations and inspire researchers and practitioners to further explore and perfect this field of engineering.

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