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REVIEW ARTICLE

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Tailings Dam Breach Outflow Modelling: A Review

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Abstract
Tailings dam breach modelling studies have received considerable attention recently due to the rise in the number of tailings dam failures and catastrophic consequences caused by downstream flooding. Numerical models are useful tools in risk management for assisting urban planners in planning for the safe evacuation of the vulnerable communities located downstream in the so-called “shadow area” of such dams. Several challenges and uncertainties exist when conducting risk assessments of tailings dam failure. In this study, recent advances in modelling approaches for tailings dam breach analysis and downstream flood wave routing are summarized and critically reviewed. This study evaluates different mudflow modelling studies that involve single-phase, quasi-two-phase, and two-phase modelling approaches; dam breach outflow modelling; tailings rheological characterization; and application of geographic information system (GIS) and remote sensing to tailings dam breach analysis. Recommendations for further research are provided based on the findings. In addition, this study will help dam engineers and practitioners to maintain industry standards and include state-of-the-art practices in their work.

Keywords Mudflow · Remote sensing · Rheology · Dam risk assessment · Bed entrainment

Introduction

Tailings are byproducts of mining operations and can contain fine solids ranging in size from sand to silt, clay, wastewater, and chemicals. Tailings dams are storage facilities used to hold the tailings and water produced during the mining operations (Wang et al. 2014). Tailings dam failures can severely impact public safety and the downstream environment (Ishihara et al. 2015; Luo et al. 2012; Martin et al. 2015; Sun et al. 2012). Recently, the number of tailings dam failures have increased due to varied reasons, such as lack of dam management, foundation failure, slope instability, and natural hazards (Lyu et al. 2019). Moreover, tailings dams are constructed in sequential lifts; that is, initially there is a starter dam, and as the reservoir behind it is filled with tailings, the dam is raised using the tailings themselves. Consequently, the failure rate of tailings dams is very much higher than that of other types of dams, and it is extremely challenging for mining operators to confirm the stability of these dams (Roche et al. 2017). Mitigation measures, emergency plans, and flood protection structures are essential (Moon et al. 2019).

The flood wave generated by a dam collapse is different from a river flood due to the often-sudden release of a damaging hydraulic bore without any warning. There have been hundreds of tailings dam disasters worldwide since the beginning of the twentieth century (Rico et al. 2008). The failure rate of tailings dams in the past 100 years has been ≈ 1.2%, which is higher than the accident rate of classical water retention dams (0.01%) according to the International-Commission-on-Large-Dams (Azam and Li 2010). Piciullo et al. (2022) conducted a statistical analysis of tailings dam failures and found that there have been an average of 2.5 failures per year and an average released volume to total stored volume ratio of ≈ 0.27. They also found that the

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upstream construction method had the highest percentage of failure (32%).

The Mount Polley tailings dam failure that took place on August 4, 2014, in British Columbia, Canada, is an example. After the breach of the Mount Polley gold and copper mine tailings pond, mining waste along with water and slurry flowed into Polley Lake, Quesnel Lake, and the Cariboo River. Water quality monitoring results in Quesnel Lake showed high levels of arsenic, selenium, and zinc. Zinc levels exceeded the exposure limits for aquatic life. Consequently, some salmon fisheries were closed (Petticrew et al. 2015).

There are several other recent examples of tailings dam failures. The Xiangfen tailings dam in China collapsed in 2008, resulting in 381 deaths (Zuoan et al. 2013). The Fundao mine tailings dam in Brazil failed in 2015, releasing 32 million m^3 of tailings (Flávio et al. 2017). The incident polluted ≈ 650 km of rivers before flowing into the Atlantic Ocean, causing serious environmental impacts (Burritt and Christ 2018). The Brumadinho dam disaster in Brazil and the Siberian gold mine disaster in Russia killed 232 and 15 people, respectively, both in 2019 (Yu et al. 2020). Satellite images for some of the historical tailings dam failures are presented in Appendix A, which accompanies the online version of this paper.

Based on the construction method, there are three types of tailings dams: upstream, downstream, and centerline. Upstream tailings dams are constructed using tailings themselves by moving the crest further upstream of the starter dam. Even though the usage of tailings reduces costs, upstream tailings dams are less stable in the event of an earthquake or under static loading. This is due to liquefaction and loss of strength of tailings materials. Downstream tailings dams are designed by progressively raising the embankment further downstream of the starter dam, with an internal drain or filter. These dams need more tailings to build than upstream dams but are more stable under dynamic loading (e.g. in the event of an earthquake). Centerline tailings dams maintain the original centerline of the starter dam while being progressively raised. They require less material to build than downstream tailings dams and have a zone of compacted tailings which holds up the impervious core. These dams are more stable than other tailings dams under dynamic loading (McLeod and Bjelkevik 2017). Typical failure mechanisms include overtopping, foundation cracking, seepage and piping, slope instability, and earthquake-induced failures. Overtopping can occur during heavy rains and floods and the embankment can be eroded in a short time frame. This is followed by a breach, tailing flow, and subsequent collapse. If the foundation is not sufficiently strong, a sudden loading can also cause deformation, which may lead to an overall collapse. Slope failures can happen if the geotechnical properties are not correctly characterized. One important factor that causes slope instability is the change in water level due to heavy rain (or snow) events. On December 17, 2012, the Gullbridge mine disaster happened due to the instability of the embankment slope (CDA 2007). In the event of an earthquake, excess pore-water pressure can develop, leading to liquefaction and failure. In Chile, seismic loading with a moment magnitude of ≈ 7 caused liquefaction and failure of two copper tailings dams in 1965. The resulting slurry flow killed more than 200 people (Liu 2018). Piping develops when there is internal erosion that can erode the embankment and lead to local dam failures (Yong et al. 2001). In 1979, a tailings dam in British Columbia failed because of piping in the sand beach of the dam, resulting in considerable damage to the property (Wise-Uranium 2024).

Tailings flows are generally highly sediment-laden flows and are non-homogeneous and non-Newtonian flood events. Fluid properties may vary considerably as they flow down steep watershed channels. An increase in sediment concentration affects fluid properties by altering the stress–strain relationship, and it is important to consider rheological properties such as shear stress, shear rate, and yield stress (Pradhan et al. 2018). Therefore, laboratory tests may be required to derive key parameters for better modelling of non-Newtonian fluid behaviour. Hence, published values have been used as estimates, and the uncertainty can be minimized by conducting a sensitivity analysis (Moon et al. 2019). Based on Labanda et al. (2004), thickened tailings can be simulated using the Herschel-Bulkley model. Various debris flow modelling studies have been conducted in recent years to analyze the fluid dynamics. Debris flow models are widely used for tailings dam failure risk assessment, even though tailings flows are more mobile than rock avalanches, nonvolcanic debris flows, and waste dump failures (Ghahramani et al. 2020).

In this study, models for breach hydrographs in the context of parametric, semi-physically based, and physically based models are compared that have not been discussed in previous studies. We also evaluated single-phase, quasi-two-phase, and two-phase models in tailings run-out analysis, and application of GIS in tailings dam breach analysis. To summarize, the objectives of this review were to: (1) investigate the state-of-the-art research in tailings dam breach outflow modelling and how it has evolved over the last few years, (2) analyze possible areas of improvement, and (3) draw conclusions from the research gaps in tailings dam failure risk assessment. We evaluated different mudflow modelling studies that involve single-phase, quasi-two-phase, and two-phase models in tailings run-out analysis, dam breach outflow modelling, tailings rheological characterization, application of GIS, and remote sensing in tailings dam breach analysis, and make recommendations for further research.

Numerical Modelling Studies

Mudflows resemble debris flows but with less boulders and granular materials and can have very steep frontal wave (Pasculli et al. 2021). Many granular debris flow modelling studies have been conducted recently to have a clear understanding of the nature of landslides and debris flows. Since tailings are composed of water, sediments and contain high concentrations of heavy metals, they can be highly concentrated and, as such, mudflow models are widely used for tailings dam risk assessment (Ghahramani et al. 2020). In this section, single-phase, quasi-two-phase and two-phase modelling studies are evaluated.

Single Phase Approach (Homogeneous Mixture)

Several numerical modelling studies reported in the past used a single-phase approach, where it is assumed that mixture density remains the same both in space and time. The solid phase is assumed to be uniformly distributed and the debris flow density variation in mass and momentum conservation equations are overlooked (Cesca and D'Agostino 2008; Hubl and Steinwendtner 2001; Chen et al. 2010; Aleotti and Polloni 2003; Juez et al. 2013; Peng and Lu 2013; Liu and Huang 2006; Mahdi et al. 2020; Sreekumar et al. 2022). Some studies like Mahdi et al. (2020), Ghahramani et al. (2020), and Sreekumar et al. (2022) used Flo-2D to simulate tailings dam breach outflow and for flood extent delineation. Wu et al. (2013) compared Flo-2D and Debris-2D for modelling debris flow induced by landslides in the village of Xinfan, in southern Taiwan. In Flo-2D, the governing flow equations (mass and momentum equations) are formulated in one dimension and applied independently in eight directions. The central difference and Newton–Raphson methods are used to solve the equations, and the non-Newtonian nature is simulated using a quadratic rheological model. In the quadratic rheological formulation, yield stress and viscosity are expressed as a function of the solid concentration and a turbulence term that considers the surface roughness is included (O'Brien and Julien 1985). The inputs include sediment concentration, viscosity, yield stress, Manning's n values, a digital elevation model (DEM), and a mudflow discharge hydrograph, which includes the water outflow hydrograph and temporal variation of solid volume concentration. Debris-2D uses mass and momentum conservation equations, and the first-order upwind method is used to discretize the convective term. The second-order central difference method is used for the remaining terms, and the third-order Adams–Bashforth method is employed for time advancement. The main model inputs are topography and initial debris source distribution. The only rheological parameter to be assigned is the yield stress. In the Flo-2D model, density remains constant in each flow direction, while in Debris-2D, yield stress and density are assumed to be constant. Debris-2D can model the commencement and stopping of debris flows, but Flo-2D simulations cannot be stopped until the user terminates the computation and that can affect the final inundated area. Flo-2D is more efficient in terms of the computation time of the central processing unit (CPU) because it employs variable time steps compared to Debris-2D, which uses a fixed time step. Flo-2D employs user-defined mudflow discharge hydrographs for flood routing. Hence, the total volume released depends on the artificially determined hydrograph, which may not be the same as the actual outflow hydrograph. However, Debris-2D simulates using real source distributions estimated through field surveys or aerial image analysis; hence, landslide-triggered debris flow events are better simulated by Debris-2D (Wu et al. 2013).

Two-phase Approach

Several two-phase debris flow modelling studies have been performed in the past (Pelanti et al. 2008; Pudasaini 2012; Pitman and Le 2005; Meng and Wang 2016; Pailha and Pouliquen 2009; Bouchut et al.2016; Greco et al. 2019; Tai et al. 2019). In these models, solid and liquid phases are regarded individually in the mass and momentum conservation equations. Flo-2D has adopted a two-phase modelling approach to simulate the breach of a tailings dam with reservoir water storage. However, in a two-layer shallow water model, if the difference between the phase velocities of the solid and liquid layers is very high, complex eigenvalues may appear and there can be loss of hyperbolicity and numerical instability (Pelanti et al. 2008). Several ways to prevent the loss of hyperbolicity have been proposed by Castro et al. (2011) and Sarno et al. (2017), but these techniques need iterative algorithms that are very computationally expensive. Another limitation of the two-phase modelling studies is that they excluded the bed entrainment or changes in the downstream channel morphology.

Quasi Two-phase Modelling Studies

In quasi-two-phase modelling approach, the mass and momentum conservation of mixtures and mass conservation of solid phases are considered individually. This approach was employed in studies by Iverson and George (2014), Rosatti and Begnudelli (2013), Kuo et al. (2013), Kowalski and McElwaine (2013), and Pasculli et al. (2021). According to this approach, the solid and fluid phase velocities are combined into the depth-averaged bulk mixture velocity and the effects of solid–fluid particle interactions in the mixture are considered. Even though this modelling approach is simplified when compared to the two-phase modelling approach, it offers better numerical stability. Hence, this approach is suitable for large-scale mud flow events that need quick evacuation planning. Riverflow2D model uses this quasi-two-phase approach in simulating mudflow. Martínez-Aranda et al. (2022) used Riverflow 2D to simulate tailings dam failure that occurred in Brumadinho (Brazil) in 2019. In the study conducted by Sreekumar et al. (2023), Riverflow 2D was used to simulate bed entrainment during the Mount Polley tailings dam failure. The comparison between single phase, two-phase, and quasi two-phase models are summarized in Table 1.

Tailings Dam Breach Modelling

Tailings dam breach modelling is often used in the mining industry. These studies are often required by regulators to approve the design of an impoundment, i.e., they want to ensure that the risks of such facilities are characterized properly and that mine owners have an emergency response plan (ERP) and emergency preparedness plan (EPP) in place to implement in case of a hypothetical dam failure. This practice has changed globally in the past 7 years, and it is not just a check box to fulfill regulatory requirements. For instance, a technical bulletin (CDA 2021) on tailings dam breach assessment and a global industry standard on tailings management by Global Tailings Review (2020) were published to begin addressing the global concerns regarding tailings dams and their potential failure. Added to this are the confidential internal guidance by mine owners that are used for management and risk evaluation of their tailings facilities. From a public perspective, tailings dam breaches have taken many lives and caused severe environmental damage worldwide. Details of some of the historical tailings dam failures are presented in Appendix A. This demands due diligence in the design and risk identification of tailings storage facilities (TSFs).

In Canada, the Canadian Dam Association (CDA) is a world-leading dam association on guidelines to better define and frame tailings dam breach analysis/assessment (TDBA). The CDA (2021) recently published a technical bulleting on TDBA, which is being used as a widely accepted guideline. The guideline provides an overview of modelling options for runout analysis as well as breach modelling, which will be further discussed in this paper.

This section of this paper only focuses on breach modelling. Modelling of the released volume downstream (i.e. routing of the flood wave) will be reviewed in a subsequent section. To this end, it is necessary to understand the mechanism of a tailings dam breach. CDA (2021) identified three general failure modes for tailings dams: (1) collapse of the foundation due to applied forces that can happen due to liquefaction triggered by earthquakes or other mechanisms, surface erosion, piping, and internal erosion; (2) overtopping due to insufficient freeboard or spillway capacity, spillway malfunction, settlement of the crest, or misoperation of the TSF; and (3) contaminated seepage failure. Multiple causes can be identified for each failure mode. Gildeh et al. (2020) reviewed 85 historic tailing dam failures and found that liquefaction, overtopping, and slope stability accounted for 60% of all failures (Fig. 1). The failure mode, in conjunction with hydrologic conditions at the time of failure, forms the dam breach scenario.

There are two common hydrologic conditions used in dam breach analysis/assessment (DBA): 1) fair-weather, which suggests normal conditions without a storm, and 2) flood-induced, which refers to extreme precipitation, snowmelt, or flooding. The term "sunny day" is interchangeably used for "fair-weather".

The breach mechanism for a tailings-retaining dam is different and more complex than that of a water-retaining dam. In most breaches, not all of the contained volume is released, and the released volume highly depends on the supernatant pond volume of the surface of the TSF and the flowable tailings volume due to liquefaction (CDA 2021). The CDA (2021) uses these two variables and defines four general cases to characterize the TDBA (see Fig. 2). For more details on each case, refer to the CDA (2021) guidelines.

The type of breach outflow varies with the amount of water and tailings released. For example, it is expected that more tailings will erode due to the pond presence in Cases 1A and 1B than in Cases 2A and 2B. It is noteworthy that the eroded tailings are different than the tailings released

Table 1 Comparison between single phase, two- phase and quasi two-phase models

Single phase	Two-phase	Quasi two-phase
Solid phase is assumed to be uniformly distributed	Solid and liquid phases are regarded individually in the mass and momentum conservation equations	Solid and fluid phase velocities are combined into the depth-averaged bulk mixture velocity
Mixture density remains the same both in space and time	Density of solid phase and liquid phase varies	Mixture density varies
Better numerical stability	Less numerical stability	Better numerical stability
E.g. Flo-2D, Debris- 2D	E.g. Flo-2D two phase model	E.g. Riverflow 2D

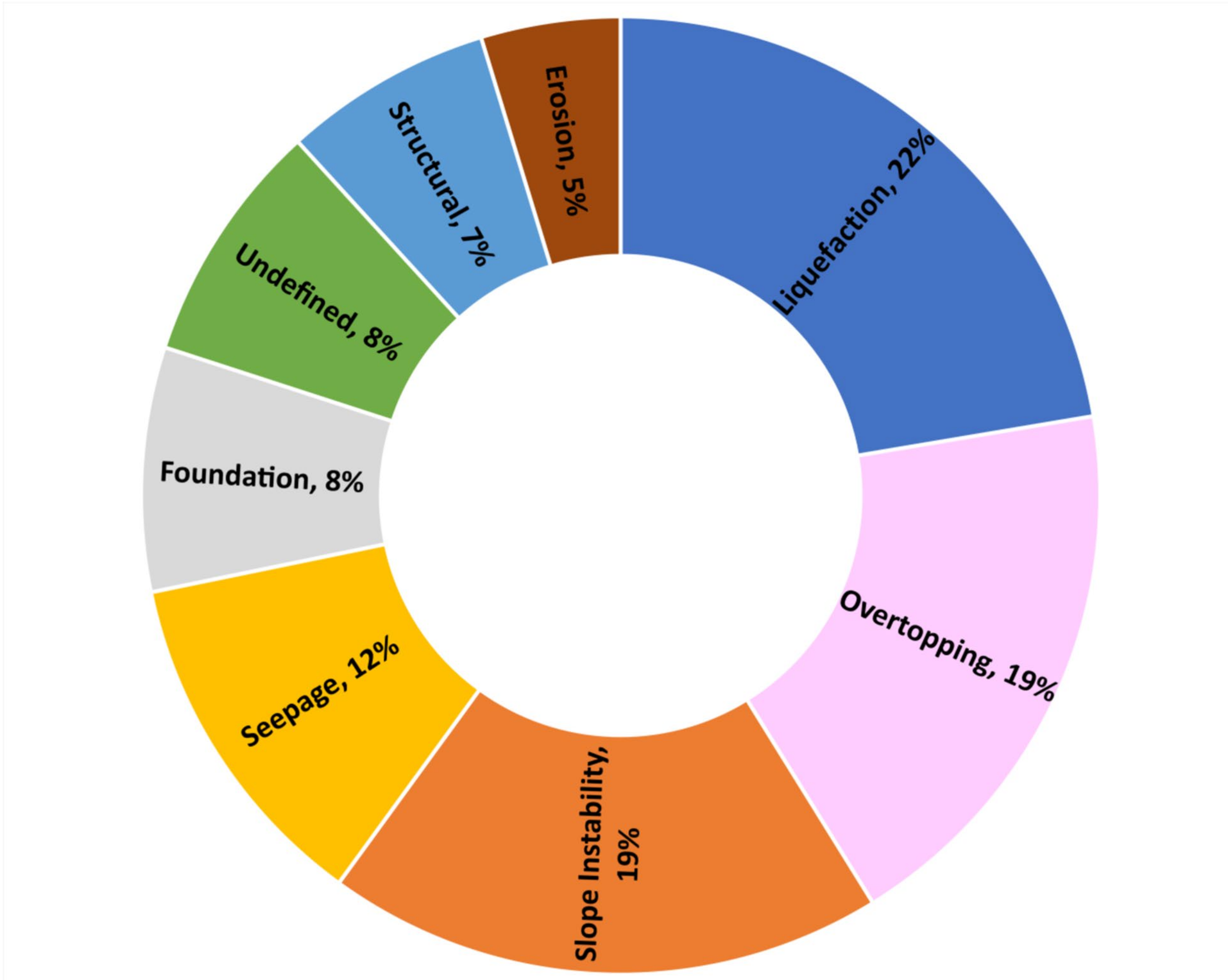

Fig. 1 Historical Failure Mode (Sample Size = 85, from Gildeh et al. 2020)

due to liquefaction. A schematic of the different stages of embankment dam deformation and breach with respect to liquefaction failure is shown in Fig. 3. Post-triggering liquefaction results in deformation of the dam, including settlement of the dam crest (Fig. 3a and b). At some point, the dam crest settles below the water level in the tailings basin, and the tailings basin pond water starts moving as a sheet flow over the deformed surface of the interior dam (Fig. 3c). With further deformation of the dam, more water flows over the deformed surface (Fig. 3d), and erosion of the surface may start if the flow-exerted shear stresses exceed the critical shear stress of the surface materials. As the deformation reaches equilibrium, the flow rate over the deformed surface may reach its maximum (Fig. 3e). This flow rate depends on the available volume of water in the tailings basin, the water level in the tailings basin when deformation stops, and the amount of erosion over the deformed surface. If the initial discharged volume is relatively small, the maximum breach outflow may occur sometime after deformation ends. The volume of water leaving the tailings basin causes erosion of the fine tailings and erosion of some of the deformed surface materials. When water overtops the total breach width due to deformation, a small amount of eroded surface is added to the outflow, and fine tailings in the upstream cell start eroding. The water flowing over the deformed surface then concentrates at the center area and cuts deeper, sending a greater amount of eroded tailings downstream.

The physical behaviour of the breach and released volume depends on many parameters that define the tailings rheology and flowability, such as the tailings composition, chemistry, gradation, and immediate downstream topography (CDA 2021). However, O'Brien (1986) classified breach outflow based on the solids concentration, as shown in Fig. 4.

Breach modelling identifies the shape of the breach hydrograph and its peak that is routed downstream. The breach prediction methods for earthen dams (i.e. most tailings dams) can be classified into three types: parametric

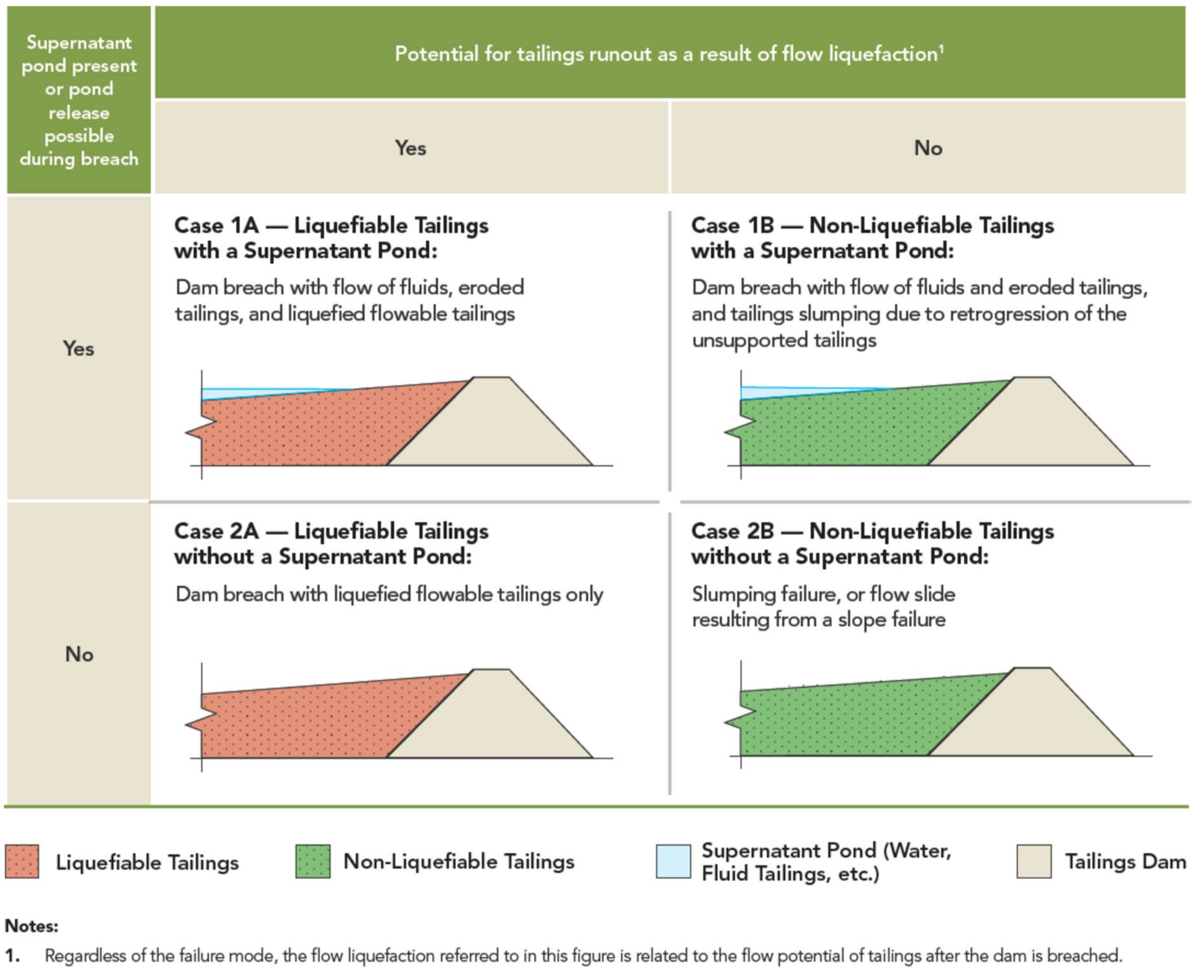

Fig. 2 Conceptual TDBA Cases (source: CDA 2021)

models, semi-physically based models, and physically based models. It is noteworthy that almost all breach models were developed for water-retaining dams and not for tailings dams. Therefore, the common practice of using these breach models is based on notable simplification.

Parametric Models

These models predict breach parameters, such as breach width and formation time, as well as breach hydrograph shape and its peak, using regression analysis of historical dam failures (Ghahramani et al. 2022). These models are very popular because of ease of use and speed. The input parameters include the following: total volume of reservoir (*Vr*); volume of water above the bottom of final breach (V_w); height of breach (*hb*); height of water above the bottom of final breach (h_w); and dam height (h_d). For a list of available parametric models, refer to West et al. (2018).

Researchers continue to improve empirical or parametric model approaches for tailings dam breach analysis. White et al. (2023) re-evaluated earlier waste dump failure databases by adding more site-specific parameters to improve the correlation between deposit volume, fall height, and run-out length. For coal mine dump failures, an empirical run-out length estimate relationship has been developed by analysing the 1966 Aberfan failure. Additional data in other locations should be used for further analysis and for expanding its applicability.

Huamanyauri et al. (2023) compared methods in estimating the volume released during a tailings dam breach. Statistical and geometric methods were both used, and the study could not determine which method was more conservative. The geometric method was more robust than the statistical method as more factors like dimensions of tailings storage facility were considered. More studies need to be conducted to understand which method is more appropriate.

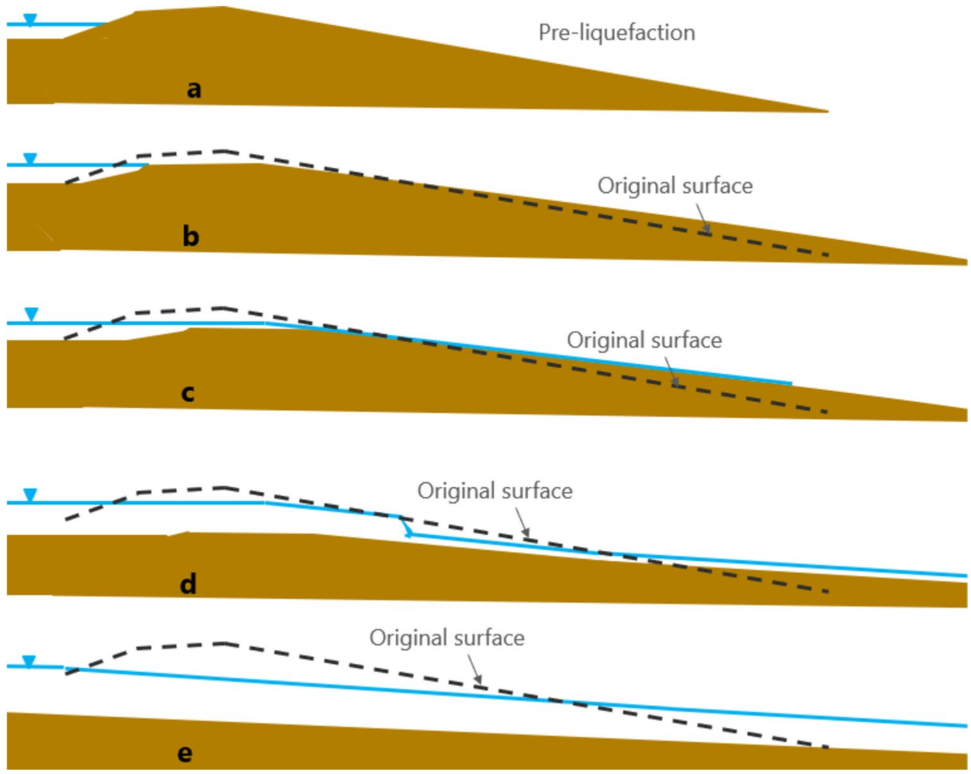

Fig. 3 Stages of Embankment Dam Deformation Due to Liquefaction

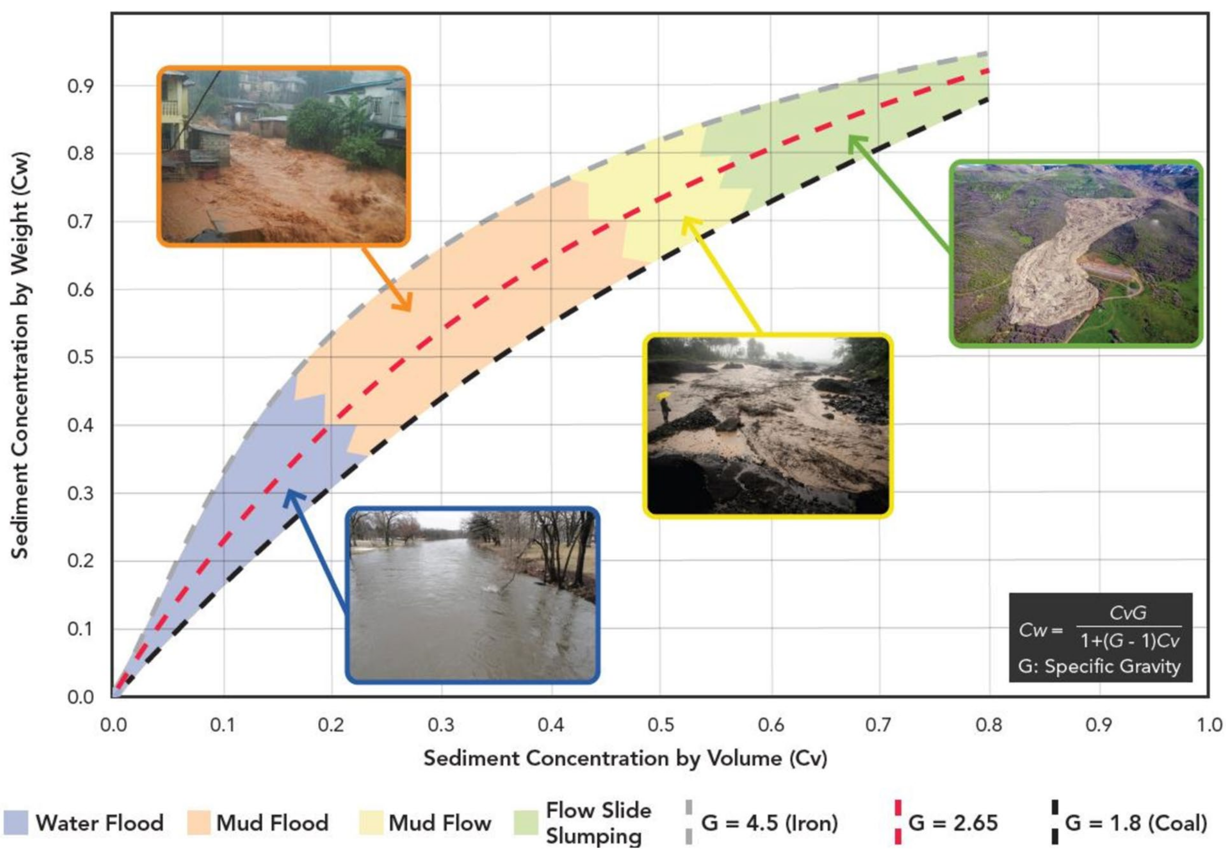

Fig. 4 Breach Outflow Classification Based on Solids Concentration (*Source*: CDA 2021)

Semi-physically Based Models

These models often use breach dimensions, breach development time, or soil erosion rate to generate a breach hydrograph (Gildeh et al. 2020). These models ignore physical processes and use simplified hydrodynamic equations, such as weir flow equations, to estimate breach hydrographs. When using semi-physically based models, these is no advancement in the accuracy of predicting breach hydrographs over parametric models, but the process of developing hydrographs is improved (West et al. 2018). HEC-RAS and FLDWAV are examples of the most popular semi-physically based models.

Tellez et al. (2023) recently performed tailings dam break analysis using HEC-RAS for a downstream raised tailings storage facility in South America. In this study, potential failure modes were analyzed, and sensitivity analysis was conducted to understand the effects of breach geometry on the results. The sensitivity analysis revealed that the downstream inundated area does not depend on the breach geometry itself but other factors like released volume and rate. In this study, predicting the final tailings storage facility involved many challenges and assumptions.

Lepage et al. (2022) studied a large-scale dam breach at Ghost Dam in Alberta using HEC-RAS. While not a tailings dam, this recent study is informative for TDBA in populated areas. They first performed a probable maximum flood (PMF) analysis and then used it for a dam breach assessment of the Ghost Dam and its impact downstream. The challenge in downstream routing was the large basin and a long flood route downstream, covering more than 1,000 km of the Bow and South Saskatchewan rivers. The model, developed using the HEC-RAS software, was split in two sub-models: a 2D model and a 1D model. This was to better manage the computational cost of such a large domain. The 2D modeling covered ≈ 140 km of the Bow River, including a large section of downtown Calgary. Two different approaches for modeling the effect of buildings on the flow conditions were compared: modeling the structure directly in the model terrain and adapting the mesh around the buildings' shape; and modifying the terrain roughness. The hydraulic model was calibrated using 2013 flood data in Calgary and they concluded that representing buildings using roughness values resulted in more realistic water levels. Although it was a water dam breach analysis (i.e. a Newtonian fluid), this is an important observation for tailings dam breach flood routing to urban areas.

Physically Based Models

Physically based models like DL Breach, EMBREA, and WinDAM consider the intricate structural, geotechnical, and hydraulic behaviour of an embankment dam and its upstream reservoir. Both breach and outflow are modelled simultaneously based on the dam's material properties and the evolution of the breach opening is predicted without the need to make assumptions regarding the breach dimensions (Lumbroso et al. 2021). McKellar et al. (2023) conducted physical and numerical modelling (using XBEACH) of tailings dam breach processes and studied the effects of different upstream slope angles, the presence of tailings dam beaches, and failure mechanisms like seepage failure, notch overtopping, and wide-width overtopping. It was concluded that a flatter upstream slope can affect the outflow hydrograph, and the presence of a tailings dam beach can reduce the peak outflow. Although these models are more time-consuming than parametric and semi-physical models, physically based models give more accurate results (West et al. 2018). To learn more about the available physically based models, refer to West et al. (2018).

Comparisons of Breach Outflow Model Hydrographs

A breach outflow hydrograph is necessary to route the breach flood downstream and map the impacted area to be used in the ERP and EPP. As mentioned above, both physically based models and semi-physically based models can generate the breach hydrograph. In this section, two sets of comparisons are made in breach outflow hydrograph generation.

Comparison 1: Two Semi-Physically Based Models vs One Parametric Model

A critical factor in choosing the appropriate software to develop a breach hydrograph is the downstream topography near the location of the breach, as it impacts the peak and shape of the hydrograph. Here the topography refers to the distance from the breach point to ≈ 100 m (for a channel with a steep slope) to 300 m (for a channel with a gentle slope). The backwater effect can affect the characteristics of the breach hydrograph (Gildeh et al. 2020). To analyze the impact of the downstream conditions on the breach hydrograph, model runs were conducted (HEC-RAS 2D, FLDWAV, and HEC-HMS) by keeping parameters for the breach and topographic conditions the same (HEC-RAS 2D and FLDWAV are the models that include downstream topographic conditions). According to Gildeh et al. (2020), the breach hydrographs of the HEC-RAS 2D and FLDWAV, both semi-physically based models, were relatively the same, particularly its shape and peak. However, the HEC-HMS model generated a wider hydrograph with a lower peak when compared to the other two models. The computed volumes were similar in all three hydrographs. Nonetheless, different peaks and shapes of hydrographs can affect the flood arrival time and flood extent. HEC-HMS is very easy in terms of model setup and run, whereas FLDWAV model takes high computational time to set up and run.

Comparison 2: HEC-RAS 2D Newtonian vs Non-Newtonian Breach

In this second comparison, one of the most popular semi-physically based models (HEC-RAS 2D) was used to compare the difference between its Newtonian and non-Newtonian (recently added to the model) modules. The same stage-storage curve was used in both modules (see Fig. 5), and the breach parameters were estimated based on the same parametric method.

For non-Newtonian fluids, the model requires rheological parameters of the tailings. For this exercise, a typical concentration by volume (Cv) of 29% and a yield stress of 4.1 Pa were selected for the released mixture of tailings and water. Two scenarios were tested for viscosity: high viscosity (57.3 Pa-s) and low viscosity (1.2 Pa-s). All models used the same topography and geometry details to ensure that the results were comparable, and they were not sensitive to the topographic and geometric conditions in the models. The results of the three models are shown in Fig. 6 where there seem to be a slight difference between the models. One potential reason for this could be the range of viscosity and yield stress tested here (i.e. values being on the lower end). The difference is more obvious in low flows, which may suggest that rheology is overwhelmed by other hydrodynamic parameters at large flows. In a communication with the HEC-RAS model developers, they confirmed that they have completed a review of the rheological parameters associated with post-wildfire events, but are still in the data-gathering phase for mine tailings. Therefore, the authors expect improvement of the non-Newtonian solver in HEC-RAS in the future.

Tailings Rheological Characterization

Tailings characteristics are often obtained from geotechnical investigations. These investigations can be in situ testing such as the cone penetration test (CPT) or laboratory testing and empirical correlations (e.g. Shuttle and Cunning 2007; Idriss and Boulanger 2008; Robertson 2009; Jefferies and Been 2015; Sadrekarimi 2016). Tailings properties can vary greatly due to the gradation, ore type and extraction method, deposition method, and mineralogy of tailings. It can also vary over the TSF life cycle; for instance, the saturated tailings in a pond could behave differently during active deposition than at the end of the operational and reclamation phases when the pond is small or non-existent (CDA 2021).

For a TDBA, it is essential to understand the susceptibility of tailings to flow during liquefaction. Tailings release during the failure of a dam is a very complex phenomenon, as mentioned before, and the tailings behave like a non-Newtonian fluid that can be described using rheological parameters. The two main parameters for characterizing the

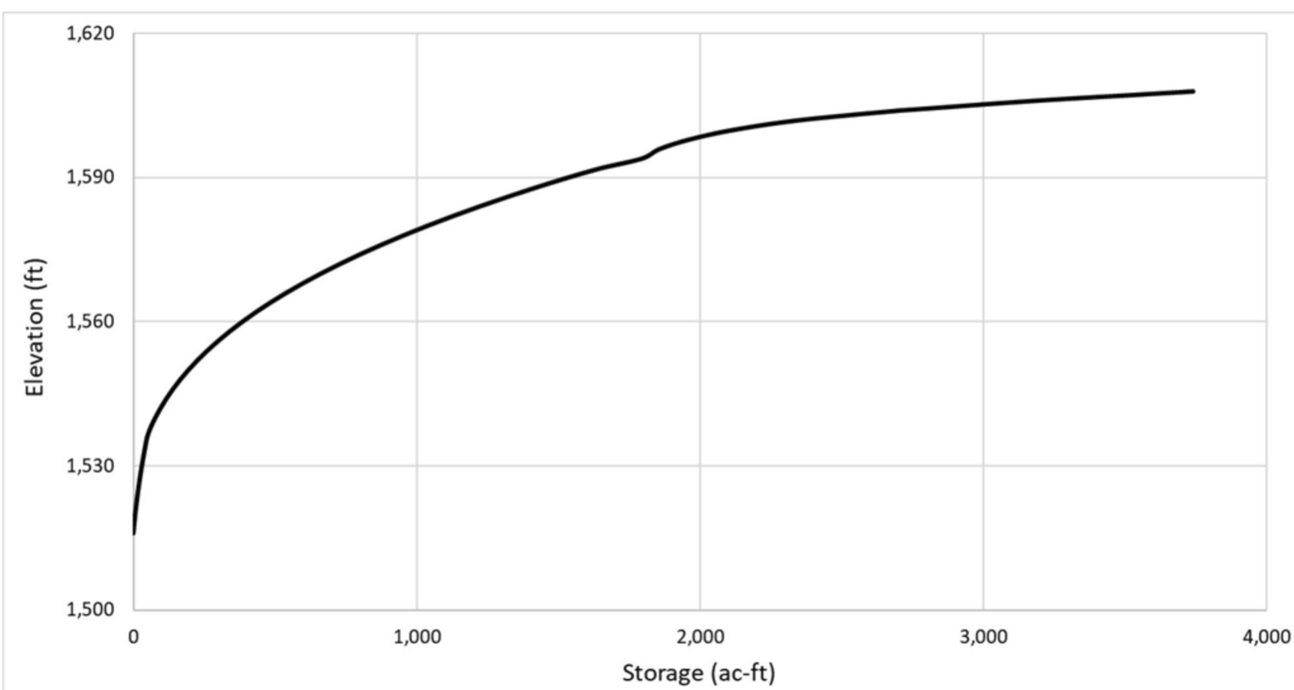

Fig. 5 Stage-Storage Curve for Modelled Breach in HEC-RAS 2D

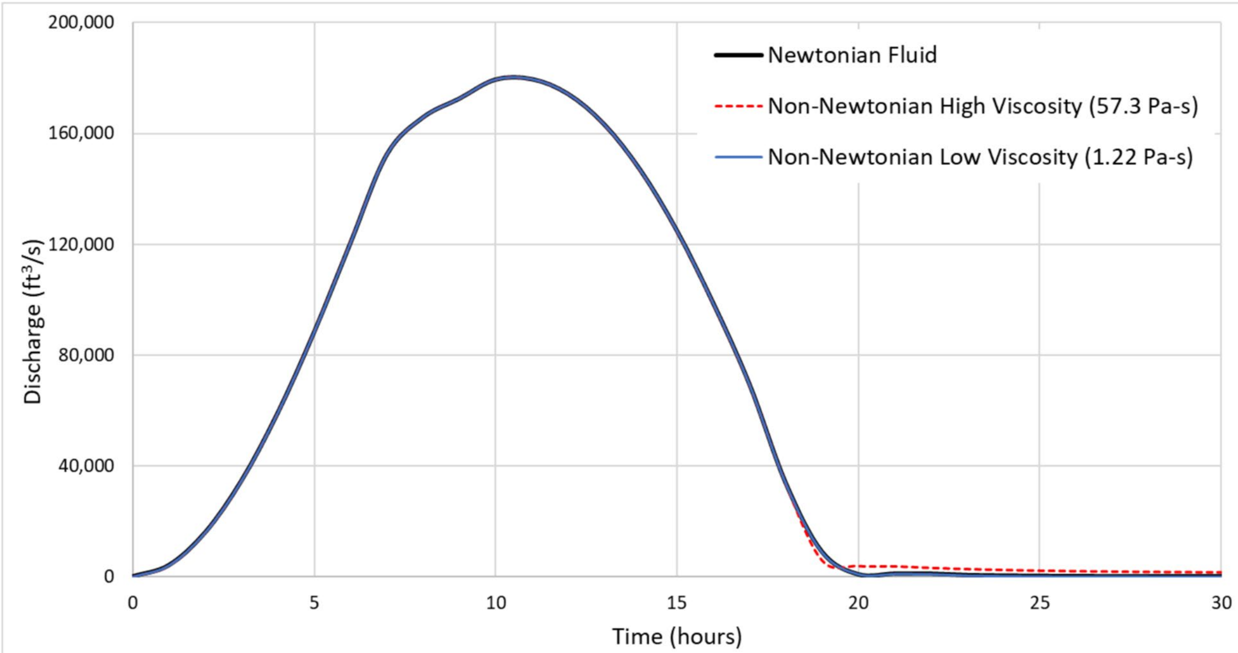

Fig. 6 Comparison of Newtonian and Non-Newtonian Breach Modules in HEC-RAS 2D

tailings flowability are viscosity and yield stress. Viscosity is a measure of the flowability of a fluid, whereas yield stress is a measure of the stress required to cause the tailings to start moving. Viscosity is not often constant, and different equations are used to estimate the complex non-Newtonian behaviour of tailings (Fig. 7). For example, if a model uses

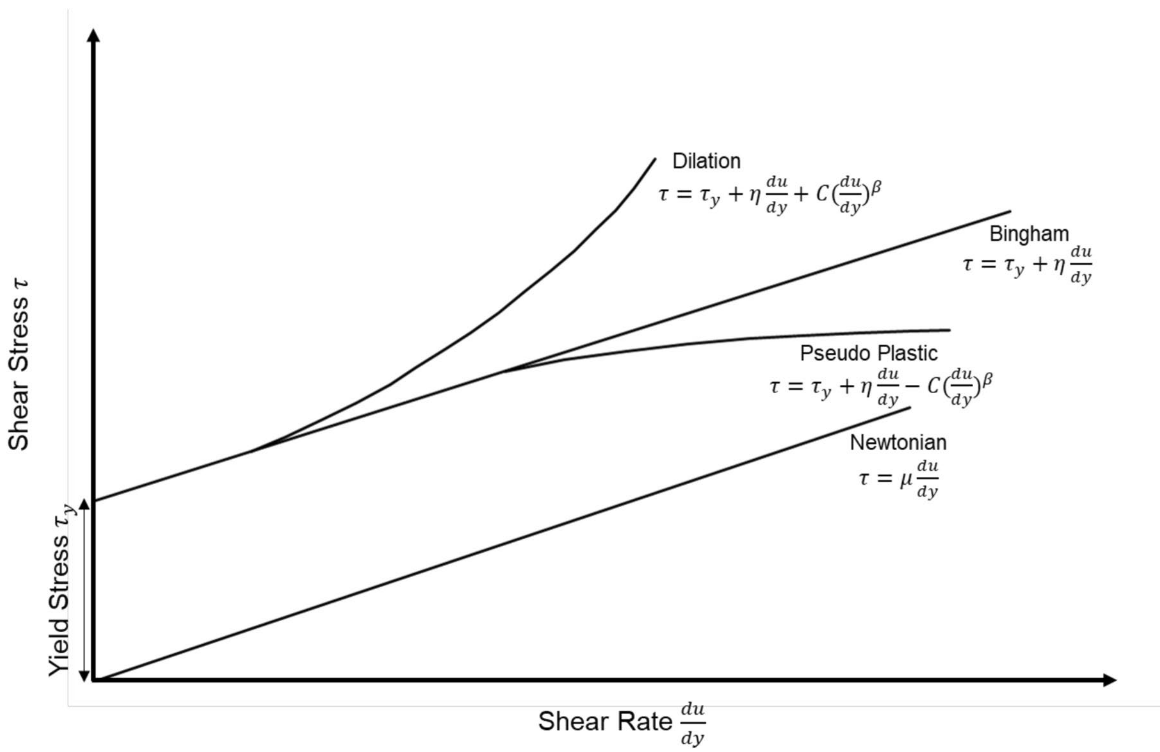

Fig. 7 Shear Stress vs Shear Rate for Fluid Deformation Models (*Source*: FLO-2D)

Bingham stresses, ignoring inertial stresses, it is assumed that the flow is highly influenced by viscous stresses.

The yield stress and viscosity can be measured in the laboratory based on samples collected from the field using a viscometer (see the "Discussion" Section for the caveats on using lab results in numerical models). The tests could be repeated under different water contents and temperatures to build an exponential relationship between the viscosity and C_v ($\eta = \alpha e^{\beta C_v}$) or yield stress and C_v ($\tau = \alpha e^{\beta C_v}$), where η is viscosity, C_v is concentration by volume, τ is the yield stress, and α and β are the coefficient and exponent of the equations. Typical graphs of these parameters are shown in Figs. 8 and 9, adopted from the Flo-2D reference manual (2023). Note that the vertical axes in both plots are on a logarithmic scale. It is a good practice for engineers performing the TDBA to always plot their rheology parameters onto these graphs to provide an understanding of where the data sit and interpret them, while knowing that the field data plotted in the Flo-2D manual are most likely different from the type of materials they are dealing with.

Roman et al. (2022) recently investigated the importance of tailings rheology in dam breach assessment and dam consequence classification of tailings storage facilities. To characterize the influence of rheological tests and their interpretation, or misinterpretation, in the TDBA results and the consequence classification, a hypothetical case of TDBA was modeled considering both unsheared (static) and sheared (dynamic) rheology test results, comparing their consequences downstream. Through inundation mapping of various scenarios modelled using FLO-2D (see below), the authors showed how important it is to choose reliable rheology parameters for TDBA. Their study also highlights the importance of sensitivity analyses on such parameters. Similarly, Roman et al. (2022) emphasized the importance of rheological properties for a breach analysis. They focused on geotechnical protocols in testing the materials and interpreting the viscosity and yield stress for dam breach analysis, as it produces quite different inundation extents.

Numerical Models

Commonly used numerical models for the analysis of hyper-concentrated flow or debris flow like Flow-3D, Flo-2D, Riverflow 2D, DAN-3D, MADflow, DAMBRK, FLDWAV, HEC-RAS, MIKE 11, MIKE 21, TUFLOW, and TELEMAC are discussed in this section. These software packages use various rheological models. Several of these rheological models and their formulations are listed in Table 2.

In Table 2, ρ is the sediment–water mixture density in kg/m^3, u is the depth-averaged flow velocity in m/s, g is the acceleration due to gravity in m/s^2, $|\tau_b|$ is the bed shear stress in Pa, τ_μ is the viscous stress in Pa, τ_y is the yield stress in Pa, τ_t is the turbulent shear stress in Pa, τ_f is the Coulomb-type frictional stress in Pa, q is the unit flux in m^2/s, θ is the bed slope, θ_b is the friction angle of the solid material in degrees, k is a resistance parameter equal to 24, C_f is the friction coefficient, h is the flow depth in m (Hydronia 2022), K is the consistency index,

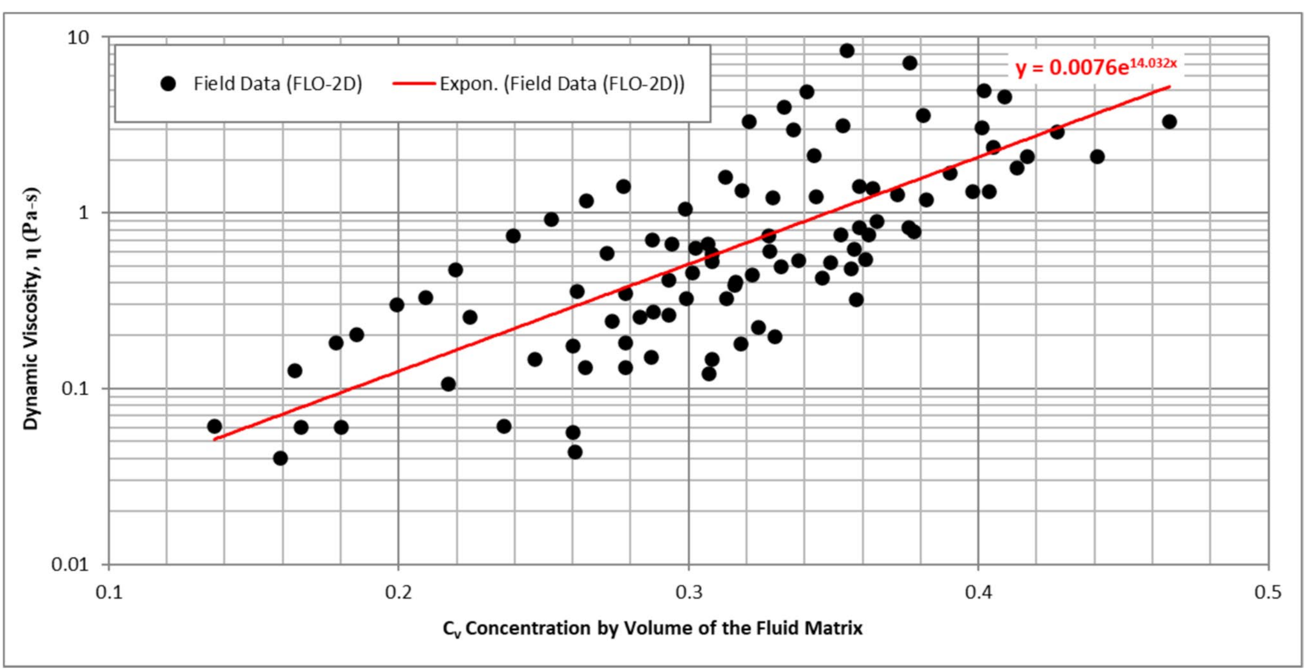

Fig. 8 Dynamic Viscosity vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)

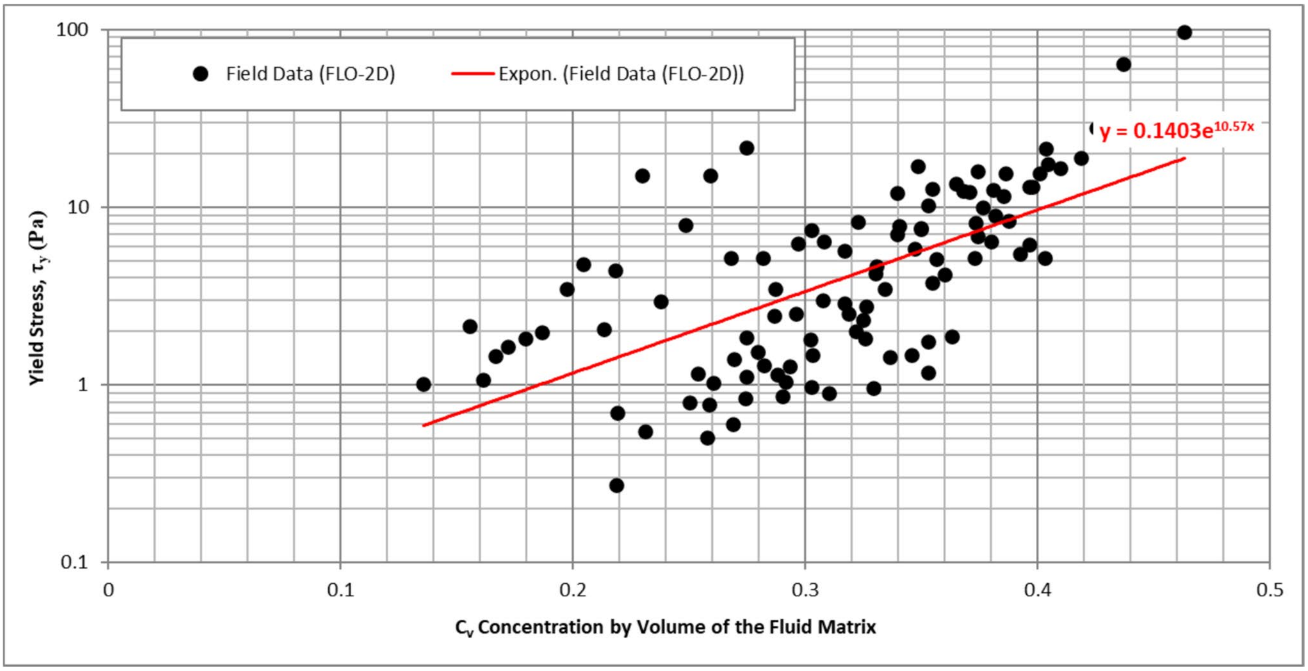

Fig. 9 Yield Stress vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)

Table 2 Rheological flow resistance formulations

Formulation	Flow resistance equation
Pure turbulent	$\lvert\tau_b\rvert = \tau_t = \rho C_f u^2$
Simplified Bingham	$\lvert\tau_b\rvert = 1.5\ \tau_y + 3\ \tau_\mu$ where $\tau_\mu = \mu q/h^2$
Turbulent & Coulomb	$\lvert\tau_b\rvert = \tau_t + \tau_f$
Turbulent and Yield	$\lvert\tau_b\rvert = \tau_t + \tau_y$
Turbulent, Coulomb and Yield	$\lvert\tau_b\rvert = \tau_t + \min(\tau_y, \tau_f)$
Full Bingham	$2\lvert\tau_b\rvert^3 - 3(\tau_y + 2\ \tau_\mu)\ \lvert\tau_b\rvert^2 + \tau_y{}^3 = 0$
Quadratic	$\lvert\tau_b\rvert = \tau_y + \tau_t\ + k/8\ \tau_\mu$
Granular	$\lvert\tau_b\rvert = \tau_f = g\rho h cos\theta \tan\theta_b$
Herschel- Bulkley	$\tau = \tau_y + K\left(\frac{du}{dy}\right)^n$
Voellmy	$\tau_b = \tau_y + \frac{\rho_m g \lvert V\rvert^2}{\xi}$
Mohr–Coulomb (Clastic)	$\tau_y = C + \sigma \tan\phi$

n is the flow behaviour index, τ is the shear stress in Pa, $\frac{du}{dy}$ is the shear strain rate related to a local u velocity, |V| is the avalanche velocity in m/s, ξ is the Voellmy coefficient (Kocyigit and Gurer 2007), C is the cohesion or cohesive strength in Pa, μ is the Coulomb friction coefficient, σ is the normal stress at the bottom of the mixture in Pa, ϕ is the internal friction angle, and ρ_m is the mixture density, (HEC-RAS manual 2023).

Flow-3D

Flow-3D (Flow Science 2021) is a commercial computational fluid dynamic (CFD) software that is used to analyze complex free surfaces as well as confined flow problems. The model is based on the finite volume method in the Eulerian reference frame and employs 3D structured grids of cubic cells for discretizing the model geometry. It solves non-hydrostatic Navier–Stokes equations with free surface. Various rheological models, such as the Herschel–Bulkley model and the Bingham rheological model, are included in this model. The Flow-3D hydro tailings model can be used to model the highly non-Newtonian behaviour of tailings and water mixtures. Fine and coarse tailing particles can be modelled separately or together. The model can consider varying tailings concentrations and the presence of a supernatant water layer above the coarse layers of tailings. Three-dimensional and 2D shallow water modelling methods are available. Tailings mixing and settling can be modelled in three dimensions and can be combined with shallow water meshes to accurately simulate the runout flow of tailings over large areas. Several turbulence models are available both in 2D and 3D modules. Examples of tailings dam breach studies using Flow 3D include Chen et al. (2022), Ghahramani et al. (2022), and Yao et al. (2020). Chen et al. (2022) investigated overtopping erosion in reinforced tailings dam by conducting physical model tests and numerical modelling was done using Flow 3D. Ghahramani et al. (2022) modelled two tailings dam breaches (1985 Stava and 1994 Merriespruit) using

Flow 3D. Yao et al. (2020) investigated the influence of particle size on the tailings dam failure process by conducting physical tests and then numerical modelling was done using Flow 3D. Gao et al. 2024 investigated the failure pattern of tailings dam under flood conditions by using a 1:100 large scale tailings dam failure model test. FLOW-3D software was used for modelling the breach process and the flood extent. The results showed that the failure mechanism under flood conditions is seepage failure. Even though there is a prototype of the model, it cannot be used for all dams, which is a limitation of the study.

Flo-2D

Flo-2D software (Flo-2D 2023) was discussed earlier in the "Single Phase Approach (Homogeneous Mixture)" section of this paper. It has been widely used to simulate mudflows in industrial practices over the past few decades. This quasi-two-dimensional model uses a finite-volume numerical method in the Eulerian reference frame (Flo-2D 2023). To consider inflow into the computational domain, the user inputs a breach outflow hydrograph at the breach location using the module Flo-2d tailings dam failure volume estimate tool. A new level of predictive analysis for tailings dam breach outflow was developed by adopting a two-phase modelling approach. This new approach can be used to simulate the breach of a tailings dam with reservoir water-storage. The model can simulate mudflow-fluid exchange along with erosion and deposition, mudflow cessation, and tributary inflow and mudflow into downstream lakes. As mentioned earlier, examples of tailings dam breach outflow modelling studies that used Flo-2D include Mahdi et al. (2020), Ghahramani et al. (2020) and Sreekumar et al. (2022).

RiverFlow2D

RiverFlow2D (Martínez-Aranda et al. 2020) is a two-dimensional hydraulic flexible-mesh model that offers a high-performance finite-volume engine for accurate and fast conservative volume computations. The model can be adapted to any terrain and boundary by using a triangular unstructured mesh. The mud and tailing flow module within Riverflow2D employs an upwind Roe-type Riemann solver and is solved on a graphics processing unit (GPU). It can model the variable-density flow of tailings mixture over an erodible bed. It solves the hydrodynamic equations, rheological formulations, and sediment transport equations, and considers settling, re-suspension, and sediment transport in the fluid column. Two-phase rheological formulations account for different friction terms and represent various non-Newtonian fluids (Martínez-Aranda et al. 2020). The rheological models used in RiverFlow2D include the pure turbulent, simplified Bingham, full Bingham, quadratic rheological, turbulent, Coulomb and yield, and granular models. As mentioned earlier, examples of tailings dam breach outflow modelling studies that used Riverflow 2D include Martínez-Aranda et al. (2022) and Sreekumar et al. (2023).

DAN-3D

DAN-3D (Cheon 2020) is a semi-empirical numerical analysis method and quasi-three-dimensional extension of the DAN-W model. This Lagrangian numerical model is based on "smoothed particle hydrodynamics" (SPH) and is primarily developed for landslide runout analysis. Mud or debris flow is modelled as an equivalent fluid and the complex flow dynamics is simplified. A meshless Lagrangian frame of reference is used and the depth-averaged velocity and nonhydrostatic internal stress distribution based on the assumptions developed from the study conducted by Savage and Hutter (1989) was adopted from McDougall and Hungr (2004a, b). The breach is modelled using a slope instability failure mechanism and the volume released is input as a source term. Five rheological models, namely Newtonian, plastic, Bingham, frictional, and Voellmy, can be used to simulate the complex dynamics of landslides and mud/debris flows (Cheon 2020). Ghahramani et al. (2022) modelled two tailings dam failures (1985 Stava and 1994 Merriespruit) using DAN 3D.

MADflow

MADflow (Chen et al. 2019) is a quasi-3D (depth-averaged) hydrostatic model that can be used for mobility analysis of gravity-driven flows of soils, tailings, rock, and water mixtures. The model uses a finite element numerical method and employs rheological models, such as frictional, Bingham, Voellmy, quadratic, Coulomb viscous, Herschel-Bulkley, plastic, Sassa, and lava flow models. The assumptions taken from the study conducted by Savage and Hutter (1989) were adopted to implement the stress in response to strain during movement for flows at a high solid concentration. The entrainment from the bed layer, hydrodynamic drag, and hydroplaning onset for submarine debris flows are also included. The user defines the location and geometry of the failure. Breach modelling can be done as a dam breach scenario or a slope instability scenario, and the volume released is calculated by inputting a hydrograph (Chen et al. 2019). Chen and Cunning (2021) conducted breach modelling and downstream routing using the MADflow model. The model was calibrated using historical dam breach events. They discussed application of critical state soil mechanics in TDBA. They also discussed how the breach hydrograph from an erosional breach could be different than that of a non-erosional breach in terms of shape and timing. They used in-situ tailings properties for analysing the mobilization of eroded tailings using an interpreted cone penetration test. Finally, Ghahramani et al. (2022) modelled two tailings dam failures (1985 Stava and 1994 Merriespruit) by employing MADflow.

DAMBRK

DAMBRK is a dam-break flood forecasting model that constitutes a breach module that uses simple parameters to give a temporal and geometrical definition of the breach. This model can simulate tailings flow by specifying rheological parameters of the fluid like its dynamic viscosity, initial shear strength, unit weight and stress rate of strain (Gildeh et al. 2020). This model estimates the breach outflow hydrograph through a broad-crested weir flow approximation that involves the corrections for approach velocities and the submergence from downstream tailwater depths. The fundamental component of the DAMBRK model is a dynamic routing approach for estimating the changes to the flood wave as it advances such as its velocity profile, travel time, and resulting flow depths. The dynamic routing technique is based on a non-linear weighted four-point finite-difference solution of the Saint–Venant equations in which variable time and distance steps can be used in the solution procedure. There are also provisions for routing subcritical flows, supercritical flows, or a mixture of each, and combining the effects of downstream obstructions such as embankments or other dams, mud/debris flows, pressurized flow, landslide-generated reservoir waves, etc. (Dodson & Associates, Inc. 2009). Xin et al. (2011) used DAMBRK for the risk assessment of the Shouyun iron mine Heshangyu tailings dam break.

FLDWAV

FLDWAV, a 1D hydraulic routing model, can be used to model the breach, emptying of the dam, and flood wave propagation. FLDWAV is generalized for broad applicability to rivers of varying roughness, irregular geometry, flow diversions, lateral inflows, off-channel storage, and head losses. It can estimate the hydraulic characteristics like the lateral extent and depth of flooding at various times and distances. FLDWAV is widely used for computing the outflow hydrograph from a dam associated with overtopping and dam-breach outflows. The flood wave is routed through rivers, reservoirs, estuaries, and canals. The governing equations are one-dimensional unsteady flow equations coupled with internal boundary equations. Thereby, it represents a rapidly varying flow through hydraulic structures like dams and embankments, which can cause a time-dependent breach. Suitable external boundary equations at the upstream and downstream ends of the routing are also used. An iterative, weighted, four-point implicit finite-difference method is used to solve the system of equations. FLDWAV can also be used to generate accurate outputs like elevation, discharge, and velocity profiles when only limited data are available. The governing equations of the FLDWAV model involve average parameters like channel width, cross-sectional area, depth of flow, and discharge and thus simplifies the inputs required for modelling. Cross-sections along the river are denoted by a table of mean top widths vs. elevations. Along the channel reach, roughness coefficients are averaged as a function of discharge or elevation. FLDWAV interpolates between river reaches for getting additional roughness data and cross-sections and for satisfying computational requirements. Hydraulic structures are also given in the model input by using average parameters like the effective area of the breach instead of breach geometry (RiverMechanics.net 2020).

HEC-RAS

The unsteady flow module of the HEC-RAS model is used for dam-break simulations. The shallow water equations (SWE) that include spatial and temporal acceleration with horizontal mixing are used in this model. The breach of a tailings storage facility (TSF) has been observed to result in high momentum waves travelling downstream and the SWE are very suited to this type of modelling. Two approaches can be followed in HEC-RAS for solving advection, namely an Eulerian Lagrangian approach (SWE-ELM) and an Eulerian approach (SWE-EM). Among these two, SWE-EM is more momentum conservative and can result in longer run times; this model is necessary only when detailed analysis is required. HEC-RAS allows the user to define the non-Newtonian nature of tailings; the non-Newtonian models include the clastic grain-Flow, O'Brien equations, and the generalized Herschel-Bulkley method. HEC-RAS does not have the capability to consider varying sediment concentration, which is a major limitation, but does have the capability to refine the computational mesh around hydraulic structures and is helpful in detailed analysis of dam breaches (Scholtz and Chetty 2021). Melo and Eleutério (2023) conducted probabilistic analysis of floods from tailings dam failures and analyzed the impact of rheological parameters on the HEC-RAS Bingham and Herschel-Bulkley models. In this study, the sensitivity analysis methodology was applied to the ICOLD (International Commission on Large Dams) case study, which involved a hypothetical dam presented by Zenz and Goldgruber 2013.

MIKE11 and MIKE21

MIKE FLOOD links two software packages namely, Mike HYDRO River (1D) and MIKE 21 (2D). Mike HYDRO River solves the 1D Saint–Venant equations by using a finite difference scheme and the breaches can be modelled by a dam-break structure. Breach initiation and formation can be defined by time series for crest level, breach width, and side slope. An erosion model formed from the Engelund-Hansen sediment transport equation is available. Breach outflow can be calculated by utilizing two sets of equations: one set of equations for flow via a generic structure (Borda losses) and the other set from the NWS DAMBRK model. MIKE 21 employs a rectangular grid and solves the 2D shallow water equations by using a finite difference scheme. This model can handle flooding, varying surface roughness, coriolis forces, eddy viscosity, and wind friction (Vanderkimpen et al. 2009). MIKE 11 does not have the capability to model non- Newtonian nature of tailings flow. Therefore, MIKE 21/3 mud transport model has been developed: this model has the option to simulate non-Newtonian fluid flow by specifying properties such as density, fluid viscosity, and yield stress. Fluid properties can change in space and time and can represent mixing of non-Newtonian fluids with water (DHI 2017). Lumbroso et al. (2021) modelled mudflow resulting from the Brumadinho tailings dam breach using MIKE 21.

TUFLOW

TUFLOW HPC allows modelling of non-Newtonian fluids in two dimensions (2D). In this model, turbulent eddy viscosity is not considered important in non-Newtonian fluids as they are highly viscous. The 2D viscosity is calculated using a viscosity model in case of shear thickening fluids. The flow regime can become turbulent in the case of shear thinning fluids. Those added turbulent shear stresses that are developed are depicted using the standard TUFLOW HPC Wu turbulence model. TUFLOW uses the Herschel-Bulkley model in which fluid shear stress is related to the shear rate in a non-linear manner. The Herschel-Bulkley model combines elements from power law and Bingham Plastic models and thus corrects some of the deficiencies seen in those models. This model is more comprehensive and allows the modelling of shear thinning behaviour of tailing slurries. In Newtonian fluids, a turbulent boundary layer is present, and the velocity profile follows the ‘law of the wall” and is commonly determined using Manning’s equation. In non-Newtonian fluids, the turbulent velocity profile is different. If the flow is in the laminar regime, a power law viscosity model is used to compute bed friction and the depth-averaged flow velocity. The Manning’s bed friction becomes more applicable as the fluid flow becomes more turbulent and begins to dominate over the non-Newtonian bed friction. It is assumed in this model is that the effect of acceleration is negligible and that the shear stress of the fluid is linear with depth (Tuflow 2021).

TELEMAC

TELEMAC-2D solves the Saint–Venant equations using the finite-volume or finite-element method and adopts a computation mesh of triangular elements. The breach outflow volume depends on the breach development rate and the resistive forces like the non-Newtonian nature and bottom friction. In TELEMAC-2D, a “widening” breach option is available and using this, the nodes on each side of the breach opening are instantaneously lowered from crest to bottom. This triggers a sudden discontinuity in the breach geometry and an increase in the outflow volume. This software also has the capability to simulate the cascade failures of downstream dams or levees. Within this software, a “pseudo-biphasic model” is available, and this can be used to model the mixing between Newtonian and non-Newtonian fluids. The volumetric sediment concentration (C_v) is represented by a passive tracer and can be given as an initial condition or boundary condition. The fluid rheological properties are then calculated as a function of C_v. Non-Newtonian rheological models treat the fluid mixture as a continuous medium and they are not combined with sediment transport models. Therefore, morphological changes linked to erosion processes cannot be modelled when conducting tailings run out analysis (Ligier et al. 2022). Ligier (2020) modelled the Brumadinho tailings dam breach outflow and studied the application of non-Newtonian rheological models in TELEMAC-2D. The rheological models available in each software are summarized in Table 3.

Discussion

Uncertainties

Several uncertainties exist in the tailings dam breach runout analysis and the technical challenges need to be addressed when conducting a risk assessment of tailings dams.

Selection of Rheological Model

Runout analysis requires the selection of suitable rheological models for different tailings materials. Since the rheological properties and sediment concentration of tailings vary among sites, the selection of a rheological model a priori can be difficult. However, the development of a physical model using fluid mud with properties similar to those of site tailings could be useful for addressing this issue. Numerical model simulations can be performed using different

Table 3 Available Software Packages for Application to Tailings Dam Breach and Runout Modelling (Source: CDA 2021)

Models	Type	Case	Case IB	Case	Case 2B	Newtonian	Non Newtonian	Rheological options	Morphological changes	Computing cost
DAMBRK	ID	Yes	Yes	–	–	Yes	–	–	No	Medium
FLDWAV	ID	Yes	Yes	Yes	–	Yes	Yes	Bingham; Quadratic model	No	Medium
HEC-RAS	1D/2D	Yes	Yes	Yes	–	Yes	Yes	Bingham; Clastic Grain-Flow; Herschel-Bulkley; Quadratic	Yes	Medium
FLO 2D	2D	Yes	Yes	Yes	–	Yes	Yes	Quadratic model	Yes	Medium
MIKE 11 and MIKE 21	1D/2D	Yes	Yes	Yes	–	Yes	Yes	Bingham, Turbulent, Hindered Settling	Yes	High
RiverFlow2D	2D	Yes	Yes	Yes	Yes	Yes	Yes	Pure Turbulent; Simplified Bingham; Full Bingham; Quadratic; Turbulent and Coulomb; Turbulent and Yield; Turbulent and Coulomb Yield: Granular model	Yes	Medium to High
TUFLOW	2D	Yes	Yes	Yes	–	Yes	Yes	Herschel-Bulkley	No	Medium to High
Telemac	2D/3D	Yes	Yes	Yes	–	Yes	Yes	Bingham; Pure Bingham	No	Medium to High
FLOW-3D	2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	Herschel-Bulkley	Yes	High
DAN3D	Quasi-3D	–	–	Yes	Yes	–	Yes	Frictional, Voellmy, Bingham, Turbulent	No	NA
MADFLOW	Quasi-2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	Frictional, Voellmy, Quadratic, Bingham Herschel-Bulkley; Coulomb viscous, Plastic, Lava flow; Sassa model	No	NA

rheological models, and the model that best agrees with the observed (experimental) data can be selected. In the study conducted by Ghahramani et al. (2022), who used the Bingham and quadratic models for the back analysis of a historical event, different viscosity values had to be assigned in each model. This emphasizes the need to study each rheological model individually to calibrate more historical events and obtain a better understanding of the selection of the numerical model in each case.

Rheometric Analysis

Rheometric analysis of tailings samples are not performed in most of the studies and published values are used to input the rheological parameters (Mahdi et al. 2020; Sreekumar et al. 2022, 2023). Based on a study conducted by Ghahramani et al. (2022), there is a lack of published viscosity measurements for tailings with solid concentrations more than 45–50%. In addition, most published measurement values are not applicable to tailings that have settled or consolidated over time. The values of yield stress and viscosity depend on many site-specific factors, such as particle size, shape, solids concentration, and shear rate. Hence, a lack of field studies and geotechnical laboratory testing can cause uncertainty in the actual values of the rheological parameters and their relationship with different numerical models. Based on Ghahramani et al. (2022), multiple sets of rheological parameter values can produce similar outputs, and selecting the most appropriate set of values requires an adequate understanding of the rheology of the tailings material. In this study, it was also noted that the input rheological parameters are not transferable between the rheological models. Thus, it is necessary to develop a stepwise technical approach to calibrate the yield stress and dynamic viscosity values. For this, a comprehensive literature review, assessment of available laboratory and field data, and sorting of these data based on tailings materials are essential.

Estimation of Breach Outflow Hydrograph

Tailings dam breach runout analysis requires estimation of the outflow hydrograph. The outflow rate is critical in the runout analysis and downstream risk assessment. There are many uncertainties in calculating breach release volume. The current industry practice is to use historic tailings dam breach shapes and slopes, or empirical formulations derived from historical datasets (Gildeh et al. 2020). The breach release volume is highly dependent on the storage volume and where the supernatant pond is located. If the supernatant pond volume is larger, there can be excessive breach release. In addition, when a tailings dam with stored water collapses, a flood wave containing mainly water may propagate downstream, and, subsequently, concentrated tailings may mobilize through the breach. The water may advance at a higher velocity, and the dense mud may only propagate a relatively short distance (Martin et al. 2015). This two-phase mudflow characteristic has not been included in most studies and is a major limitation. In most models, the breach development time used in estimating the hydrograph is taken from data mainly adopted from previous water dam breach studies (Mahdi et al. 2020; Sreekumar et al. 2023). The peak of the breach outflow hydrograph estimated by software is also based on historical data and this can have an impact when conducting risk assessments. The tailings release volume also depends on the type of failure mechanism and slope of the breach and hence a thorough site-specific failure mode analysis should be performed. Sensitivity analysis should be conducted by accounting for different breach slopes and a range of breach release volumes should be developed when performing a risk assessment.

Consideration of Downstream *Erosion* and Deposition

Water retention dam failures and their impact on downstream channel morphology due to erosion and sediment deposition have been analyzed extensively (e.g. Acker et al. 2008; Baynes et al. 2015; Carrivick et al. 2010; Chen et al. 2015; Jiang et al. 2021; Lane et al. 2007; Marchi et al. 2009). Geomorphic processes can cause increased discharge, morphological channel evolution, and immense destruction (Eagle et al. 2021; Guan et al. 2016; Rickenmann and Koschni 2010). Likewise, the tailings flow after a tailings dam breach is not limited to the flow of hyper-concentrated fluids, but there can be extensive morphodynamic impact. Sediments can be entrained from the bed or be deposited on the channel bed, changing the sediment supply and ultimately changing the channel morphology. As a result, fluid properties, such as viscosity, density, and yield stress, can vary ove space and time. Most modelling studies conducted in the past considered mudflow over a fixed bed, which is a simplified approach. In the case of the Mount Polley tailings dam failure, the influence of the tailings flow on downstream channel morphology was considerable and similar to the changes resulting from severe debris flow and flooding events (Cuervo et al. 2017). Hence, a mobile bed modelling approach may be needed when conducting risk assessments.

In the study conducted by Mahdi et al. (2020), Flo-2D was used to simulate the Mount Polley tailings dam breach outflow and for flood extent delineation. The erosion of the downstream terrain along the tailings spill path and transport of eroded materials were neglected. These conservative approaches greatly affected the estimation of the volume of sediments that reached the downstream lake. In the study conducted by Sreekumar et al. (2023), Riverflow 2D was used to model the Mount Polley tailings dam breach outflow and the morphological evolution in the downstream channel during the tailings flow. Erosion and deposition of sediments during the tailings flow were considered and the model successfully predicted immediate physical impacts following a failure, such as channel avulsion, erosion, and deposition zones.

Based on the experimental study conducted by Iverson et al. (2011), it was found that the fluid velocity of mudflow can either rise or fall with sediment transport and that it depends on the bed material water content. Likewise, in the study conducted by Pudasaini and Krautblatter (2021) on landslide dynamics, it was found that erosive landslides can increase or decrease mobility, and this trend depends on the site as well as the tailings material. Sreekumar et al. (2023) studied the effects of sediment exchange on the dynamics of tailings flow and compared the flow over mobile and fixed beds. From the model results, it was concluded that when sediment transport is considered, the maximum mudflow depth of the flood wave was higher, and when it was neglected, the downstream flood arrival time was underestimated. Thus, to predict the immediate physical impacts following a failure, such as channel avulsion, erosion, and deposition zones, a mudflow mobile bed model that accounts for variable density and multiple sediment classes is necessary. For verification, pre- and post event DEMs can be used to obtain a difference DEM, and maximum erosion depth, maximum deposition depth, volume of erosion and deposition, etc. can be compared. There was a large difference in velocity between the mobile and fixed bed models and they produced completely different flood arrival time (Sreekumar et al. 2023). However, in this 2D modelling study, velocities of both solids and fluids were combined into the bulk mixture velocity. When a tailings dam with supernatant pond breaches, a water flood wave initially travels downstream, and this is followed by a dense mudflow. This two-phase mudflow characteristic was not considered in the modelling study of Sreekumar et al. (2023) and is a major drawback. The vertical variability of properties such as density, viscosity, and yield stress can influence the modelling results and thus may have serious consequences when conducting risk assessments and while planning for evacuation. A flow chart showing different uncertainties in tailings dam breach studies is shown in Fig. 10.

Application of GIS and Remote Sensing in Tailings Dam Breach Analysis

Remote sensing and geographic information systems (GIS) are mainstream technologies for the study, identification, and monitoring of natural hazards. This technology provides tools for the collection and analysis of spatial data for pre-disaster preparedness and post-disaster restoration (Luscombe and Hassan 1993). Earth observation satellite images

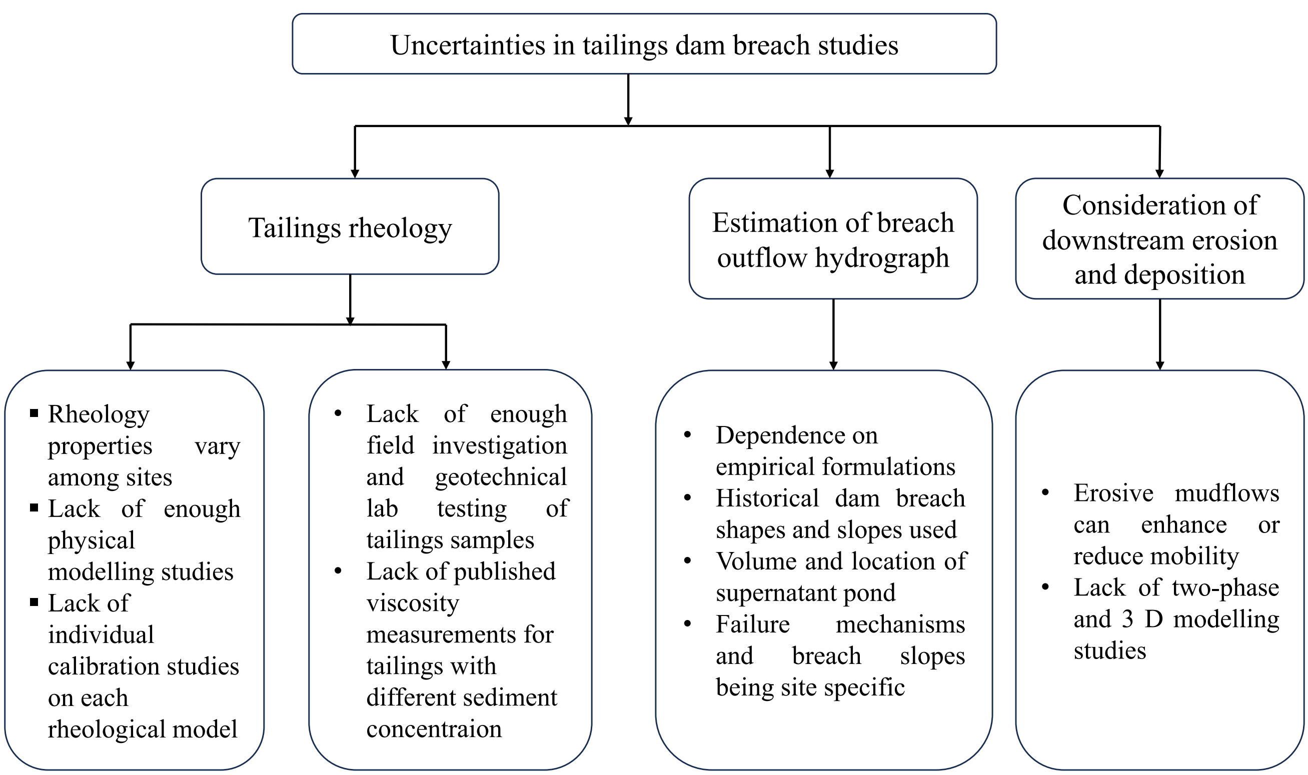

Fig. 10 Flow chart showing different uncertainties in tailings dam breach studies

have large-scale scientific applications such as environmental monitoring, weather prediction, and archaeological surveys. These images are important data sources for rebuilding historical records and monitoring the performance of different hydraulic structures, such as dams (Schumann et al. 2018). Using GIS techniques integrated with hydraulic modelling software, potential dam-break flood hazards can be forecasted, and an early warning system can be set up. A 3D visualization of the spatiotemporal variations of dam-break floods, risk assessment of dam-breaks, flood disaster management, and land use planning downstream can also be implemented (Derdous et al. 2015). Geometric data can be prepared and directly imported into hydraulic models. Moreover, the data generated by the hydraulic model can be moved to a GIS, and inundation maps can be prepared for further analysis. (Pandya and Jitaji 2013).

Pre-event and Post-event Elevation Data

According to Rotta et al. (2020), satellite-driven soil moisture index, interferometric synthetic aperture radar (InSAR), and multispectral high-resolution imagery can be used to evaluate pre-disaster scenarios and the reasons of tailings dam failure. Rotta et al. (2020) examined the case study of the Brumadinho tailings dam collapse in Brazil and their study showed a declining trend in the moisture content at the surface; hence, it could be concluded that seepage erosion was the reason for the tailings dam collapse. The volume of the tailings dam can be compared with the mining company's declared volume given in the environmental licenses' processes using remote sensing data because if the volume of tailings exceeded the declared volume, chances of failure are higher. Geoprocessing tools can be used to measure the volume of the tailings. A digital terrain model (DTM) from before the dam was built can be subtracted from the DTM constructed during the study year to obtain this measurement. The results can be used to check if the dam complies with environmental legislation, and this methodology could be used for the precise monitoring of tailings dams. During the tailings flow following a dam breach, sediment materials can be eroded from the downstream terrain, and this can change the morphology of downstream channels. Pre-event and post-event DEM of the study site can be used to quantify these changes caused during the event. The nearest neighbor technique can be used to resample the pre-event and post-event DEMs to the same resolution and when subtracted, a difference DEM can be computed (Sreekumar et al. 2022). This DEM can be used to analyze the event in detail, know the changes in the downstream area, and estimate the volumes of final erosion and deposition. Using this difference raster, the spatial variation in erosion and deposition patterns and the site features, such as the inundated area, erosion depth, and deposition depth, can be obtained.

Estimation of Runoff Coefficient

Tailings dams are often located in valleys and the surrounding terrain can pose a threat to the stability of tailings dams. During rainy days, the runoff from upstream subcatchments can enter the tailings pond and can cause a failure. In different study areas with the same soil type and rainfall conditions, surface slopes directly affect the generated runoff, and the runoff coefficient increases with increasing slope angle. In short, the slope is one of the elements that influences runoff generation. The topography parameters, including ridges, river courses, and mountain peaks can be calculated from the elevation models. Another factor is vegetation coverage, which plays a key role in reducing runoff and soil consolidation. Moreover, the rainfall interception and blockage effect of different vegetation vary, which can greatly affect the runoff coefficient. The soil consolidation and rainfall retention capacity of different vegetation types are different. Fractional vegetative coverage (FVC) is an important indicator of the distribution of surface vegetation and ecological environment. FVC is the ratio of the vertically projected vegetation area to the total surface extent and is mostly expressed in relation to the unit area (Evans et al. 2006). Remote sensing has many efficient methods for retrieving FVC at local and global scales (Wanjuan et al. 2017). The pixel dichotomy model based on normalized difference vegetation index (NDVI) is widely used to estimate FVC. The pixel dichotomy model is a remote sensing estimation model in which it is assumed that a pixel consists of vegetated and non-vegetated areas (Gutman and Ignatov 1998). In this model, the spectral data captured by the remote sensing sensor are linearly weighted on the basis of the component. The pixel dichotomy model is given by Eq. 1:

$$FVC = \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \tag{1}$$

where $NDVI_{min}$ and $NDVI_{max}$ are the minimum and maximum NDVI values, respectively, in the region. $NDVI_{min}$ and $NDVI_{max}$ values may be within a confidence level range due to the inevitable noise; the real situation of the remotely sensed image determines the confidence level (Che et al. 2018). Remote sensing images can be used to derive vegetation information, and vegetation classification can be performed using the support vector machine (SVM) method; this machine-learning method is based on statistical learning theory (Shi and Yang 2015). Slope, vegetation type, and vegetation coverage can be used to estimate the runoff coefficient of the area using the analytic hierarchy process (AHP – a multiple criteria decision-making method based on weight assignment) model (Oliva et al. 2017). Apart from the runoff coefficient, the catchment area size contributes significantly to the determination of the surface runoff.

Both the average runoff coefficient and catchment area are determining factors for the risk assessment of tailings ponds. The risk index is the product of the catchment area and runoff coefficient and can be used to assess the risk of tailings ponds. This could be used to identify low-risk, moderate-risk, and high-risk tailings ponds, to monitor if there are chances of seepage or overtopping during rainy days, and to provide focused safety monitoring during the rainy season (Che et al. 2018). These steps are summarized in the flow chart shown in Fig. 11.

Spatial Resolution, Pixel Size, and Scale of Images

Tailings slurry runout can submerge communities located downstream. Microtopography in the form of bridges, buildings, and levees, can obstruct and resist dam-break flows. The smallest building dimension should be used as the critical length scale of downstream areas. If the model resolution is insufficient, such features may not be captured, and the performance of the model may deteriorate. Hence, it is appropriate to choose scales larger than the size of the elements to enhance the modelling outcomes. For example, the scale chosen must be larger than the mean river width to properly delineate those channels and ensure flow connectivity between the channel and the floodplain.

Bank elevation is a critical factor in calculating overbank flooding. An overbank flow happens when the channel water elevation reaches the floodplain elevation. As the grid size increases, the crest of the floodplain adjacent to the main channel is averaged and smoothed out and the elevation of bank is lowered. This can overestimate overbank flooding in the simulation (Jung and Jasinski 2015). The vertical accuracy of DEMs is important because it provides local differences among adjacent elevation values and defines the intricacies of channel geometry, such as slope and aspect. If the river gradients are too low, only data with high vertical accuracy can capture small variations in the height differences. In most previous studies, remote sensing data with large vertical inaccuracies were used, which affects the modelling of the water depth and inundation patterns (Mahdi et al. 2020). The chosen scale was also larger than the channel dimensions (width), and the results overestimated the extent of flooding. If LiDAR data with high horizontal and vertical resolutions are available, they can be used to model narrow creeks. Low-resolution satellite images are recommended only for large rivers. Hence, such scale issues need to be considered in modelling, but currently, there are limitations to the available data products.

Relatively low-resolution global DEMs are used for back analysis of historical events in most tailings dam breach studies (Sreekumar et al. 2022). The main reason for the reduced accuracy of the low-resolution DEM results is the resolution is coarser than the downstream channel dimensions and hence, the channel is not properly delineated. The limited vertical accuracy could lead to more fluid flow from channel cells to floodplain cells and could result in an increased flood extent. Thus, when conducting a detailed risk assessment, using a low-resolution DEM to generate the model grid can reduce accuracy. Elevation data from multiple sources can be used concurrently until a high-resolution

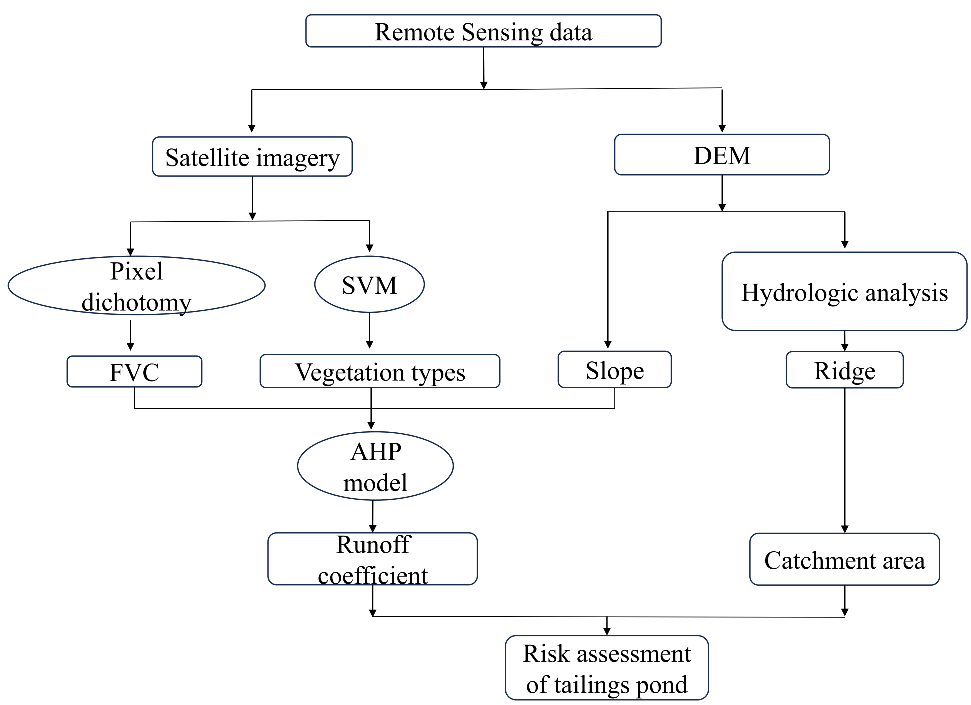

Fig. 11 The flow chart of the risk assessment for tailings pond due to flow contribution from the watershed. (Che et al. 2018)

global DEM is available (Sreekumar et al. 2022). It is also necessary to ensure that parts of the DEM with different resolutions are stitched together using a proper merging procedure and that the fine details at the boundary are preserved. If DEMs of different scales are merged and if there is no smooth transition at the merging location, the flow can be obstructed and there can be an error in the estimation of the flood extent.

3.3. Research Directions.

As discussed in this paper, TDBA and modelling are complex and uncertain tasks. However, the importance of such analyses is increasingly recognized by the public, mine owners, consulting engineers, emergency planners and has attracted the attention and focus of academia. For example, number of journal and conference publications on TDBA have increased over the past decade and are still growing. The following are a few research directions to consider:

Breach Parameters for Tailings Dam

Almost all empirical models (parametric models) developed for breach parameters are based on water retaining dams and not tailings dams. Given the tailings data based on breaches with known TSF characteristics and released volumes, the same regression relationships can be developed for tailings dam breaches. It is suggested that this analysis be completed based on tailings types and not combining all data together, so that each category represents the same ore type, materials, rheology, etc.

Physically Based Breach Models

More complex breach modelling is a major requirement. Physically based breach models will have to be employed by both academics and practicing engineers for breach modelling, as such models should better characterize the complex geotechnical behaviour of earthen embankment breaches by simulating the complex geotechnical characteristics of the embankment during the breach. Pore-pressure monitoring can also be done to address the cause of failure. HEC-RAS 2D developers recently implemented a dam/levee (DL) breach module in their model that can be further explored and tested for breach hydrograph modelling. Coupling the breach modelling and downstream flood routing in the HEC-RAS 2D model by applying a non-Newtonian solver should also be further investigated.

Data Base for Tailings Rheology

The tailings industry has created a database for historical dam breaches (e.g. Wise-Uranium 2024) to catalogue tailings dam failures worldwide. However, to the best of the authors' knowledge, a comprehensive database of rheology does not exist. The authors encourage mine owners to be open to sharing the tailings rheology information of their TSFs and contribute to a shared effort. A template could be prepared and shared on a sharing platform site accessible to mine owners worldwide to catalogue the rheology of tailings and embankment materials at different stages of TSF development. This database will be of great help to practicing engineers and researchers to better model tailings dam breach and routing. There are also several abandoned tailings storage facilities, and it is important to ensure that mining companies and their industry associations actively address issues associated with those facilities.

Downstream Routing Models

The CDA (2021) guidelines summarize the industry-accepted software packages for tailings dam breach and routing modelling (Table 3). However, engineers must be knowledgeable about the state-of-the-art modelling tools that best estimate the complex breaching processes. For example, a tailings flood wave has a much higher potential of eroding the flow path and streams downstream than a water flood wave. However, most two-dimensional (depth-averaged) hydraulic models either do not have this capability or are not used as coupled models of hydrodynamics and sediment transport. With the advancement of CFD models, the use of three-dimensional models should also be explored for TDBA.

Climate Change Impacts

Climate change impacts have also not been considered explicitly in most tailings dam breach studies. There has been increasing uncertainties caused by climate change and hence it is necessary to factor these into the associated risks when designing tailings dams. For developing a life cycle plan for historic, current, and future mining operations, it is essential to incorporate climate change adaptation, and for that, active data are required. The models must be updated based on the effect of climate change on risk components, and new modelling scenarios must be developed that consider climate projections and use predictive tools like those of the U.S National Oceanic and Atmospheric Administration (NOAA).

Conclusions

The conclusions drawn from this study are summarized below:

- It is necessary to assess the suitability of the empirical regression relationships for breach hydrographs developed from water retention dam failures for application to tailings dam breaches. New analyses should be conducted specifically for tailings dam failures. The analysis should be completed based on tailing types and not by combining all data so that each category indicates the same ore type, materials, and rheology.
- More physically based breach models should be employed for breach modelling, as they better characterize the complex geotechnical behaviour of earthen embankment breaches.
- There are different rheological models, such as the Herschel-Bulkley, frictional, Voellmy, Bingham, and turbulent models. There is a pressing need to study each rheological model individually to assess its suitability for modelling historical failure events and to obtain a better understanding of the preferred rheological model to be selected for TDBA risk assessments.
- The lack of field investigation and geotechnical laboratory testing causes uncertainty in the actual values of the rheological parameters and their relationship with different numerical models. To resolve this, assessments of available laboratory and field data and sorting of these data based on tailings materials are essential. Further laboratory tests are also recommended to better estimate the rheological parameters of tailings materials.
- The multi-layer flow of saturated tailings and water for dams where the tailings are capped by supernatant water is not modelled in most tailings dam failure risk assessment studies. There is a need to consider the presence of a supernatant water layer above the coarse layers of tailings, and it is necessary to model mixing and settling while predicting the extent of inundation.
- Two-phase mudflow modeling should be further investigated against available data.
- The entrainment of additional solids from the bed layer during the tailings flow can dramatically increase the sediment supply and cause considerable changes in the channel morphology. Only a limited number of two-dimensional morphodynamic modeling studies have evaluated such scenarios. With the advancement of CFD models, the use of non-hydrostatic three-dimensional models can also be explored to consider downstream erosion and deposition during TDBA and flood wave routing.
- Sensitivity analysis with respect to various parameters such as grid, choice of rheological model, fluid properties, sediment properties, and failure mechanisms needs to be conducted. Also, advanced uncertainty analysis methods should be developed to analyze the range of uncertainty in the final results linked to the uncertainties in estimating the breach development time and outflow volume.
- Remotely sensed satellite imageries (e.g. SPOT) and elevation data (e.g. GeoBase DEM, Lidar) have large-scale scientific applications and play a key role in the identification and monitoring of natural hazards. Advanced remote sensing and GIS methods can be used to study the movement of tailings ponds and identify the causes of failure.

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Data Availability Enquiries about data availability should be directed to the authors.

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