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TECHNICAL ARTICLE

Insights from the Compilation and Critical Assessment of Breach and Runout Characteristics from Historical Tailings Dam Failures: Implications for Numerical Modelling

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Abstract

Numerical models are used for detailed and site-specific tailings dam breach analyses (TDBAs) to estimate the downstream inundation and deposition resulting from a potential breach at a tailings dam. The results of TDBAs are key inputs into risk assessments, consequence classification, and emergency planning. This paper describes the research and development of a database of 12 tailings dam breach events with a specific focus on observations that are needed for numerical modelling, in conjunction with an assessment of existing dam breach conventions to improve consistency in reporting. The characteristics relevant to modelling include outflow volumes, breach processes, breach geometries, and runout observations local to the downstream area. This study and the new database shed light on the diversity of outflow materials, facility arrangements, breach processes, and downstream environments that affect the breach development and tailings runout. Familiarity with case studies is a crucial element of expert judgement for forward-analysis TDBAs, which this database supports. The database can also be used to define model inputs for back-analysis of additional tailings dam breach events, and simultaneously provides calibration or validation constraints with the runout observations. Continued review and critical assessments are needed to reduce uncertainties and to enhance case history data availability and quality in this database.

Keywords Anthropogenic hazards · Catastrophic mass movements · Inundation · Modelling

Introduction

Tailings are the waste of mineral processing that are commonly stored behind dams in impoundments, called tailings storage facilities (TSFs). The breach or failure of these tailings dams may result in casualties, environmental impacts, economic costs, and other societal consequences (Rana et al. 2021a, 2022), as evidenced by recent incidents in Brazil (the 2015 Fundão event, Morgenstern et al. 2016; the 2019 Feijão event, de Lima et al. 2020), South Africa (the 2022 Jagersfontein event, Torres-Cruz and O'Donovan 2023), and Tanzania (the 2022 Williamson event, Petley 2022). One aspect of risk management for a TSF is a tailings dam breach analysis (TDBA), where the consequences of a hypothetical tailings dam breach are estimated. The estimated consequences can be used to inform design criteria, emergency preparedness plans, and other risk management practices. These TDBAs are a legal requirement in some jurisdictions, such as in the Province of British Columbia, Canada (BCMEM 2017) and Brazil (ANM 2022). Regardless of any legal requirement, several national and international guidelines highlight the importance of performing TDBAs (e.g. CDA 2013, 2021; ICMM 2020; ICOLD 2022).

Desktop-level analyses, which are based on relatively simple methods without numerical models, can be used for preliminary TDBAs, alternative siting studies, or for

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portfolio and regional-scale studies (e.g. Innis et al. 2022). Numerical modelling is typically required for developing or updating emergency preparedness plans, TSFs with high potential consequences, or whenever detailed estimates of consequences are desired. A TDBA does not estimate the probability of a breach occurring (CDA 2021); however, some TDBAs may include probabilistic estimates of breach parameters, runout parameters, and consequences if a breach occurs. Several recent guidelines summarize the process and considerations for a detailed TDBA (e.g. CDA 2021; ICOLD 2022). The probability of various conditions leading to a breach could be assessed in a failure modes and effects analysis (FMEA), which is typically conducted as a separate undertaking to a TDBA.

TDBAs are an evolving practice, and there are inherent uncertainties involved with modelling approaches and determining inputs related to the breach and flow characteristics of tailings dam failures (CDA 2021). Several software packages and various approaches exist for breach analysis and runout modelling, some of which combine breach analysis and runout modelling with a single simulation. These programs or modelling tools and associated methods used in TDBAs have been described in CDA (2021), Ghahramani et al. (2022), and Martin et al. (2022). Regardless of the specific programs or modelling tools used, TDBAs involve many common inputs that cannot be calibrated in forward-analyses (i.e. predictive simulations) and therefore must be estimated or selected by the TDBA practitioner. This estimation can be informed by measured material properties, insights from collections of back-analyses of historical events, direct comparisons with analogous historical events, empirical equations based on many historical events, or professional judgment and experience.

Narratives of tailings dam failures and breach characteristics exist in academic, technical, and civilian reporting, but they can be scattered and plagued by inconsistent conventions or definitions of breach characteristics (Adria 2022; Ghahramani et al. 2020; Rana et al. 2021a; Rico et al. 2008; Sanz-Ramos et al. 2022). For example, the 1997 Aznalcóllar (Los Frailes) event in Spain is often labelled as one of the better-documented tailings dam failures, but Sanz-Ramos et al. (2022) provided a thorough summary of disputed and contradictory reporting regarding the breach and runout characteristics of the event. Dam heights, impounded volumes, total outflow volumes, and runout extents have been included in previous databases of tailings dam breaches. However, to date there is limited information on breach parameters or other inputs necessary in detailed TDBAs to support direct comparisons of analogous historical events or empirical equations. These inconsistent narratives and definitions, and uncertainties for past events negatively affect forward-analysis TDBAs.

Back-analysis numerical modelling of historical events can be used to provide insights on breach processes and runout behaviour, supplementing direct observations or knowledge of historical events and professional judgement used in forward-analysis. Tailings dam failures that have been back-analysed using various numerical modelling programs include: (i) the 1985 Prestavèl (Stava) event in Italy (Ghahramani et al. 2022; Pirulli et al. 2017); (ii) the 1994 Harmony 4A (Merriespruit) event in South Africa (Daneshvar and Zsaki 2018; Ghahramani et al. 2022; Petkovšek et al. 2021); (iii) the 2014 Mount Polley event in Canada (Mahdi et al. 2020; Petkovšek et al. 2021; Sreekumar et al. 2022); (iv) a portion of the 2015 Fundão event in Brazil (Machado 2017); and (v) the 2019 Feijão event in Brazil (Gibson et al. 2022; Lumbroso et al. 2021; Novell Morell 2022). Between these ten studies, eight different programs were used, four of which are not publicly available. Ghahramani et al. (2022) concluded that more back-analyses with numerical models are needed to better support forward-analysis in TDBAs, and insights may not be strictly transferable between different programs. Sanz-Ramos et al. (2022) also attributed the lack of back-analysis numerical modelling for the Aznalcóllar failure to the lack of available data to support such analysis.

The goal of this present research is to help fill the data gaps described above and make the new data available to other researchers and TDBA practitioners. This paper describes the development of a novel database comprising general facility descriptions, breach characteristics, and runout observations for 12 historical tailings dams that experienced a breach, based on a critical assessment of the facilities, the failures themselves, and the ensuing reporting. The compiled values use consistent conventions from previous dam breach work or new definitions as appropriate and required for tailings dam breach-specific considerations. Definitions and observations of breach and runout characteristics are explored in the context of tailings dams in finer detail than previously, before finally discussing the implications of these details and insights for numerical modelling in forward analysis TDBAs. The complete database is provided in an open-access data repository hosted at Borealis (Adria et al. 2023).

Database Impetus and Development

The tailings dam breach events considered in the database are listed in Table 1. A flowchart is shown in Fig. 1 that demonstrates the simplified methodology to compile the various data. The events were chosen primarily based on the data availability for the breach characteristics, and therefore the amount of runout observations varies by event in this database. The various parameters are briefly defined in the following subsections, before the details, context, and insights

Table 1 Tailings dam breach events included in the present database

ID	Event (colloquial or alternate names)	Date of Failure	Country
1	Prestavèl (Stava)	July 19, 1985	Italy
2	Gillibrand Pond No. 6 (Tapo Canyon)	January 17, 1994	USA
3	Harmony 4A (Merriespruit)	February 22, 1994	South Africa
4	Aznalcóllar (Los Frailes)	April 25, 1998	Spain
5	Tashan (Taoshi, Xiangfen)	September 8, 2008	China
6	MAL Reservoir X (Ajka, Kolontár, Red Mud Accident)	October 4, 2010	Hungary
7	Kayakari	March 11, 2011	Japan
8	Mount Polley	August 4, 2014	Canada
9	Fundão (Mariana, Bento Rodrigues, Samarco)	November 5, 2015	Brazil
10	Tonglüshan (Tonglvshan)	March 12, 2017	China
11a	Cadia NTSF Event I	March 9, 2018	Australia
11b	Cadia NTSF Event II	March 11, 2018	Australia
12	Feijão (Brumadinho)	January 25, 2019	Brazil

regarding each parameter are discussed in the subsequent sections.

Breach Parameters

A major component of a detailed TDBA is the breach analysis (CDA 2021). This involves estimating several important parameters: (i) the volume that mobilizes and discharges during the breach; (ii) the volumetric solids concentration of the resultant flow (i.e. the ratio of tailings solids to water in the outflow volume); (iii) the breach process or mechanism of how the outflow volume discharges during the breach; (iv) the time that it takes for the breach to fully form (i.e. the formation time, following the definition from Wahl 2014); and (v) the size and shape of the breach in the dam through which the outflow volume discharges.

Over the past 10 years, it has been increasingly recognised that tailings dams are substantially different from water retention dams, which limits the applicability of empirical-statistical approaches only derived from water retention dam failures (CDA 2021; Martin and Akkerman 2017; Rana et al. 2021a). To date, there is sparse information directly on other breach parameters for tailings dam failures, beyond the results of research on total outflow volume and runout extent. Some databases and regression equations specific to tailings dams have been developed to fill this gap. These databases and regression equations include early work by Rico et al. (2008) and subsequently by Bowker and Chambers (2015), Concha Larrauri and Lall (2018), Ghahramani et al. (2020), Rana et al. (2021a, b), and Piciullo et al. (2022). Most of these authors focus on using the dam height and impounded volume to estimate the total outflow volume or runout extent. Basic facility characteristics, downstream area details, and other background information for each event have been used for qualitative refinement in the statistical analysis of runout parameters (e.g. Ghahramani et al. 2020; Piciullo et al. 2022; Rana et al. 2021a), and for understanding causative and preconditioning factors and global trends of TSF failures (Piciullo et al. 2022; Rana et al. 2021a, 2022; Stark et al. 2022). Preconditioning factors and global trends, while useful for understanding the broader risk assessment context, are of limited benefit for estimating other breach parameters in forward-analysis simulation for a specific TSF.

The current database includes 23 different parameters relating to the facility and the breach, which are listed and briefly defined in Table 2. Ten of these parameters have never been compiled into a single database for tailings dam breaches (parameters 1, 4, 7, 8, 16, 17, 18, 21, 22, and 23); four parameters were developed during the present research to address the conditions unique to TSFs (parameters 11, 15, 19, and 20); and nine parameters were given consistent definitions, and occasionally values or characteristics were refined or updated after the investigation and research found evidence warranting revision from previous databases (parameters 2, 3, 5, 6, 9, 10, 12, 13, and 14). Geotechnical details related to the dam material densities, grain size distributions, erodibility coefficients, and critical shear stresses that may be used in semi-physical breach models (e.g. EMBREA-MUD, Petkovšek et al. 2021) are rarely available for tailings dams and were therefore not included in the current database.

Runout Observations

The next step after breach analysis in a detailed TDBA is to use a numerical model to simulate the tailings flood wave or runout through the area downstream of the TSF. The results of a numerical model include the simulated arrival time, inundated area, flow velocities and depths, and other features of the tailings flood wave (or runout). These modelled results then inform the estimated consequences of a dam breach, in

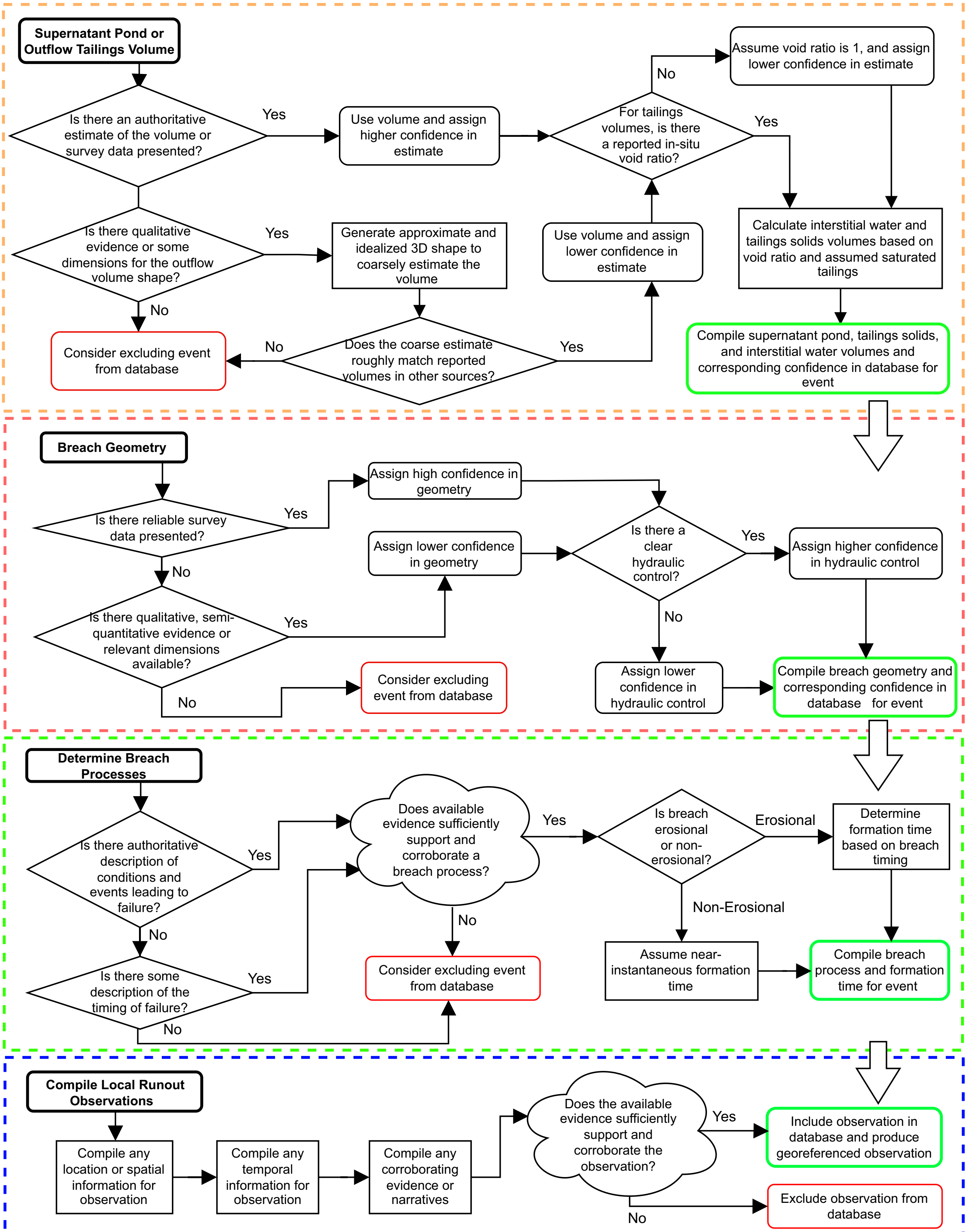

Fig. 1 Summary methodology for data compilation

Table 2 Definitions of compiled facility and breach parameters

Category	Parameter	Definition
Facility (1–6)	1. Facility arrangement	Geometric arrangement (configuration) of the facility compartments: ring-dyke, side-hill, cross-valley, composite, or stepped. See Fig. 3 and Blight (2010) for more detail
	2. Dam raise method	The direction of dam raises: upstream, centreline, and/or downstream. See Fig. 2 and Vick (1990) for more details
	3. Primary type of tailings	The mineral commodity of interest from which the tailings were processed for storage in a facility. The hard or soft tailings classification follows Small et al. (2017)
	4. Regulatory dam height	The maximum dam height at the time of the breach, following the definition from ICOLD (2011). The location of the maximum dam height may not necessarily correspond to the location of the breach
	5. Impounded volume	The total volume impounded in the compartment(s) at the time of the breach, including tailings solids, interstitial water, and supernatant pond volumes
	6. CDA classification	A qualitative, 2-by-2 matrix following Small et al. (2017) and CDA (2021)
Outflow volumes (7–11)	7. Tailings solids	The volume of solid tailings particles during the breach
	8. Interstitial water	The volume of pore water (in the tailings) released during the breach
	9. Supernatant pond	The volume of water impounded within the supernatant pond that discharges during the breach
	10. Total outflow volume	The sum of tailings solids, interstitial water, and supernatant pond volumes in the breach outflow
	11. Tailings discharge mechanism	The tailings discharge mechanism: liquefaction, erosion, or slumping. This is based on qualitative or quantitative information as interpreted from case history references. Multiple mechanisms may be present, but the dominant mechanism was assigned for each event
Breach process (12–18)	12. Failure conditions	The conditions or variables that led to increased susceptibility to failure. (See Rana et al. 2021a, b for details)
	13. Failure mode	Following the CDA Dam Safety Guidelines (2013): Collapse, Overtopping, or Contaminated Seepage
	14. Failure mechanism	Following the CDA Dam Safety Guidelines (2013): The specific events that occur shortly before the breach that directly lead to a failure
	15. Dominant breach process	Erosional or non-erosional. Erosional indicates the breach is progressed by erosional means and is associated with internal erosion or overtopping erosion during the breach, with durations of minutes to hours. Non-erosional indicates the breach is progressed by liquefaction, slope instability, foundation instability or other non-erosional failure processes, which take place on the order of seconds
	16. Initiation time	The breach initiation time begins with the first awareness that the safety of the dam is at risk and would initiate warning, evacuation, or potential for dam failure. The breach initiation time ends at the start of the breach formation phase (see Wahl 1998 for details)
	17. Formation time	The duration of time between the first breaching of the upstream face of the dam until the breach channel is fully formed (see Wahl 1998 for details)
	18. Outflow duration	The duration of time between the start of the breach formation and the time when the outflow from the dam has ceased
Breach geometry (19–23)	19. Dam height at breach location	The difference in elevation between the dam crest and the dam toe, prior to the breach, along the cross section of the deepest section of the breach
	20. Crest height at breach location	The difference in elevation between the dam crest prior to the breach, and the foundation directly below the dam crest along the cross section of the deepest section of the breach
	21. Breach height	The difference in elevation between the dam crest, prior to the breach, and the breach invert directly below the dam crest, along the cross section of the deepest section of the breach
	22. Breach width	The width of the breach measured at the setting-out-line. Provided for each event at the crest elevation and breach invert elevation
	23. Breach side slope	Average side slope of the breach trapezoid. Provided for each side (left and right, when looking downstream through the breach)

conjunction with identification of elements of value exposed in the downstream area (e.g. populated centres, environmentally sensitive areas, or any feature of high cultural or economic value). The inputs to a numerical model include some representation of the downstream topography, the resistance to flow from the landcover or features not explicitly captured in the topography (e.g. Manning's roughness or roughness height), the non-Newtonian flow characteristics of the tailings flow, and hydrologic conditions in downstream waterbodies (CDA 2021; Ghahramani et al. 2022; Martin et al. 2022).

Runout observations have been compiled to support calibration and validation of models using back-analyses of the events in the database. The planimetric area impacted or inundated by a geohazard such as a tailings dam failure is a simple but powerful model calibration metric (Heiser et al. 2017). Inundation areas have been previously assessed and compiled by Ghahramani et al. (2020) and Rana et al. (2021a, b) and are reassessed in this work for some of the events. Local-scale observations, such as the maximum depth of flow or breach flood wave arrival time, are equally important calibration or validation tools as inundation areas (Ghahramani et al. 2022; Gibson et al. 2022).

The present work focused on observations of the tailings flow depth and arrival times at specific (i.e. point) locations. Depth and arrival time have a few variations in the context of hazard mapping in forward-analysis TDBAs; similarly, there are variations of depth and arrival time in the eyewitness accounts or other investigations. Consistent definitions were applied for the local-scale observations, but nuance in the observation description was maintained where required. Other event-scale observations include, but are not limited to, fatalities and economic losses. While knowledge of these human-related impacts is useful to support consequence assessments for forward-analysis, the scope of this work and database is limited to the observations of the runout processes.

Topography, landcover, and hydrologic conditions are highly site-specific and multi-dimensional data and are outside the scope of this database. Runout parameters are infrequently available in the literature for these events, as they require extensive laboratory testing, back-calibration with a numerical model, expert judgement, and commonly all three. The aim of this database is to provide confirmed and direct observational data of real events to support numerical modelling; therefore, it would be inappropriate to include values determined from numerical models in a database of observed characteristics.

Breach Characteristics

Facility and Tailings Attributes

TSFs can vary substantially in layout, construction, and conditions. The dam itself can be constructed using upstream, centreline, or downstream raises (Vick 1990), as shown in Fig. 2. The arrangement of the facility can be a ring-dyke, side-hill, or cross-valley (Blight 2010), as shown in Fig. 3. Ponds may exist on top of the tailings, either as part of operations or after flood inflows. The tailings may be liquefiable due to numerous static or dynamic triggers, including the breach event itself (CDA 2021; Small et al. 2017). Hard and soft rock type tailings can also have different geotechnical and rheological attributes (Ghahramani et al. 2020; Rana et al. 2021a; Small et al. 2017).

Multiple "compartments" for tailings storage can also be arranged in close proximity to one another, which are termed "composite" or "stepped" by Adria (2022), resulting in further facility variations. Composite TSFs are where sections of the impounded tailings volumes are divided by internal embankments and potentially used for different types of tailings solids or supernatant ponds (e.g. Harmony mine, Wagener 1997; Aznalcóllar mine, McDermott and Sibley 2000; MAL Red Mud Reservoir, Turi et al. 2013). Stepped facilities comprise one compartment downstream of another (e.g. the Prestavèl mine, Luino and de Graff 2012; the Cadia mine, Jefferies et al. 2019). Figure 3a and c shows examples of these compartment variations. A TSF with both composite and stepped compartments is not impossible, but to the authors' knowledge, there have been no failures of such combined arrangements.

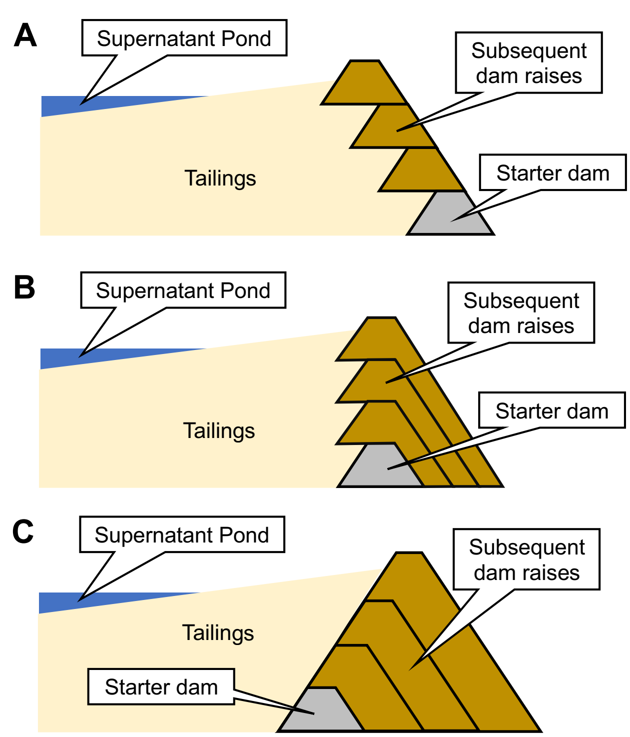

Fig. 2 Schematic of tailings dam cross sections for different construction raises. **a** Upstream construction, **b** centreline construction, and **c** Downstream construction

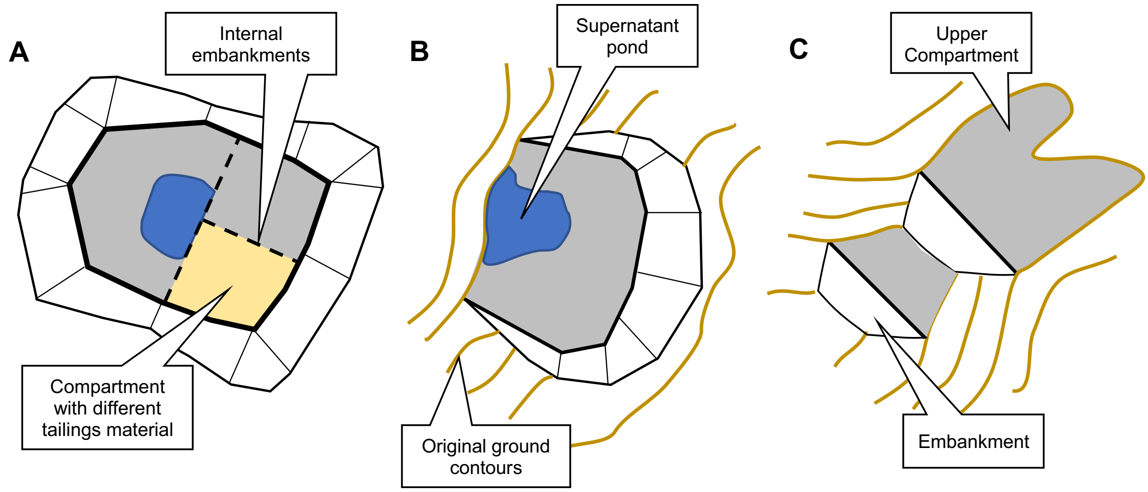

Fig. 3 Schematic of various TSF arrangements: **a** ring-dyke with composite compartments, **b** side-hill, and **c** cross valley with a compartment stepped above the lower compartment

The descriptors above can be determined through cursory review of a historical tailings dam failure. The dam raising method is often included in databases, but the remaining attributes are rarely mentioned or discussed as they may relate to breach characteristics.

Outflow Volumes

The composition of the outflow volume from a tailings dam breach can be heterogenous, potentially comprising: (i) a supernatant pond; (ii) multiple tailings solids types (e.g. from different ore processing methods, variation in geology over the life of the mine, or separate compartments); (iii) the interstitial water (pore water) within the tailings; and (iv) dam fill material (CDA 2021). The volumetric solids concentration of the outflow volume, or the ratio of tailings solids to the total outflow volume (i.e. the sum of the supernatant pond, interstitial water, and tailings solids), has a strong influence on the flowability and subsequent runout characteristics (CDA 2021; Martin et al. 2022). All else being equal, the flow is typically faster, more turbulent, and more mobile with a lower volumetric solids concentration; however, there are many other tailings characteristics that affect flowability and the range of measured rheology values vary by orders of magnitude for tailings at the same volumetric solids concentration (Martin et al. 2022).

Furthermore, the tailings can discharge through several mechanisms, including erosion, liquefaction, or slumping, which may also be associated with different volumetric solids concentrations and runout characteristics. Despite this heterogeneity, the total outflow volume has been commonly reported as a single scalar value (e.g. Rico et al. 2008), or occasionally segregated into the supernatant pond and tailings (i.e. the sum of the interstitial water and tailings solids) when such data was available (e.g. Ghahramani et al. 2020; Rana et al. 2021b).

For the present database, each volume was separately assessed, compiled, or estimated to enhance the single total outflow volume previously available in most databases. Furthermore, the discharge mechanism was qualitatively estimated for each event and tailings compartment (as relevant). This was completed in conjunction with a critical review of the breach process, as described in the following section. Specific details on the estimation and segregation methods are provided in supplemental content in the database.

Once the tailings volume was confirmed for an event, the tailings were proportioned into tailings solids and interstitial water, if not previously separated in existing sources. This was done by assuming saturated conditions and using the void ratio reported in Rana et al. (2021b) to estimate the proportion of interstitial water and tailings solids, according to Eqs. 1 and 2:

$$V_T = V_S + V_I \tag{1}$$

$$V_I = V_T\left(\frac{e}{e+1}\right) \tag{2}$$

where V_T is the total tailings volume, V_S is the tailings solids volume, V_I is the interstitial water volume, and e is the pre-failure void ratio. When no void ratio for the tailings prior to failure was reported, it was assumed to be 1. This implies that half of the released tailings volume is tailings solids and half is interstitial water (i.e. a volumetric solids concentration of 50%). This assumption was based on the range of void ratios in Vick (1990) for conventional hydraulically placed tailings, and in Rana et al. (2021b) for tailings dam breach events. Rana et al. (2021a) also indicate there is a strong prevalence for the TSFs in these events to have poor drainage, suggesting that the assumed saturation is reasonable for the estimates herein. It is recognized that the void ratio depends on different factors, including the type of tailings, particle size distribution, and degree of consolidation; therefore, the void ratio varies between different projects, and also varies spatially and temporally within a single TSF. Naturally occurring debris flows have volumetric solids concentrations of about 50% (O'Brien 1986) and exhibit similar flow characteristics as tailings flows of comparable solids concentrations (e.g. the 1985 Prestavèl event, Takahashi 2014).

Breach Processes and Formation Time

There is extensive literature and a substantial body of data available for causative variables or failure modes, for both water reservoir dams and tailings dams (CDA 2013, 2019, 2021; Piciullo et al. 2022; Rana et al. 2021a, b; Wahl 1998, 2014). Like the facility and tailings attributes discussed in a previous section, these data and frameworks are useful to know; however, they may not necessarily describe the physical process during a dam breach. CDA (2021) discusses two types of breach development processes, which are termed 'erosional' and 'non-erosional' herein, as a better descriptor of the actual breach.

A breach by the erosional process occurs when the dam or tailings material is primarily carried away by flowing water, which is similar to the breaching process of water reservoir embankment dams (e.g. Froehlich 2008; Wahl 1998; Walsh et al. 2021; Xu and Zhang 2009). Erosional breaches are commonly caused by overtopping or internal erosion mechanisms. Such failures involve relatively high supernatant pond volumes and are characterized by long duration outflows (i.e. many minutes to hours).

Non-erosional breaches occur when the dam material is mobilized through any other phenomena. Such failures are often described as brittle and are near-instantaneous, with one example being the 2019 Feijão event that was captured on video (Robertson et al. 2019). Non-erosional breaches of tailings dams can be initiated by, but are not limited to, slope instability (e.g. the 1985 Prestavèl event, Takahashi 2014), foundation failure (e.g. the 2017 Tonglüshan event, Zhuang et al. 2022), or tailings liquefaction (e.g. the 2015 Fundão event, Morgenstern et al. 2016).

The primary consideration for assigning the breach process is the timing of specific stages during the breach. Previous definitions and work from water reservoir failures (i.e. Froehlich 2008; Wahl 1998, 2014) proved to be applicable for erosional breaches of tailings dams. The initiation time begins with the first awareness of potential for dam failure and lasts until the formation time starts. The formation begins when the breach channel first intersects the upstream face of the dam or tailings beach and lasts until the ultimate breach dimensions are reached and is equivalent to 'Stage 3' for laboratory scale experiments (e.g. Walsh et al. 2021). The formation time does not include the initiation time or total duration of the breach outflow. For the present database, the initiation time and formation time were estimated for erosional breaches using eyewitness accounts and narratives. This involves some level of uncertainty and subjectiveness but is likely comparable to the uncertainty associated with estimating formation times for water reservoir embankment dam breaches (e.g. Wahl 2014).

There was commonly no pre-failure awareness of breach development for the non-erosional events in the database. Modern techniques, such as InSAR and dedicated onsite monitoring, may aid in early detection (Carlà et al. 2019; Rana 2023). These approaches were either not available at the time of these events (e.g. 1985 Prestavèl event, Takahashi 2014), resources were not allocated for them, or monitoring was misinterpreted (e.g. the 2014 Mount Polley event, Morgenstern et al. 2015; the 2019 Feijão event, Robertson et al. 2019). In this study, the formation time of all non-erosional breaches was considered instantaneous (i.e. 0 s). While any breach is not truly instantaneous, the events with direct evidence or reliable eyewitness accounts suggest formation times equivalent to 10 s or less for non-erosional breach events (e.g. the 1985 Prestavèl event, Takahashi 2014; the 2015 Fundão event, Morgenstern et al. 2016; the 2019 Feijão event, Robertson et al. 2019). Reducing the time for loss of strength and breach progression from near-instantaneous to instantaneous is a well-known and commonly used simplification in landslide modelling and breach analysis of concrete arch dams (e.g. Aaron et al. 2018; USBR 1988).

Breach Geometry

Breach geometry is defined here following the same conventions as commonly used in water reservoir dam breaches. However, additional clarity is needed for the arrangements of tailings dams. In simple terms, the breach "channel" through the dam is approximated as a vertical trapezoid at the hydraulic control, generally assumed to be in line with the "setting-out-line". The concept of a "setting-out-line" for referencing the dimensions and mechanism of the Mount Polley breach was used by Morgenstern et al. (2015) and is visualized in Fig. 4. It is noted that the setting-out-line is a two-dimensional plane, not a one-dimensional line as implied by its name. The setting-out-line was considered to project directly downwards from the dam crest alignment. Additional commentary on the hydraulic control with reference to tailings dam breaches, particularly for non-erosional failures, is included in the supplemental content in the database.

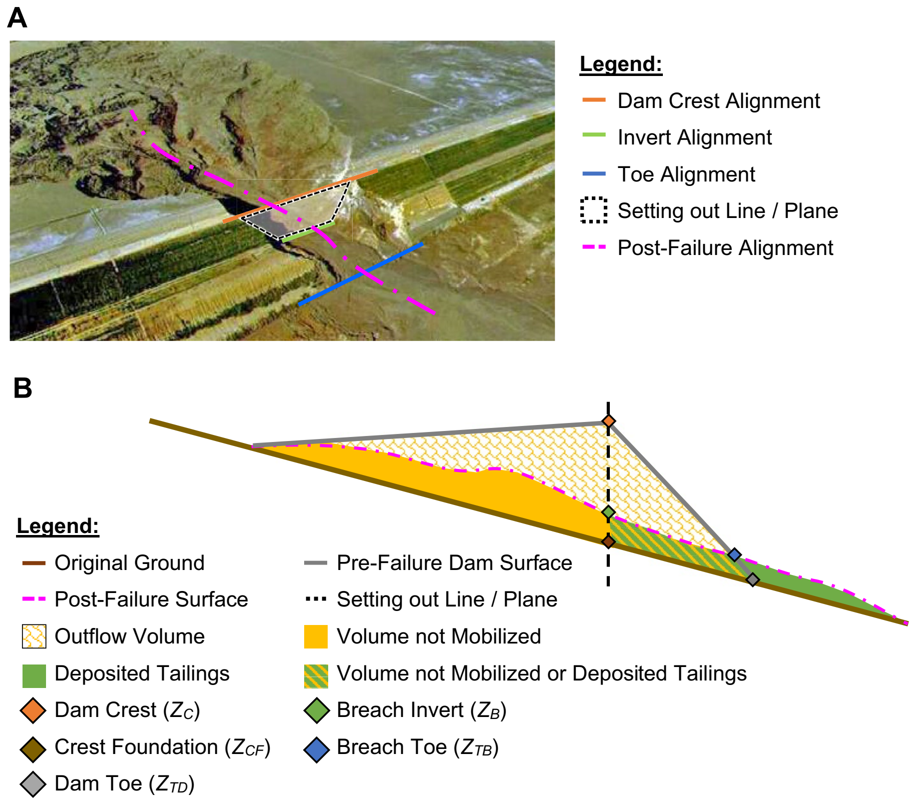

Fig. 4 Breach hydraulic control shown with **a** annotated oblique photo of the Harmony 4A Breach, and **b** hypothetical profile

Height Conventions

The dam height is the difference between the lowest elevation of the dam toe and the highest elevation of the crest (ICOLD 2011). This may not be the same location where a breach historically occurred. For example, the dam height of the Cadia NTSF in 2014 was 94 m under the ICOLD definition; however, the crest was only 68 m above the foundation where the breach occurred (Jefferies et al. 2019). Furthermore, TSFs can be built on steep slopes; therefore, the dam height can be noticeably taller than the maximum possible height of the hydraulic control (i.e. at the setting-out-line) in a breach. Lastly, the breach may not progress to the pre-dam topography.

Confusion regarding these possible height definitions was found to be prevalent in reporting. Consequently, four separate parameters are explicitly defined here: maximum dam height, dam height at the breach location, crest height at the breach location, and breach height. The maximum dam height corresponds to the ICOLD definition, and may be useful for regulatory or classification purposes, whereas the breach height is most relevant to the hydraulic control and actual outflow. The crest height at the breach location is approximately the maximum potential breach height. These definitions are shown visually in Fig. 5a.

An alternate convention was used for the 2010 Kayakari event and the 2018 Cadia Event I and Event II. When the maximum thickness of the tailings outflow volume measured normal to the average post-failure surface slope was larger than the breach height, the event in question was considered using a different convention. This scenario is shown schematically in Fig. 5b. This distinction was made as the hydraulic control was assessed to be at the breach toe in these failure events (e.g. the 2010 Kayakari event, Ishihara et al. 2015). The source area for this scenario is visually similar to slab avalanche source areas as defined by UNESCO (1981). Consequently, the tailings dam breach events that meet this criterion are termed ‘avalanche events’. This convention was developed, as it was found that the geometry at the breach toe was better suited as the hydraulic control, rather than at the setting-out-line.

Breach Shape

An approximation of the breach shape used for water reservoir embankment dams is a trapezoid (e.g. Froehlich 2008; Wahl 1998, 2004). The trapezoid is defined using the breach height, top breach width, and bottom breach width. The trapezoid alternatively can be defined with the average breach width and the slopes of the left and right sides of the breach, which do not necessarily need to be the same. The trapezoid approximation can be further simplified to a rectangular breach shape (using vertical breach side slopes) or a V-shaped breach (using 0 m for the bottom width).

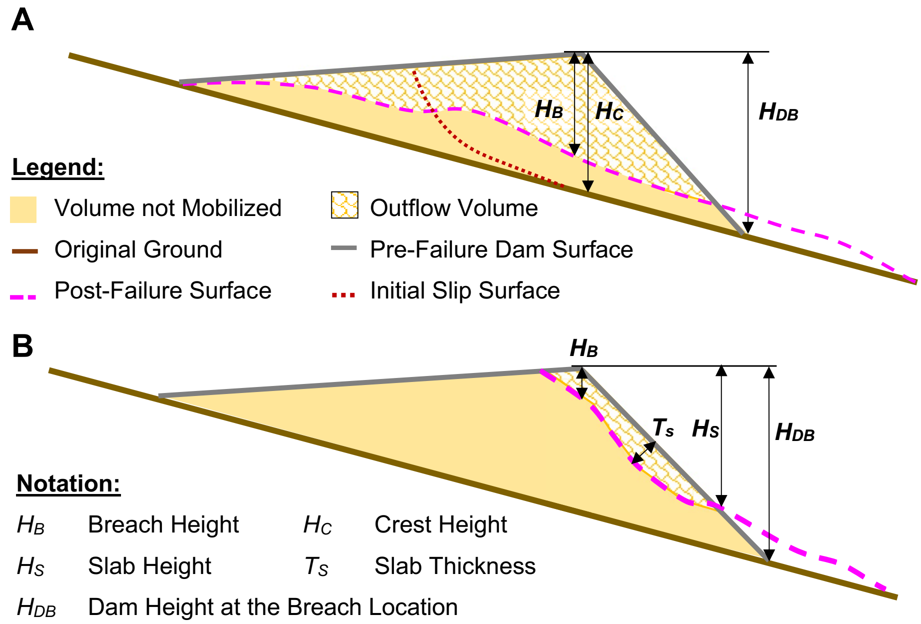

Fig. 5 Height conventions and dimensions. **a** Standard breach geometry, and **b** Avalanche breach geometry

The trapezoid approximation is often applied in forward-analysis for water reservoir embankment dam breaches for its simplicity and flexibility (Froehlich 2008). Observations of past water reservoir breaches and large-scale embankment failures also showed that a trapezoid approximated the breach shape well (Froehlich 2008; Morris et al. 2007). The downside of a trapezoid breach shape is that it may not be representative of highly irregular, composite, or curvilinear breach shapes.

For the present database, the breach geometry was typically measured at the setting-out-line at the dam crest alignment. Minor simplifications of the setting-out alignment were needed in some instances. For example, the Fundão dam has a curving crest with a setback and was built on uneven valley topography, so the breach geometry was measured from a straight line between each abutment. For the avalanche events, the geometry was measured at the breach toe instead. Publicly available information used to estimate the geometry ranged from detailed post-breach surveys presented in scaled drawings (e.g. the 1985 Prestavèl event, Muramoto et al. 1986; the 2014 Mount Polley event, Morgenstern et al. 2015; the 2018 Cadia NTSF, Jefferies et al. 2019) to unscaled and oblique photographs of the breach, which cannot provide the same level of detail and confidence. Froehlich (2008) noted similar approximations were also required for water reservoir dam breach databases. A schematic of the breach geometry conventions is shown in Fig. 6.

Runout Characteristics

Event-Scale Observations

The convention for measuring runout distance has not been defined in previous databases (e.g. Concha Larrauri and Lall 2018; Ghahramani et al. 2020; Rico et al. 2008). It can be measured along the river centreline or thalweg, along the centreline/streamline of the tailings flow (i.e. not necessarily the river centreline), or along the shortest straight-line distance. These conventions are shown conceptually in Fig. 7a. It appears that all three conventions have been used in previous databases, and sometimes even within the same database.

Ghahramani et al. (2020) established a convention for separating the impacted area into two zones to improve consistency in reported runout characteristics, as shown in Fig. 7b. Zone 1 is the primary impact zone, defined as the extent of the main solid tailings deposit, which is characterized by remotely visible or field-confirmed sedimentation, above typical bankfull elevations if extending into downstream river channels. Zone 2 is the secondary impact zone, defined as the area downstream of Zone 1 that is further affected by the tailings flow in some way. Secondary impacts may include flood or displacement wave impacts (i.e. fluid impacts above typical downstream water levels) and sediment plume impacts (i.e.

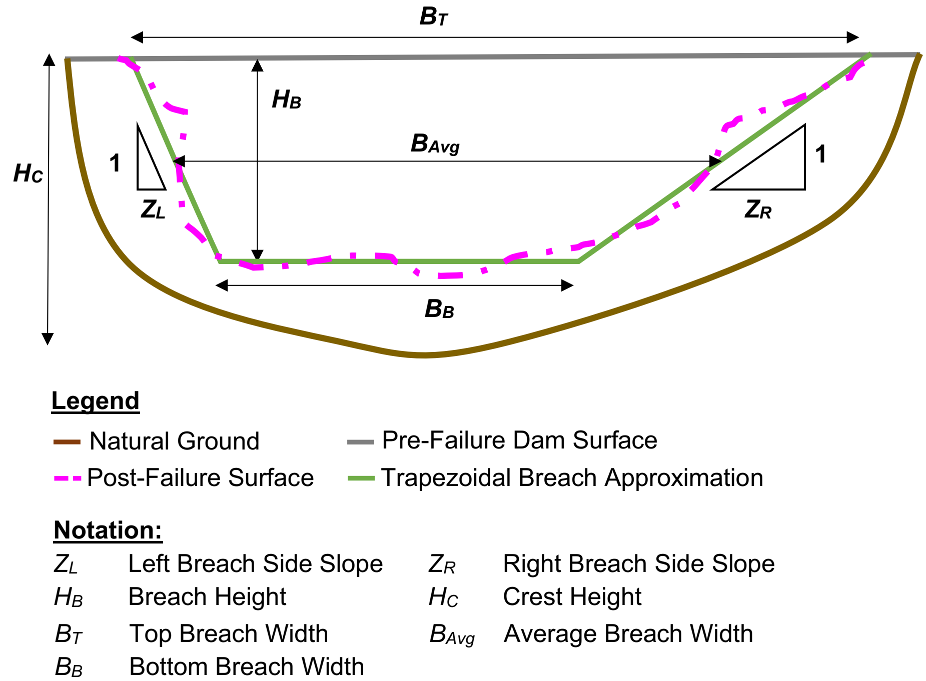

Fig. 6 Trapezoid breach geometry. The orientation of the breach cross-section is taken looking in the downstream direction

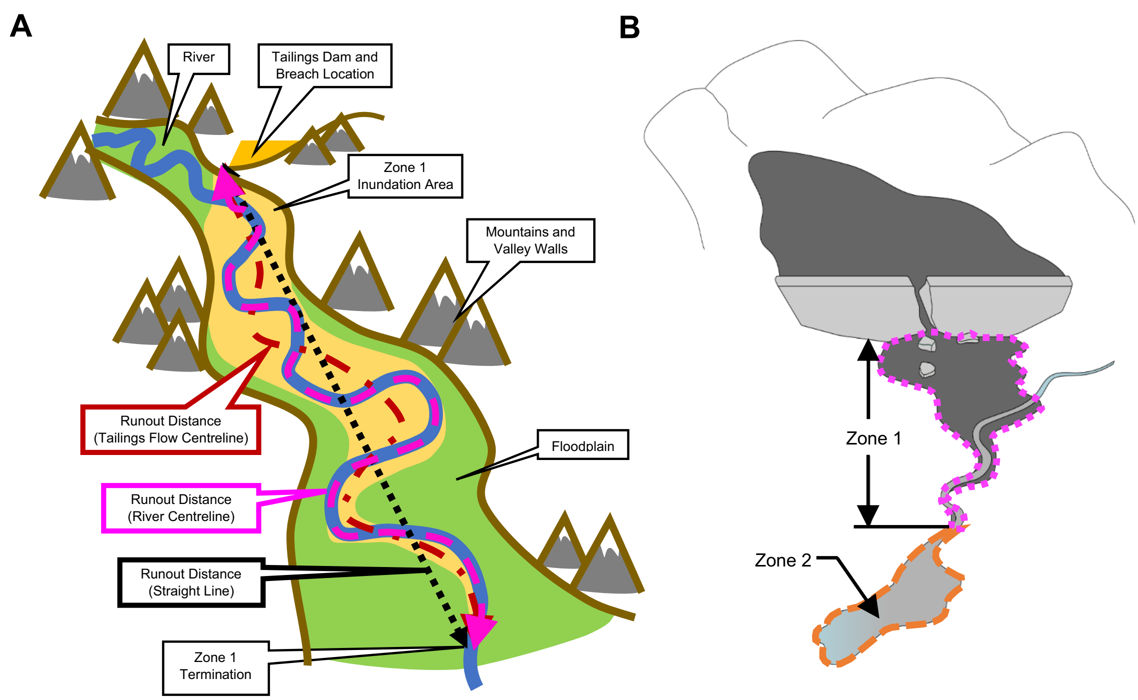

Fig. 7 Tailings runout conventions. **a** Various runout distance conventions, and **b** the Zone 1 and Zone 2 impact area convention from Ghahramani et al. (2020)

below typical downstream water levels). Ghahramani et al. (2020) further classified the downstream area from 33 historical events as unconfined or confined, which Rana et al. (2021a, b) extended to 52 events (and renamed confined to channelized). The present work focused on the Zone 1 inundation area. Several Zone 1 inundation areas from Ghahramani et al. (2020) and Rana et al. (2021a, b) were updated based on newly obtained information or interpretations. The Zone 1 shapefiles for each event are included in the present database.

Local-Scale Observations

Local-scale observations are defined here to be some quantitative measure of flow characteristics at a unique time and space within the impacted area. These types of observations can occur throughout the downstream area impacted by the tailings outflow, and therefore can have multiple individual scalar values for the same observation parameter. Despite this, it is rare that historical events have more than a few local-scale observations. The most prevalent local scale observations were the flow depth and arrival time; however, other miscellaneous types of observations exist as well.

One of the key aspects of this research was verifying the location for each observation and the definition of any reported value, as these observations can often have many similar, but not identical meanings. Observations were excluded if they did not have any location information or corroborating observations associated with them, except if they came from comparatively trustworthy sources. For example, a national news organization reporting that the government moved to neutralize the tailings flow at a specific bridge at a specific time is likely to be reliable and would be included in the database without corroboration. On the other hand, an eyewitness account of flow depths and velocities high enough to "sweep people off their feet" or to "snap trees like twigs" at an undetermined location would not be sufficient to use for model calibration, unless multiple accounts and corroborating evidence allowed for these observations to be used qualitatively, or as approximate quantitative constraints in calibration.

Each local-scale observation is included in the database as a georeferenced point, line, or polygon, and can be brought into any GIS platform or Google Earth to support calibration or validation during back-analysis. Most of the local-scale observations are within the Zone 1 impact area; however, observations from Zone 2 were included if they provided insight for Zone 1 impacts (e.g. arrival times were outside Zone 1, but no other timing information existed). Some observations are presented as polygons when they conceptually should be points. This was done when the confidence in the value of a particular observation was low, or only a general indication of the location was provided (e.g. the highest stain mark was human height within the "village"), but only if there were repeated observations or corroborating evidence to warrant this inclusion as a verified observation.

Flow Depth

The flow depth is one of the basic elements of hazard mapping in TDBAs (CDA 2021), and is used in model validation or calibration for back-analysis (e.g. Ghahramani et al. 2022). The depth may represent the peak depth of the tailings runout or the final deposit depth. Tailings runout can leave indicators of the maximum flow depth as mud high-water marks on buildings, trees, and infrastructure. These indicators can be safely observed and photographed after the event without sophisticated survey equipment and are the most common measures of depth available (e.g. the 1994 Harmony 4A event, Wagener 1997; the 1998 Aznalcóllar event, Eptisa 1998).

The final depths of the tailings deposit may be reported from field visits for forensic engineering and impact studies (e.g. the 1998 Aznalcóllar event, Gallart et al. 1999). Final depths can also be surveyed throughout the impact area (e.g. the 2018 Cadia Event I and II, Jefferies et al. 2019), but some survey information prior to the failure is necessary for proper change detection analysis. These full surveys are infrequent, as they are generally limited to more recent events with shorter runout distances, where detailed topographic surveys were feasible. For some events, eyewitnesses recounted their observation of flow depth at a time likely around the maximum flow velocity or depth (e.g., the 1985 Prestavèl event, Takahashi 2014). These types of accounts are much more difficult to verify in terms of location and reliability, particularly when compared to photographs or post-event expert interpretation.

Arrival Time

The arrival time is the time that it takes for the released tailings to reach a particular location. The arrival time may represent either the arrival of the tailings runout front (frontal arrival time), the peak depth of the tailings, or the peak flow of the tailings, all of which are commonly used in hazard or inundation maps in industry practice (CDA 2021). For forward-analysis, the arrival time is reported as a relative value from a defined point in time (e.g. the arrival time of the tailings outflow at the river is 40 min since the beginning of the breach formation). For the present database, the arrival times are reported as absolute values (e.g. the breach occurred at 12:28 hh:mm and the tailings outflow arrived at the river at 13:10 hh:mm) to be more precise and prevent confusion with relative timing.

Unfortunately, the arrival time cannot be observed after an event unless timestamped video or scientific instruments register the event (see following section). This limits observations primarily to eyewitness accounts, which are difficult to validate, primarily due to the lack of specific location information provided with the eyewitness account. The timing of broken power or communications cables in the path of the breach flood wave can be used to give the general indication of inundation (e.g. the 2014 Mount Polley event, Morgenstern et al. 2015), but it can be difficult to determine whether it is representative of the frontal arrival time, peak discharge, or some time in between. Two or more observations at two or more different locations are needed to use arrival time as a back-analysis model calibration and validation tool. The time of the onset of failure at the tailings dam is often one of the time and location pairs that can be used to determine the relative timing further downstream for back-analysis. The requirement for two observations for a single model calibration and the absence of location information prevented the inclusion of many reported arrival times in the database, more so than any scepticism in the reported timing.

The average velocity of the tailings runout is occasionally reported (e.g. the 2015 Fundão event, Morgenstern et al. 2016; the 1985 Prestavèl event, Takahashi 2014). These estimates are usually based on arrival time (i.e. the distance between two locations divided by the difference in arrival time between them) rather than a direct measurement of velocity. Therefore, the original arrival times for each location were considered a more appropriate model calibration and validation tool than the average velocity between them.

Other Types of Observations

Beyond the simple measurements of depth and arrival time, some events had secondary observations reported where their values come from additional interpretation or are derived from a combination of other observations. In rare cases, scientific instruments installed in the vicinity of the tailings runout for other purposes captured some features of the runout. The data from these sources may require additional expert interpretation, but generally can provide multi-faceted information invaluable to support model calibration and validation. These more complex observations were found to be rare compared to the simple measurements of depth and arrival time.

Hydrometric gauges can provide a time-series of the tailings runout depth if they were in the Zone 1 impact area. These time-series can give information about the arrival time of the flood wave front, peak tailings depth, arrival time of the peak tailings depth, final (deposited) tailings depth, and the general trend in depth and timing between all of these elements. Hydrometric gauges are also useful outside of Zone 1, as they can constrain the arrival time or other runout characteristics (e.g. the 2019 Feijão event, CPRM 2019). Such quantitative information is useful in model calibration and validation, but caution and judgement should be exercised. Depth time-series are preferred to flow time-series for model calibration and validation. Most stage-discharge rating curves at hydrometric gauges are invalid for events like extreme floods or tailings runouts, therefore, the calculated flow may not be reliable (Ayala-Carcedo 2004; Lang et al. 2010).

Seismograph data require expert interpretation to invert the frequency into a force–time function. These force–time functions have provided insight into the timing, duration, and dynamics of landslide events (e.g. Mitchell et al. 2022, and the references therein) and for a limited number of tailings dam breach events (e.g. Takahashi 2014). No seismic inversion analysis was completed in this research, but interpretations by others are referenced.

For some tailings dam breach events, pre- and post-failure surveys were completed by other parties; however, due to uncertainties or other considerations, the actual survey data is not reported or shown by the other parties. Instead, the total tailings volume deposited in an area or the total tailings volume that passed a location are reported, as calculated from the change in topography between the pre-and post-failure surveys. These values were assumed to be reliable, like outflow volumes calculated using survey information. The sub-areas of deposition were estimated based on descriptions in the original source and are provided in the database.

Discussion

Facility Arrangements and Outflow Volumes

Geometric or temporal details were explicitly discussed and included in the database. For example, the 1985 Prestavèl event in Italy, has been widely described to be a cascading failure of a stepped facility (Luino and De Graff 2012; Takahashi 2014); however, this arrangement for Prestavèl is commonly not mentioned in databases that include this event (e.g. Concha Larrauri and Lall 2018; Piciullo et al. 2022; Rico et al. 2008), or in numerical modelling of the event (e.g. Pirulli et al. 2017; Takahashi 2014). The 2018 Cadia NTSF event in Australia has previously been simplified to a single event, despite two different flow characteristics and outflow volumes that occurred with 48 h passing between the events (i.e. an initial slump of 1,170,000 m^3 and a subsequent flow of liquefied tailings of 160,000 m^3). Similarly, the 2015 Fundão event in Brazil discharged 32.2 M m^3 of tailings on the day of the primary failure, and then an additional 11.5 M m^3 of tailings over the next several months during multiple separate rainfall events (Fundação Renova 2016). The cumulative discharged tailings volume of 43.7 M m^3 that is commonly reported in databases (e.g. Piciullo et al. 2022) lacks the nuance or context regarding the timing of the discharges. These simplifications may have been necessary for the scope and purpose of the previous work, but they obscure the phenomena or considerations that would be useful for forward-analysis of facilities with similar arrangements or conditions. Furthermore, insights from back-analysis can be misleading if the numerical modelling does not reflect the physical arrangement, flow phenomena, and outflow volumes that actually occurred.

The total outflow volume from a tailings dam breach has substantial influence on the resulting impacts. Rico et al. (2008) noted difficulties with high uncertainties in compiling outflow volumes, which have been echoed by subsequent authors. The present research was similarly affected by this uncertainty despite the extra effort spent on details, and the uncertainty carries through to forward analysis based on these findings. Ultimately, presenting scalar volumes introduces a loss of three-dimensional information, even when segregating the volume into supernatant pond, tailings solids, and interstitial water.

Industry practice includes generation of simplified outflow volume shapes for each facility and failure scenario in TDBAs using post-failure residual tailings slopes (e.g. cones of depression, as described in CDA 2021). Site-specific tailings characterization and strength information from cone penetration testing or laboratory testing are preferred for forward analysis TDBAs, but these types of data are not always available. Residual slopes for past tailings dam breach events included in Lucia et al. (1981), Blight and Fourie (2005), or Robertson (2022) can be used to inform the slopes for these cones; however, these databases are limited in the number of events and do not include more recent events. A useful approach would be to digitize or compile the available three-dimensional surfaces for facilities pre- and post-failure, to supplement site-specific testing and to confirm whether a simplified cone approach is appropriate or sufficiently conservative. Remote sensing tools can provide these surfaces for recent events (e.g. Rivet 2023), but this technology is still in its infancy.

Failure Conditions, Causes, and Mechanisms

A useful insight obtained during this research is that the conditions and causes that lead to failure are not necessarily exclusively tied to the breaching process. The pond at the Harmony 4A compartment overtopped the dam after a rainfall event (Wagener 1997), which under conventional knowledge suggests an erosional breach process. In reality, the knickpoint from the overtopping erosion initiated a slope failure and static liquefaction in the upstream dam, such that the breach occurred in seconds, like “an explosion” according to eyewitnesses (Blight and Fourie 2005; Mánica et al. 2021). Therefore, a non-erosional breach process is more appropriate to describe this failure. As an alternative example, a local foundation weakness under the Mount Polley Perimeter Embankment initiated the dam failure (Morgenstern et al. 2015). This suggests a non-erosional breach and is reinforced by the label of a “brittle” failure mechanism by BCMEM (2015); however, the actual crest subsidence was limited to a few metres (Morgenstern et al. 2015), with most of the breach formation driven by erosion from the overtopping of a large supernatant pond over several hours.

Any back-analysis modelling of the breach for each of these events based on the descriptions of their causes rather than their actual breach process would lead to misconceptions and incorrect findings, which in turn have potential to affect forward-analysis TDBAs. While a discussion on the risk analysis process (e.g. potential failure modes analysis, or failure mode and effects analysis) is not within the scope of this paper, understanding the connections between specific risks to a dam, potential breach types, and the resulting hypothetical consequences is important. The risks would be mischaracterized if emergency personnel operated under the belief that they may have minutes to hours to respond to an erosional breach when a near-instantaneous non-erosional breach is more likely to occur. Fortunately, this nuance between failure causes and breach processes is not always complex. Contrasting the previous examples is the Feijão failure, where the tailings liquefaction and the absence of a supernatant pond are aligned with a non-erosional breach process.

Breach Characteristics

The erosional breaches of tailings dams in this database generally demonstrated slower formation times compared to events in water reservoir dam breach databases (e.g. Froehlich 2008; Wahl 1998). This aligns with the findings in physical flume scale experiments described in Walsh (2019), where the presence of a tailings beach slowed down breach formation to a large degree. The fastest erosional breach, MAL Reservoir X, involved aspects of foundation failure and block failure of its brittle, lightly bonded dam, which sped up the erosion process (Bánvölgyi 2018; Turi et al. 2013). Despite these non-erosional features, the breach took roughly 15 min, which is much slower than the other non-erosional breaches in the current database.

Other breach characteristics from the erosional tailings dam failures, such as breach height, breach width, and breach side slopes, appear approximately in line with water reservoir dam failures, with a defined trapezoidal hydraulic control at the breach location. This makes sense intuitively, as despite the differing conditions and mechanisms leading to the breach (e.g. Mount Polley was a hybrid centreline-upstream dam, while MAL Reservoir X and Aznalcóllar were downstream; MAL Reservoir X was built of brittle fly ash, while the Mount Polley and Aznalcóllar were rockfill), erosional processes are the dominant physical factors for the breach development and characteristics.

The nine upstream-raised dams evaluated in this research that underwent a failure are labelled as non-erosional breaches, while the centreline and downstream dams are labelled as erosional breaches. However, this is not meant to suggest that any hypothetical breach of an upstream dam must be considered non-erosional. The events in the database were selected based on data availability, which is typically higher for high-profile, destructive events, which appear to occur more often with non-erosional breaches. This may introduce a form of selection bias. Site-specific data and conditions should inform whether a non-erosional breach is the critical breach process for an upstream dam; however, it is acknowledged that upstream dams require greater care (Morgenstern 2016).

Due to these concerns, a non-erosional breach may be the initial assumption for forward-analysis TBDA of an upstream dam, with erosional breaches considered if further assessment and evidence suggests an erosional breach process is relevant. This would be analogous to the approach in geotechnical design of tailings dams where tailings are assumed to have the capacity to liquefy until proven dilatant (Morgenstern 2016). Likewise, non-erosional breaches should not be immediately excluded for centreline or downstream tailings dams without valid reasons to do so. For example, the Edenville dam was a water retention embankment that underwent a non-erosional breach due to liquefaction of the embankment (France et al. 2022).

Non-erosional breaches in this research demonstrated more variability with respect to breach parameters. Some failed to their foundation, while others had breach heights roughly half of the crest height at the breach location. The average breach width for the non-erosional failures tended to be wider than in the erosional failures (when normalized by breach height, as in Wahl 1998), and in other water reservoir dam breach guidelines) and displayed more scatter. The average breach width to breach height ratio for the erosional breaches ranged between about three and five, while it ranged between one and 20 for non-erosional breaches.

Identifying the hydraulic control also proved to be more difficult and subjective for non-erosional events. Common subjectivities were encountered when the breach location occurred at a corner of a tailings facility (e.g. the left setback at the Fundão Dam I) or a large portion of the outflow volume would have originated downstream of the crest and beneath the upstream raised embankment (e.g. the Prestavèl upper basin or the Cadia NTSF Event I).

These differences in breach characteristics may be related to differences in failure conditions, where specific conditions have a greater influence than for erosional events. The 2010 Kayakari event involved a sliver of tailings sliding off of an upstream dam without complete collapse, despite a substantial potential liquefaction trigger due to the Mw 9.1 Tōhoku earthquake (Ishihara et al. 2015). Determining if a non-erosional breach results in a localized failure of a portion of the tailings dam (e.g. Kayakari), or in a global failure of nearly the entire dam and tailings deposit (e.g. Feijão) is a complicated task. Such work may involve 3D limit equilibrium analysis (e.g. Castellanos et al. 2022) or strain-weaking constitutive modelling, such as FLAC-3D modelling (e.g. Robertson et al. 2019).

Runout Observations and Back-Analysis Calibration

Inundation areas provide more spatial information than the runout distance (i.e. two-dimensional information vs. one-dimensional) and are less subjective than runout distances. However, there is still some subjectivity evident in mapping the observed inundation area. Therefore, it is recommended that the planimetric inundation shapes and the evaluation metric proposed by Heiser et al. (2017) be used in any back-analysis model calibration or validation, with runout distances only used for general reference of scale or relative location.

Ideally, a hydraulic model is calibrated to meet spatial and temporal constraints, but it is generally more difficult to meet the latter (Adria 2022; Ghahramani et al. 2022; Gibson et al. 2022). There is a distinct lack of arrival time information for most of the events investigated, reducing the confidence in any calibrated values for such events. An absence of temporal calibration may introduce greater uncertainty and be of greater concern than equifinality errors during calibration and non-transferability of values between different tailings types and numerical models.

As noted earlier, reliable arrival time estimates were difficult to obtain. For example, the arrival time of the Feijão tailings runout to the Paraopeba River, some 10 km downstream of the dam, was commonly reported as 1.5–3 h based on news anecdotes repeated by Lumbroso et al. (2021), Gibson et al. (2022), and Novell Morell (2022). This estimate appeared to become the de facto accepted arrival time for this event and was used for calibrating numerical models. The National Water Agency (ANA) operated a hydrometric gauge 1.1 km upstream of the Paraopeba River confluence (the Alberto Flores station, #40740000), which can be used to estimate the arrival time to the river. This station reported a dramatic increase in river stage 32–47 min after the Feijão failure initiated at 12:28:21 (noting that the data were recorded in 15-min intervals), although no tailings reached the location of the hydrometric station. The Geological Survey of Brazil (CPRM) performed field studies of the hydrology, water quality, and sediment transport of the region after the failure, including an assessment of the data from the Alberto Flores station. They concluded that the sudden increase in stage was directly attributable to the tailings damming the river and causing backwatering, and that the tailings runout reached the Paraopeba River in about 30 min (CPRM 2019), rather than the 90 min commonly repeated in the literature.

The ultimate goals of Lumbroso et al. (2021) and Gibson et al. (2022) were to understand how warning times could affect life loss and to verify whether the newly added non-Newtonian capabilities in HEC-RAS would produce the same results as other numerical models, respectively. Those specific findings may remain valid despite their numerical models being calibrated to an incorrect arrival time of 1.5 h; however, it cannot be said that they are an accurate representation of the flow velocities and destructiveness of the actual Feijão failure event.

This issue extends beyond calibration of models, as chronic underestimates of the true severity of potential runout propagate to decisions regarding resource allocation and tolerated or accepted risk. Prior to the Harmony 4A failure and the impacts on the village of Merriespruit, it was not commonly believed that gold tailings could flow such a distance (Fourie et al. 2001). Similarly, the owner of the Fundão Dam I believed that a potential flow would be limited to the village of Bento Rodrigues, within 10 km of the TSF (de Carvalho 2019).

Runout Modelling Parameters and Inputs

There are several existing semi-quantitative methods and other guidance documents that can be used to select the roughness values (e.g. Arcement and Schneider 1989; and Janssen 2016 for Manning's n values) used as inputs in numerical models. Defining the non-Newtonian flow parameters also needed as inputs to numerical models is more challenging and is frequently only available through calibration back-analysis of past events. These back-analysis values are not recommended to be transferred between events or numerical models (Ghahramani et al. 2022) and are sometimes criticized (e.g. Iverson 2003; Iverson and George 2014). However, calibration is sometimes a necessary step for other insights on tailings flow behaviour or modelling approaches (Adria 2022) and can have some explanatory and predictive uses when sufficient case histories are compiled (Aaron et al. 2018, 2022).

The recommended approach for forward-analysis simulation is to obtain site-specific characterizations (through laboratory or field tests) of the tailings to inform input parameter selection, and when not available, use characterizations of similar tailings (CDA 2021; ICMM 2020; ICOLD 2022; Martin et al. 2022). There are two events in this database, the 2015 Fundão and 2017 Tonglüshan events, where measured rheology parameters (i.e. not from back-analysis) from the tailings runout or the TSF have been published (see Machado 2017 and Días 2017 for the Fundão tailings data, and Zheng 2018 and Zhuang et al. 2022 for the Tonglüshan tailings data). Future back-analyses of these events should consider the real data. Martin et al. (2022) published a multi-source collection of measured rheology parameters for tailings and natural materials, which illustrates the orders of magnitude range in values that can be expected for TDBAs.

High-resolution and high-quality topographic data input can have a larger influence on the estimated runout than any individual or combined modeller choice (Adria 2022; Sreekumar et al. 2022; Turner et al. 2022). High-quality bare-earth elevation data is sometimes regarded as prohibitively expensive at the scale and for the remote locations needed for many forward-analysis TDBAs. This may lead TDBA practitioners to rely on publicly available global datasets, such as SRTM or ALOS World3D-30. Low-resolution and low-quality data often have erroneous features that present themselves as artificial obstructions and ridges that impede the runout. These errors may not be representative of bare-earth conditions (e.g. vegetation, bridges, or other surface structures not removed). Furthermore, these errors have also been noted in cheaper commercial data that claim to represent bare-earth conditions suitable for flood modelling by the data producer (Adria 2022). Such errors frequently result in smaller inundation areas and slower arrival times, and ultimately lead to underestimated consequences of tailings dam failures.

Limitations

The compiled parameters and characteristics from the 12 events in this database support more detailed trends and insights that may be used for forward-analysis TDBAs, but some caution is warranted. The greater thoroughness and breadth of the investigated characteristics comes at the expense of the total number of events that could have been investigated. More events should be compiled to strengthen, refine, or repudiate the conclusions herein. The selection of the events was primarily based on the availability of information; therefore, investigations of other events prior to 2020 may be hampered by insufficient evidence for many of the parameters.

Independent forensic expert panel investigations of failure events with full access to the site and past information for the facility, including site-specific testing, are the most valuable sources of information (e.g. Jefferies et al. 2019; Morgenstern et al. 2015, 2016; Robertson et al. 2019). The recent events at the Jagersfontein and Williamson mines have had limited investigations completed to date. Much of the data required for these types of investigations are perishable. Satellite remote sensing may be useful to fill some of the gaps in knowledge (e.g. Torres-Cruz and O'Donovan 2023; Rivet 2023), but it does not offer a replacement for laboratory testing and field investigations.

Continued investigations of the same events in this database are also encouraged. It is possible that additional field observations from those who have had closer involvement (e.g. mine owners, industry consultants, academics, and impacted stakeholders) can provide greater clarity on the breach and runout characteristics. This would be particularly true for the events in non-English speaking countries, where details may have been lost in the translations by artificial intelligence (i.e. Google, ChatGPT, and Linguee) used in this study.

Not all TSFs have poor designs, construction, or operations, and therefore some insights derived from this research and database may represent a relatively conservative perspective. For instance, a broad downstream constructed tailings dam on competent foundations with a small supernatant pond would generally be associated with a relatively less likely and less severe breach in a forward-analysis TDBA. Notwithstanding this comment, TDBAs are often prepared for the purpose of assessing consequences for dam safety management and emergency preparedness planning (CDA 2021), and therefore using conservatively high but still credible outflow volumes and breach parameters may be appropriate. Conversely, some of the events in the database had atypically limited breach outflows and may not represent the possible worst-case scenario for the given facility, which could make these particular events inappropriate examples for emergency planning.

Conclusions

Breach and runout observations from novel interpretations and investigations for 12 tailings dam breach events were researched and compiled. These observations are detailed in an online data repository that compiles information for 23 different parameters relevant for breach analysis. The breach database used the existing frameworks for dam breaches, while considering aspects that are specific to TSFs. Clear definitions are provided for the parameters within this database to support further research on tailings dam breaches. Of the total 23 parameters, 6 parameters refer to the general conditions of the TSF prior to failure, five relate to the outflow volumes, seven describe the breach process and timing, and the remaining five define the geometry of the breach in the dam. The types of runout observations that are included in the database vary between the 12 events, but generally include observations of depth or arrival time at specific locations within the impacted area downstream of the breached tailings dam.

The compiled breach characteristics can be used as direct inputs for back-analysis numerical modelling, while the runout observations can be used as constraints for numerical model calibration or validation. The breach characteristics and runout observations cannot be directly used for forward-analysis simulations. Instead, knowledge of the facility and downstream area descriptors can be used to select analogous past events relevant for cross-checking the selected breach parameters and modelled runout results for realism and conservatism. Ultimately, the information in this database and subsequent back-analyses can support the professional judgement necessary for conducting TDBAs and reducing uncertainty in risk assessments.

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Data Availability The breach characteristics, runout characteristics, georeferenced locations for the runout characteristics, and supplemental content are available at: https://borealisdata.ca/dataset.xhtml?persistentId=doi:10.5683/SP3/JXT1XH, a publicly accessible online data repository hosted at Borealis (Adria et al. 2023).

References

Aaron JB, Stark TD, Baghdady AK (2018) Closure to "Oso, Washington, landslide of March 22, 2014: dynamic analysis" by Jordan Aaron, Oldrich Hungr, Timothy D. Stark, and Ahmed K. Baghdady. J Geotech Geoenviron 144(9):2014–2017. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001934

Aaron JB, McDougall S, Kowalski J, Mitchell A, Nolde N (2022) Probabilistic prediction of rock avalanche runout using a numerical model. Landslides 19:2853–2869. https://doi.org/10.1007/s10346-022-01939-y

Adria DAM (2022) Compilation and critical assessment of observations from a selection of historical tailings dam breach events for numerical breach and runout modelling. MASc thesis, Univ British Columbia. https://doi.org/10.14288/1.0421782

Adria DAM, Ghahramani N, Rana NM, Martin V, McDougall S, Evans SG, Take WA (2023) A database of tailings dam breach and runout observations. Borealis Can Dataverse Reposit. https://doi.org/10.5683/SP2/NXMXTI

ANM (Agência Nacional de Mineração) [National Mining Agency of Brazil] (2022) Directive no. 95, 7 Feb. 2022 https://anmlegis.datalegis.inf.br/action/UrlPublicasAction.php?acao=abrirAtoPublico andnum_ato=00000095andsgl_tipo=RESandsgl_orgao=ANM/MMEandvlr_ano=2022andseq_ato=000andcod_modulo=405andcod_menu=6783. Accessed 26 Jun 2023 (**in Portuguese**)

Arcement GJ Jr, Schneider VR (1989) Guide for selecting manning's roughness coefficients for natural channels and flood plains. United States Geological Survey, Water Supply Paper 2339. https://doi.org/10.3133/wsp2339

Ayala-Carcedo J (2004) The 1998 breakdown of the Aznalcóllar (Spain) mining waste pond and the consequent ecological disaster of the Guadiamar River: causes, effects and lessons. Bol Geol Min 115:711–738 (**in Spanish**)

Bánvölgyi GG (2018) The failure of the embankment of the Red Mud Reservoir at Ajka (Hungary). In: Reverdy M, Lamacchia R, Panov A, Arlettaz M, Potocnik V (eds) Proceedings of the 36th International ICSOBA Conference, Belem, Brazil, 29 October–1 November, pp 387–400

BCMEM (British Columbia Ministry of Energy and Mines) (2015) Mount Polley Mine tailings storage facility breach, August 4, 2014: investigation of the Chief Inspector of Mines. Victoria, Canada

BCMEM (2017) Health safety and reclamation code for mines in British Columbia. Victoria, Canada

Blight GE (2010) Geotechnical engineering for mine waste storage facilities. CRC Press/Balkema, Leiden

Blight GE, Fourie AB (2005) Catastrophe revisited—disastrous flow failures of mine and municipal solid waste. Geotech Geol Eng 23:219–248. https://doi.org/10.1007/s10706-004-7067-y

Bowker LN, Chambers DM (2015) The risks, public liability and economics of tailings storage facility failures. Univ of Maine Press, Orono, pp 1–55

Carlà T, Intrieri E, Raspini F, Bardi F, Farina P, Ferretti A, Colombo D, Novali F, Casagli N (2019) Perspectives on the prediction of catastrophic slope failures from satellite InSAR. Sci Rep 9(1):14137

Castellanos J, Yong S, Martin V (2022) Application of the 3D limit equilibrium method in tailings dam breach analysis. In: Proceedings of tailings and mine waste conference

CDA (Canadian Dam Assoc) (2013) Dam safety guidelines 2007 (2013 edition)

CDA (2019) Technical bulletin application of dam safety guidelines to mining dams

CDA (2021) Technical bulletin tailings dam breach analysis

Concha Larrauri P, Lall U (2018) Tailings dams failures: updated statistical model for discharge volume and runout. Environments 5(2):1–10. https://doi.org/10.3390/environments5020028

CPRM (Companhia de Pesquisa de Recursos Minerais) [Mineral Resources Research Company, Geological Survey of Brazil] (2019) Special monitoring from the Paraopeba River Basin: report I hydrological and sediment metric monitoring. https://doi.org/10.13140/RG.2.2.11245.84966 (**in Portuguese**)

Daneshvar P, Zsaki AM (2018) Simulation of tailings flow resulting from a dam breach using smoothed particle hydrodynamics. Environ Eng Geosci XXIV(3):263–279

de Carvalho DW (2019) The ore tailings dam rupture disaster in Mariana, Brazil 2015: what we have to learn from anthropogenic disasters. Nat Resour J 59:281–300

de Lima RE, de Lima Picanço J, da Silva AF, Acordes FA (2020) An anthropogenic flow type gravitational mass movement: the Córrego do Feijão tailings dam disaster, Brumadinho, Brazil. Landslides 17:2895–2906. https://doi.org/10.1007/s10346-020-01450-2

Días NA (2017) Determination of rheological properties of mining waste through rotational rheometer hypotheses. MS thesis, Federal Univ Espírito Santo (**in Portuguese**)

Eptisa (1998) Investigation of the failure of the Aznalcóllar tailings dam (**unpublished**)

Fourie AB, Blight GE & Papageorgiou G (2001) Static liquefaction as a possible explanation for the Merriespruit tailings dam failure. Can Geotech J 38:707–719. https://doi.org/10.1139/cgj-38-4-707

France JW, Alvi IA, Miller AC, Williams JL, Higinbotham S (2022) Investigation of failures of Edenville and Sanford Dams. May 4. https://damsafety.org/MI-Final-Report

Froehlich DC (2008) Embankment dam breach parameters and their uncertainties. J Hydraul Eng 134(12):1708–1721. https://doi.org/10.1061/(ASCE)0733-9429(2008)134

Fundação Renova (2016) Updated integrated environmental recovery plan. https://www.fundacaorenova.org/wp-content/uploads/2016/12/prai_renova-foundation-dez16-english.pdf. Accessed 26 Jun 2023

Gallart F, Benito G, Martin-Vide JP, Benito A, Prio JM, Regues D (1999) Fluvial geomorphology and hydrology in the dispersal and fate of pyrite mud particles released by the Aznalcóllar mine tailings spill. Sci Total Environ 242:13–26. https://doi.org/10.1016/S0048-9697(99)00373-3

Ghahramani N, Mitchell A, Rana NM, McDougall S, Evans SG, Take WA (2020) Tailings-flow runout analysis: examining the applicability of a semi-physical area-volume relationship using a novel database. Nat Hazards Earth Syst Sci 20:3425–3438. https://doi.org/10.5194/nhess-20-3425-2020

Ghahramani N, Chen HJ, Clohan D, Liu S, Llano-Serna M, Rana NM, McDougall S, Evans SG, Take WA (2022) A benchmarking study of four numerical runout models for the simulation of tailings flows. Sci Total Environ 827:154245. https://doi.org/10.1016/j.scitotenv.2022.154245

Gibson S, Moura LZ, Ackerman C, Ortman N, Amorim R, Floyd I, Eom M, Creech C, Alejandro S (2022) Prototype scale evaluation of non-Newtonian algorithms in HEC-RAS: mud and debris flow case studies of Santa Barbara and Brumadinho. Geosciences 12(3):134. https://doi.org/10.3390/geosciences12030134

Heiser M, Scheidl C, Kaitna R (2017) Evaluation concepts to compare observed and simulated deposition areas of mass movements. Comput Geosci 21(3):35–343. https://doi.org/10.1007/s10596-016-9609-9

ICMM (International Council on Mining and Metals) (2020) Global industry standard on tailings management

ICOLD (International Commission on Large Dams) (2011) Constitution of the International Commission on Large Dams

ICOLD (2022) Tailings dam safety, bulletin 194

Innis S, Ghahramani N, Rana NM, McDougall S, Evans SG, Take WA, Kunz NC (2022) The development and demonstration of a semi-automated regional hazard mapping tool for tailings storage facility failures. Resources 11(10):82. https://doi.org/10.3390/resources11100082

Iverson RM (2003) The debris-flow rheology myth. In: Rickenmann D, Chen CL (eds) Proceedings of debris-flow hazards mitigation: mechanics, prediction, and assessment, pp 303–314

Iverson RM, George DL (2014) A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. Physical basis. Proc R Soc A. https://doi.org/10.1098/rspa.2013.0819

Janssen C (2016) Manning's n values for various land covers to use for dam breach analyses by NRCS in Kansas. https://rashms.com/wp-content/uploads/2021/01/Mannings-n-values-NLCD-NRCS.pdf. Accessed 26 Jun 2023

Jefferies M, Morgenstern NR, Wates J (2019) Report on NTSF embankment failure

Lang M, Pobanz K, Renard B, Renouf E, Sauquet E (2010) Extrapolation of rating curves by hydraulic modelling, with application to flood frequency analysis. Hydrol Sci J 55(6):883–898. https://doi.org/10.1080/02626667.2010.504186

Lucia PC, Duncan JM, Seed HB (1981) Summary of research on case histories of flow failures of mine tailings impoundments. In: Mine

waste disposal technology, proceedings, Bureau of Mines Technology Transfer Workshop, pp 46–53
Luino F, De Graff JV (2012) The Stava mudflow of 19 July 1985 (northern Italy): a disaster that effective regulation might have prevented. Nat Hazards Earth Syst Sci 12(4):1029–1044. https://doi.org/10.5194/nhess-12-1029-2012
Lumbroso D, Davison M, Body R, Petkovšek G (2021) Modelling the Brumadinho tailings dam failure, the subsequent loss of life and how it could have been reduced. Nat Hazards Earth Syst Sci 21:21–37. https://doi.org/10.5194/nhess-21-21-2021
Machado NC (2017) Back analysis of the floodwave propagation from the Fundão dam rupture with different numerical models and simulation hypotheses. MASc thesis, Federal Univ of Minas Gerais (**in Portuguese**)
Mahdi A, Shakibaeinia A, Dibike YB (2020) Numerical modelling of oil-sands tailings dam breach runout and overland flow. Sci Total Environ 703(10):134568. https://doi.org/10.1016/j.scitotenv.2019.134568
Mánica MA, Arroyo M, Gens A, Monforte L (2021) Application of a critical state model to the Merriespruit tailings dam failure. Proc Inst Civ Eng Geotech Eng 175(2):151–165. https://doi.org/10.1680/jgeen.21.00001
Martin V, Akkerman A (2017) Challenges with conducting tailings dam breach assessments. In: Proceedings of 85th annual meeting of international commission on large dams, paper ID 249
Martin V, Adria DAM, Wong H (2022) Inundation modelling of non-Newtonian tailings dam breach outflows. In: Proceedings of 27th world congress of the international commission on large dams, question 105, response 28
McDermott RK, Sibley JM (2000) The aznalcóllar tailings dam accident—a case study. Miner Resour Eng 9(1):101–118. https://doi.org/10.1142/S0950609800000111
Mitchell A, Allstadt KE, George D, Aaron J, McDougall S, Moore J, Menounos B (2022) Insights on multistage rock avalanche behavior from runout modeling constrained by seismic inversions. J Geophys Res Solid Earth. https://doi.org/10.1029/2021JB023444
Morgenstern NR, Vick SG, Van Zyl D (2015) Report on Mount Polley tailings storage facility breach. https://www.mountpolleyreviewpanel.ca/final-report. Accessed 26 Jun 2023
Morgenstern, NR (2016) Geotechnical risk, regulation, and public policy. Sixth Victor de Mello lecture. https://www.victorfbdemello.com.br/arquivos/Lectures/6TH_VICTOR_DE_MELLO_LECTURE.pdf. Accessed 26 June 2023
Morgenstern NR, Vick SG, Viotti CB, Watts BD (2016) Fundão tailings dam review panel report on the immediate causes of the failure of the Fundão dam
Morris MW, Hassan MAAM, Vaskinn KA (2007) Breach formation: field test and laboratory experiments. J Hydraul Res 45:9–17. https://doi.org/10.1080/00221686.2007.9521828
Muramoto Y, Uno T, Takahashi T (1986) Investigation of the collapse of the tailings dam at Stava in the northern Italy. Ann DPRI 29A:19–52 (**in Japanese**)
Novell Morell M (2022) Modelling of dam breach flows; past and future mine tailings dam cases. MSc thesis, Delft Univ of Technology. https://repository.tudelft.nl/islandora/object/uuid%3A8f79272c-c5d8-4288-9086-9f9b4b7b611b
O'Brien JS (1986) Physical processes, rheology, and modeling of mud flows. PhD Diss, Colorado State Univ, Fort Collins, Colorad
Petkovšek G, Hassan MAAM, Lumbroso D, Collell MR (2021) A two-fluid simulation of tailings dam breaching. Mine Water Environ 40:151–165. https://doi.org/10.1007/s10230-020-00717-3
Petley D (2022) Another tailings dam failure: the Williamson Mine in Tanzania. The Landslide Blog. https://blogs.agu.org/landslideblog/2022/11/08/williamson-mine-1/
Piciullo L, Storrøsten EB, Liu Z, Nadim F, Lacasse S (2022) A new look at the statistics of tailings dam failures. J Eng Geol 303(2020):106657. https://doi.org/10.1016/j.enggeo.2022.106657
Pirulli M, Barbero M, Marchelli M, Scavia C (2017) The failure of the Stava Valley tailings dams (northern Italy): numerical analysis of the flow dynamics and rheological properties. Geoenviron Disast. https://doi.org/10.1186/s40677-016-0066-5
Rana NM (2023) Global study of tailings dam failures by statistical and remote sensing methods. PhD Diss, Univ Waterloo, Waterloo, Canada. http://hdl.handle.net/10012/19335
Rana NM, Ghahramani N, Evans SG, McDougall S, Small A, Take WA (2021a) Catastrophic mass flows resulting from tailings impoundment failures. J Eng Geol 292:106262. https://doi.org/10.1016/j.enggeo.2021.106262
Rana NM, Ghahramani N, Evans SG, McDougall S, Small A, Take WA (2021b) A comprehensive global database of tailings flows. Borealis Can Dataverse Reposit. https://doi.org/10.5683/SP2/NXMXTI
Rana NM, Ghahramani N, Evans SG, Small A, Skermer N, McDougall S, Take WA (2022) Earth-science reviews global magnitude-frequency statistics of the failures and impacts of large water-retention dams and mine tailings impoundments. Earth Sci Rev 232(July):104144. https://doi.org/10.1016/j.earscirev.2022.104144
Rico M, Benito G, Díez-Herrero A (2008) Floods from tailings dam failures. J Hazard Mater 154(1–3):79–87. https://doi.org/10.1016/j.jhazmat.2007.09.110
Rivet (2023) Preliminary survey report for jagersfontein: orthophotos, topographic surveys (DEM), and reconstructed surfaces produced from archive satellite imagery. https://marketing.photosat.ca/MDC/Article/Jagerfontein/Feb. Accessed 26 Jun 2023
Robertson PK (2022) Evaluation of flow liquefaction and liquefied strength using the cone penetration test: an update. Can Geotech J 59:620–624. https://doi.org/10.1139/cgj-2020-0657
Robertson PK, de Melo L, Williams DJ, Wilson GW (2019) Report of the expert panel on the technical causes of the failure of Feijão Dam I, http://www.b1technicalinvestigation.com. Accessed 26 Jun 2023
Sanz-Ramos M, Bladé E, Dolz J, Sánchez-Juny M (2022) Revisiting the hydraulics of the Aznalcóllar mine disaster. Mine Water Environ 41:335–356. https://doi.org/10.1007/s10230-022-00863-w
Small A, James M, Al-Mamun M (2017) Advancing the state of practice for tailings dam breach assessment using empirical correlations. In: Proceedings of Canadian Dam Association annual conference, session 7B
Sreekumar U, Rennie C, Mohammadian A, Nistor I, Lovitt J, Zhang Y (2022) Modelling the transport of tailings after Mount Polley tailings dam failure using multisource geospatial data. Can J Civ Eng 49:1870–1884. https://doi.org/10.1139/cjce-2021-0596
Stark T, Moya L, Lin J (2022) Rates and causes of tailings dam failures. Adv Civ Eng 2022:7895880. https://doi.org/10.1155/2022/7895880
Takahashi T (2014) Debris flow disasters and their reproduction by computer simulations. In: Takahashi T (ed) Debris flow: mechanics, prediction and countermeasures, 2nd edn. CRC Press, Boca Raton, p 572
Torres-Cruz LA, O'Donovan C (2023) Public remotely sensed data raise concerns about history of failed Jagersfontein dam. Sci Rep 13:4953. https://doi.org/10.1038/s41598-023-31633-5
Turi D, Pusztai J, Nyari I (2013) Causes and circumstances of red mud reservoir dam failure in 2010 at MAL Zrt factory site in Ajka, Hungary. In: Proceedings of 7th international conf on case histories in geotechnical engineering, Paper No. 3.14a ,https://scholarsmine.mst.edu/icchge/7icchge/session03/10

Turner J, Ellithorpe A, Ng A, Krupa A (2022) Impact of topography errors on tailings dam breach analysis. In: Proceedings of tailings 2022 online conference

United Nations Educational Scientific and Cultural Organization (UNESCO) (1981) Avalanche atlas. UNESCO, Paris

US Department of the Interior Bureau of Reclamation (USBR) (1988) Downstream hazard classification guidelines

Vick SG (1990) Planning, design, and analysis of tailings dams, 2nd edn. BiTech Publishers Ltd, Vancouver

Wagener F (1997) The Merriespruit slimes dam failure: overview and lessons learnt. J S Afr Inst Civ Eng 39:11–15

Wahl TL (1998) Prediction of embankment dam breach parameters: literature review and needs assessment. Dam Safety Research Report. U.S. Dept of the Interior, Bureau of Reclamation

Wahl TL (2004) Uncertainty of predictions of embankment dam breach parameters. J Hydraul Eng 130(5):389–397. https://doi.org/10.1061/(asce)0733-9429(2004)130:5(389)

Wahl TL (2014) Evaluation of erodibility-based embankment dam breach equations. U.S. Dept of the Interior, Bureau of Reclamation

Walsh A, McDougall S, Evans SG, Take WA (2021) Effect of upstream dam geometry on peak discharge during overtopping breach in noncohesive homogenous embankment dams; implications for tailings dams. Water Resour Res. https://doi.org/10.1029/2020WR029358

Walsh A (2019) Physical modelling of tailings dam breach. MASc thesis, Queen's Univ. http://hdl.handle.net/1974/27522

Xu Y, Zhang LM (2009) Breaching parameters for earth and rockfill dams. J Geotech Geoenviron 135(12):1957–1970. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000162

Zheng Z (2018) Research on rheological properties of tailings and dynamic properties of dam break in copper-iron tailings pond. MSc thesis, Shanghai Jiaotong Univ (**in Mandarin**)

Zhuang Y, Jin K, Cheng Q, Xing A, Luo H (2022) Experimental and numerical investigations of a catastrophic tailings dam break in Daye, Hubei. China Bull Eng Geol Environ. https://doi.org/10.1007/s10064-021-02491-0