CDA technical bulletin on tailings dam breach analyses

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ABSTRACT: Understanding the consequences of a tailings dam breach ultimately leads to designing safer dams and properly preparing for emergencies. Guidelines for dam breach studies are available for water dams, but none of these deal with the hydrodynamic and geotechnical issues related to tailings flows. Since 2013, the Mining Dams Committee of the Canadian Dam Association (CDA) has been working on developing methodologies to improve the way tailings dam breach analyses (TDBA) are conducted. Workshops were organized in 2014 and 2015 to understand the state of practice at the time. In 2016 a CDA Working Group was established to develop guidelines specific to tailings dams. The Working Group led the development of the TDBA Bulletin and feedback was obtained on several drafts including a workshop in 2017.

The CDA Technical Bulletin for TDBA will provide the key steps that should be undertaken. The differences between water retaining and tailings dams will be addressed. The presence of a supernatant pond and the potential of the tailings to liquefy and flow, are the key parameters influencing the runout potential and outflow volume. The physical processes occurring during a TDBA will be discussed with guidance provided on estimating the volume of released tailings during a breach and predicting where the tailings could flow. The TDBA is planned to be issued in 2019.

RÉSUMÉ: Pour concevoir des barrages plus sécuritaires et de bien se préparer aux situations d'urgence, il faut comprendre les conséquences d'une brèche de barrage minier. Des lignes directrices pour les études des brèches de barrage sont disponibles pour les barrages hydrauliques, mais aucun s'appliquer spécifiquement aux problèmes hydrodynamiques et géotechnique des écoulements des résidus miniers. Depuis 2013, le Comité des barrages miniers de l'Association canadienne des barrages (ACB) développe des méthodes pour améliorer comment les études des brèches de barrages sont menées. Des ateliers ont été organisés en 2014 et 2015 pour comprendre l'état de la pratique à l'époque. En 2016 un groupe de travail de l'ACB était établi pour développer des lignes directrices spécifiques aux barrages miniers. Le groupe de travail a développé le bulletin technique et des commentaires sur les brouillons ont été reçus, comprenant aussi un atelier en 2017.

Le bulletin technique de l'ACB pour les études des brèches de barrages miniers énonce les étapes clés à suivre. Les différences entre les barrages hydrauliques et les barrages miniers seront abordées. La présence d'un bassin surnageant et le potentiel de liquéfaction et d'écoulement des résidus sont les paramètres clés qui influencent le potentiel de ruissellement et le volume de sortie. Les processus physiques qui se produisent au cours d'une brèche de barrages miniers seront discutés et des conseils sont fournis pour estimer le volume de résidus miniers rejetés lors d'une brèche et la prévision de l'endroit où les résidus pourraient s'écouler. Le Bulletin sera publié en 2019.

1 INTRODUCTION

This paper provides an update on a guidance document that is being prepared by the Canadian Dam Association (CDA) for tailings dam breach analyses (TDBA). The CDA provides a forum to gather and distill consensus on what constitutes good practice for dam safety in Canada. The process to develop the Technical Bulletin on Tailings Dam Breach Analyses involved four years (2016-2019) of collaboration by CDA members. The draft Bulletin is currently undergoing reviews by various CDA committees and external reviewers.

A Tailings Dam Breach Working Group (WG) was established by the CDA Mining Dams Committee (MDC) to focus on the development of the guidance for TDBA. Discussions and workshops were held at annual CDA conferences and a number of revisions were made to incorporate the feedback received. The Bulletin is nearing completion and will expand on the 2007 CDA Technical Bulletin *Inundation, Consequences and Classification for Dam Safety* and on the 2014 CDA Technical Bulletin *Application of Dam Safety Guidelines to Mining Dams*.

The CDA Bulletin on TDBA is intended to provide dam safety professionals with guidance on the general process and scope for conducting these analyses. While the Bulletin will provide a step by step procedure for such analyses, it is up to the dam owners and the professional engineers to agree on the scope that meets the objectives and the requirements set by the Regulators. Reliable TDBA and mapping are critical for tailings dam design and safety management as they help identify and characterize threats to public safety and the environment. The results of the study are typically presented on inundation and deposition maps (as appropriate) and could be used for various purposes including dam consequence classification, emergency planning, dam safety management, failure mitigation planning in case a failure occurred, and mine closure and dam decommissioning planning.

There is little published guidance specific to TDBA currently available. Practitioners often refer to guidelines for dam breach analysis of water retaining dams, such as the *CDA* (2007), or the Washington State (1992) and FEMA (2013) guidelines. Those guidelines were primarily developed for water retaining dams, and while all those documents provide details on dam beach analyses, none of them addresses the hydrodynamic and geotechnical issues related to tailings flows that are critical to tailings dam breach events. The CDA Bulletin on TDBA will aim to fill this gap in the literature and will offer a basis for discussion between dam owners, dam safety professionals, and tailings dam safety regulators.

The physical processes of breaching for tailings dams are complex, as they may include flow of fluids (supernatant water and eroded and/or fluid tailings), combined with a flow of liquefied tailings and/or slumping of solid tailings. The rheological behaviour of the released materials differs from that of water and impacts the total volume of tailings released. Studies of previous tailings dam failures show that the volume of mobilized tailings could range from as low as 1% to as high as 100% of the total storage volume (Lucia et al. 1981; ICOLD 2001; Rico et al. 2008; Azam&Li 2010; Small et al. 2017).

A tailings dam failure can be defined as the inability of the dam to meet its design intent, whether in terms of management, operational, structural or environmental function, resulting in loss to the stakeholders and the environment. For the purposes of this Bulletin, a tailings dam failure is a physical breach of the dam followed by an uncontrolled release of stored materials that could include fluids and tailings. The uncontrolled release of contaminated seepage without a physical breach of the dam was not considered for dam breach assessment purposes in the Bulletin.

The characteristics of a tailings impoundment or a tailings storage facility (TSF) and its foundations, construction method, as well as operations, maintenance and environmental conditions (e.g., rain, wind, earthquake, etc.) inform possible failure modes. Failure modes commonly considered for tailings dams include collapse and overtopping of the dam, or a combination of these two modes that are considered under fair weather and flood induced conditions, as required. Collapse of the dam can occur due to various mechanisms like slope or foundation instability, piping, erosion, seismic event, etc. Overtopping can occur either due to an extreme flood event, or inadequate operation of the facility.

This paper provides an overview of the proposed key steps to be undertaken during a TDBA. Various considerations specific to tailings dams are discussed.

2 KEY STEPS FOR TAILINGS DAM BREACH ANALYSES

In the CDA Bulletin on TDBA, a step by step process will be provided for conducting these analyses. Figure 1 provides a flow diagram for the different steps to be undertaken in a typical TDBA. A description of these key steps is provided in subsequent sections, focusing on those steps that are specific to tailings dams.

2.1 *Objectives and scope*

The objectives are determined at the onset of the assessment including what the results will be used for (e.g., consequence classification, emergency planning, etc.). This then dictates the required scope including the resolution and accuracy of the analyses (e.g., populated vs. non-populated areas), and determines the level of effort and tools used. Desktop TDBA generally rely on simpler, qualitative type analyses and do not result in detailed inundation and/or tailings deposition maps. Detailed or quantitative TDBA rely on complex computer modelling and may include additional hydrologic, slope stability, or tailings liquefaction analyses. The results of a detailed TDBA are used to prepare inundation and/or deposition maps, as required.

2.2 *Background information and review*

The available information is collected and reviewed at the onset of the assessment, and data gaps are identified that are related, but not limited to:

- The TSF design and staging of the dams and other relevant facilities, including relevant plans and cross-sections for the dams
- The tailings characteristics and susceptibility to flow liquefaction due to various trigger mechanisms including lateral unloading developed as a result of a dam breach
- Estimates of stored volumes of tailings and water
- Hydrologic information for the facility and the downstream drainage network
- Topographic and bathymetric data and type of terrain downstream of the TSF dams
- Identification of downstream points of interest including population at risk, environmental, cultural, and infrastructure/economic values.

2.3 *Failure modes and dam failure scenarios*

Depending on the study purpose, the dam configuration and construction method needs to be reviewed (e.g., upstream, downstream, centerline, zoned earth fill, rock fill, etc.), and failure modes (i.e., overtopping or collapse) identified for all relevant phases of the TSF development (e.g., construction, operations, closure and post-closure), as applicable for the TDBA. The number of TSF dam breach scenarios that need to be analyzed should be determined for the facility based on the number of dams, the number of stages, and the relevant failure scenarios under fair weather (sunny day) and flood induced (rainy day) conditions.

In the case of tailings dams, some of the failure modes and mechanisms may not be credible for a given dam depending on the life stage and configuration; however, most failure modes and mechanisms would be considered credible in general. For example, an overtopping failure scenario for a TSF that does not store a supernatant pond would represent a non-credible failure mode under fair weather conditions.

It is important to note, however, that the credibility of a failure mode should not be considered if the TDBA is conducted to establish the dam classification, which determines the design criteria for the dam. The dam classification is to be based on the consequences of failure regardless of the credibility of failure. If after evaluating the failure modes, there are no credible failure modes that could result in a dam breach, then a hypothetical dam breach failure mode should be investigated to support the dam classification. The dam breach analysis provides an indication of the level of the hazard that is represented by the dam in such cases. For example, if a dam failure represents a hazard that would result in an extreme classification, then the design criteria should be consistent with that level of hazard. On the other hand, emergency preparedness and response plans should be based on credible failure modes in order to provide a useful tool for emergency planning.

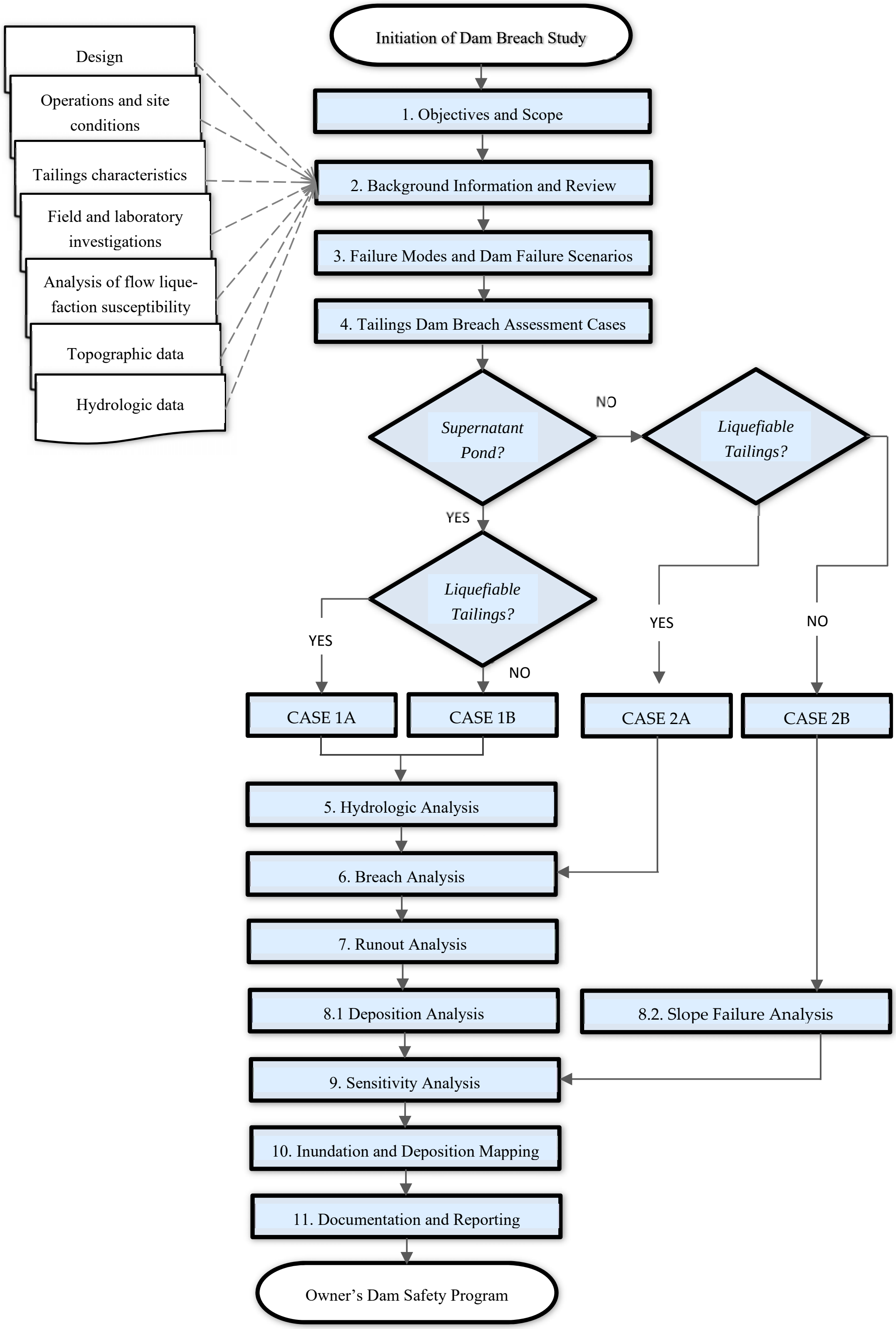


Figure 1. Process flow diagram for tailings dam breach assessments.

2.4 *Tailings dam breach assessment cases*

The engineering characteristics of a TSF can vary greatly and are dependent on many factors such as the tailings mineralogy, the physical and chemical ore extraction processes, the degree of consolidation and drainage, the method of deposition, etc. The characteristics of the materials stored in a TSF may also vary with time during the mining cycle. Unlike in case of water dams, the rheological properties of the tailings material, and the composition and flow characteristics of the materials contained in the TSF (i.e., fluids and tailings) should be well understood before undertaking a TDBA.

The suggested approach in the draft Bulletin considers a selection of appropriate TDBA cases, which will then inform additional considerations in the analysis. There are two main factors that are expected to have an important impact on the character and volume of the outflow from the TSF during a breach event:

- The presence of fluids (supernatant water and/or fluid tailings) on the surface of the impoundment near the dam; and
- The potential for liquefaction induced flowability of the tailings material, which may be due to various trigger mechanisms, including the breach itself.

These factors are used to define four types of TDBA cases that are useful in describing the breach event and in supporting the estimates of fluids and tailings that may be mobilized. These four TDBA cases were presented at CDA workshops in 2015 and 2017, and in Small et al. (2017) and are reproduced in Table 1.

Table 1. Tailings dam breach assessment cases

Presence of supernatant pond near the dam	Potential for tailings runout as a result of flow liquefaction*	
	Yes	No
Yes	Case 1A – Liquefied Tailings with a Pond: Dam breach with flow of fluids and eroded and liquefied flowable tailings contributing additional volume of materials released	Case 1B – Non-Liquefied tailings with a Pond: Dam breach with eroded tailings, transported and deposited by the flow of fluids
No	Case 2A – Liquefied tailings without a Pond: Dam breach resulting from slope failure with mudflow or debris type flow of liquefied flowable tailings (depending on the degree of saturation)	Case 2B** – Non-Liquefied tailings without a Pond: Slope failure of the dam

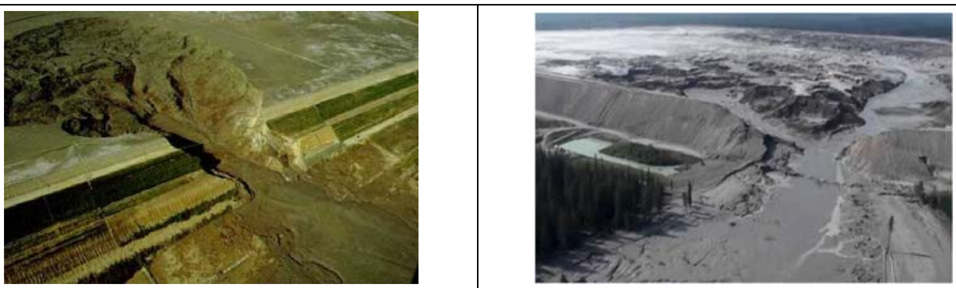
* Flow liquefaction of tailings could be induced by any potential trigger (static or cyclic/seismic) including shear strains in the tailings as a result of the dam breach (e.g., lateral unloading).

** Hydrotechnical analyses or inundation mapping similar to other three cases would not be required for Case 2B. Landslide runout analysis may be more appropriate.

It is worth noting that saturated loose contractive tailings materials can liquefy and demonstrate high flowability when the moisture content is relatively high and the solids content is relatively low. On the other hand, consolidated and densified tailings that would have a relatively lower moisture content and higher solids content, may not demonstrate the same flowability as the looser, less consolidated materials. Lowering the moisture content in a given tailings slurry (liquefied saturated tailings) would change its rheological characteristics from high flowability (at high moisture contents) to semi-flowable and then to non-flowable (at relevant lower moisture contents). These variations in tailings flowability can be evaluated by considering the rheology to soil mechanics continuum, as discussed in Adams et al. (2017a, 2017b.), and MEND, 2017.

Examples of the four TDBA cases with corresponding relevant photos shown on Figure 2 are as follows:

- Case 1A – the Merrispruit tailings dam failure occurred in South Africa in 1994 (Figure 2a), or the 1978 Mochikoshi dam failure in Japan.
- Case 1B – the Mount Polley TSF failure occurred in British Columbia, Canada, in 2014 (Figure 2b).
- Case 2A – the Fundao dam failure in Brazil in 2015 (Figure 2c), the 1994 Tapo Canyon tailings dam failure in the United States, or the recent Feijão dam failure near Brumadinho, Brazil, in January 2019.
- Case 2B – the Clinton Creek Mine failure in Yukon, Canada, in 1985 (Figure 2d), the 1950 Castle Dome failure in the United States, or the 2018 Cadia dam failure in Australia.



(a) Case 1A: Merrispruit 1994

(b) Case 1B: Mount Polley 2014

(c) Case 2A: Fundao 2015

(d) Case 2B: Clinton Creek 1985

Figure 2. Examples of past failures and tailings dam breach study cases (Photo sources: [a] http://www.tailings.info/casestudies/merriespruit.htm; [b] http://www.cbc.ca/news/canada/british-columbia/mount-polley-mine-spill-78-larger-than-1st-estimates-1.2755974; [c] http://g1.globo.com/minas-gerais/fotos/2015/11/barragem-se-rompe-e-distrito-de-mariana-e-inundado.html#F1833790; and [d] http://powergeolab.com/fieldsites/)

2.4.1 *Physical processes for tailings dams breaches*

The physical processes of breaching vary substantially depending on the TDBA case. The breaching process for cases with a pond near the dam is driven by the initial discharge of fluids from the supernatant pond. It can be assumed that two processes, or two interrelated discharge mechanisms occur (Martin et al., 2015):

- Process I - initial discharge of supernatant pond that carries tailings and dam fill material creating an initial flood wave (both Cases 1A and 1B), and
- Process II - discharge of flowable tailings due to tailings liquefaction (Case 1A, Case 2A), or progressive slumping (failure) of unsupported tailings (Case 1B).

The two processes are not independent and do not necessarily occur in sequence; however, different modelling tools may need to be utilized to simulate each process more adequately, and a phased approach may need to be adopted for the analysis.

As the breach develops during Process I, discharge of the supernatant fluid and down-cutting through the dam occurs. The tailings mass is eroded and mobilized as the flow propagates towards the breach opening. This process creates an initial flood wave that can propagate far downstream causing extensive erosion and inundation of the downstream environment. Lateral unloading also starts to develop, during which tailings may liquefy. It can be assumed for modelling purposes that the initial flood wave is followed by more tailings discharging from the TSF during Process II. Depending on the rheological characteristics, the liquefied tailings may be less fluid compared to flows discharging during Process I, and would consequently deposit closer to the breach location.

Both fair weather and flood induced scenarios for Cases 1A and 1B assume a significant pond near or at the dam. The amount of tailings that would be mobilized and transported downstream would depend on the amount of water in the supernatant pond. On the other hand, some TSFs that do not store water under normal operating conditions may be classified as Case 2A or Case 2B for fair weather scenarios, but may need to be evaluated as Case 1A or Case 1B for flood induced scenarios. During a flood induced scenario, the amount of water is typically significantly larger than in a fair weather scenario. A larger pond volume increases the volume of tailings that could be mobilized with the initial flood wave during Process I.

The solids concentration in the breach outflow changes during the event. Furthermore, the solids concentration in the initial flood wave varies through time depending on the breaching stage and the volume of mobilized tailings, and in space depending on the downstream erosion and deposition. The physical behaviour, or the flow characteristics for different flow types, was investigated by O'Brien (1986). The description of flow characteristics presents useful guidance for understanding the behaviour of different flow regimes. It was adapted in the draft CDA Bulletin to fit the TDBA cases, as shown in Table 2, and graphically illustrated on Figure 3. There is some overlap between the TDBA cases and the ranges shown should be considered indicative only.

Table 2. Flow behaviour as a function of solids concentration (adapted from O'Brien 1986)

Dam Breach Study Cases	Flow Type	Sediment Concentration		Flow Characteristics
		by Volume	by Weight	
Case 1A Case 1B	Water Flood	<0.20	<0.41	Water flood with conventional suspended load and bedload
	Mud Flood	0.20 - 0.30	0.41 - 0.54	Distinct wave action; fluid surface; all particles resting on bed in quiescent fluid condition
		0.30 - 0.35	0.54 - 0.59	Separation of water on surface; waves travel easily; most sand and gravel has settled out and moves as bedload
		0.35 - 0.40	0.59 - 0.65	Marked settling of gravels and cobbles; spreading nearly complete on horizontal surface; liquid surface with two fluid phases appears; waves travel on surface
Case 2A		0.40 - 0.45	0.65 - 0.69	Flow mixes easily; shows fluid properties in deformation; spreads on horizontal surface but maintains an inclined fluid surface; large particle (boulder) setting; waves appear but dissipate rapidly
	Mudflow	0.45 - 0.48	0.69 - 0.72	Flow spreading on level surface; cohesive flow; some mixing
		0.48 - 0.55	0.72 - 0.76	Flow evident; slow creep sustained mudflow; plastic deformation under its own weight; cohesive; will not spread on level surface
Case 2B	Landslide/ Debris Flow	0.55 - 0.65	0.76 - 0.83	Block sliding failure with internal deformation during the slide; slow creep prior to failure
		0.65 - 0.80	0.83 - 0.91	Will not flow; failure by block sliding

Based on O'Brien (1986), low solids concentrations are associated with water floods and mud floods, which move faster than mudflows, debris flows, or landslides. Consequently, these flows may result in larger and deeper inundation and faster flood wave propagation. The concentration of solids is just below 70% by weight (about 50% by volume) at the upper end of mud floods. Higher solids concentrations would tend to result in mudflows, and finally in landslides and debris flows for solids concentrations above approximately 76% by weight (55% by volume).

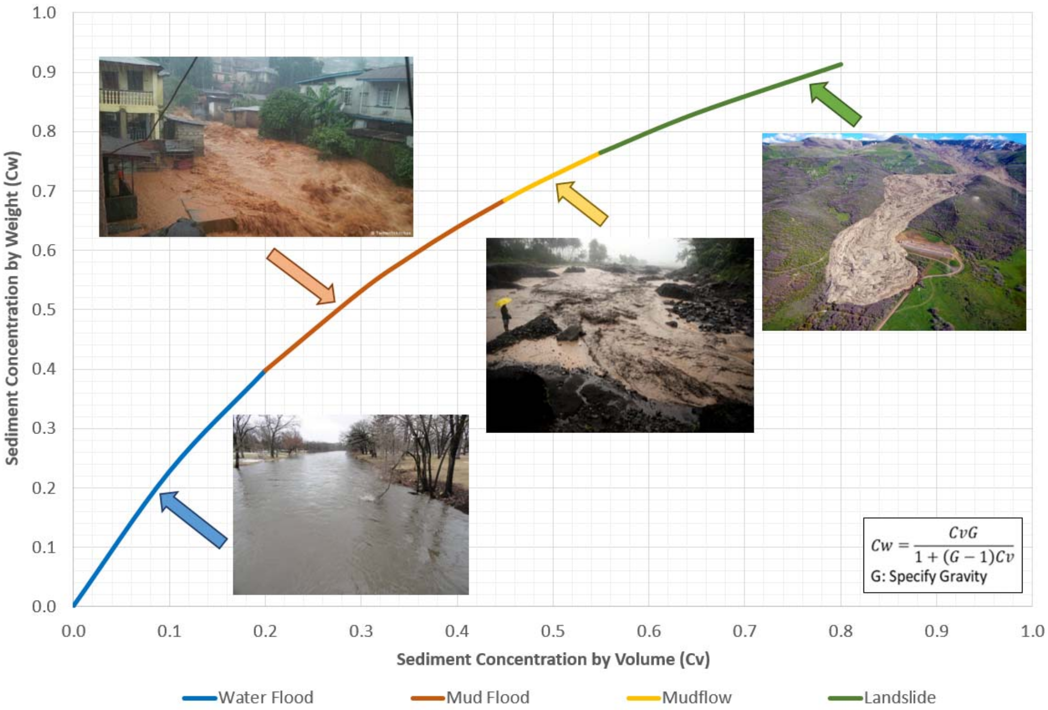


Figure 3. Flow types as a function of solids concentration (Photo sources: https://patch.com/illinois/bolingbrook/dupage-river-floods-bolingbrook; https://www.dw.com/en/hundreds-feared-dead-in-sierra-leone-mudslide/a-40085698; https://www.thepeninsulaqatar.com/article/27/01/2018/Philippines-warns-of-volcanic-mudflows-from-heavy-rains; and http://www.geologyin.com/2014/06/west-salt-creek-landslide.html#3CIo6ubOwM4cuYoB.99)

If there is no supernatant pond present in the TSF or near the breach, the breaching process is not driven by the discharge of fluids. An initial flood wave (Process I) cannot be formed similar to Cases 1A and 1B, and the breaching process would be more similar to that described for Process II. In Case 2A, the tailings mass has a potential to undergo liquefaction and become flowable due to various static or cyclic (seismic) trigger mechanisms including lateral unloading resulting from containment removal due to a dam breach. The released tailings mixture would likely behave as a mudflow, progressively depositing downstream, and may have a solids concentration higher than 70% by weight (about 50% by volume), depending on the dry density of the stored tailings and the volume of interstitial water. Based on observations from past failures, the post-liquefied residual angle in the TSF would be expected to be shallow at 3.5-5° (6-9%), while the slope of the tailings deposited downstream may be even shallower at 1-4° (2-7%) (Lucia et al. 1981, Blight and Fourie, 2003). The slope of the tailings deposited downstream would also depend on the downstream topography.

In Case 2B, the tailings mass would not have the potential to liquefy and develop flowable characteristics. The volume of mobilized tailings can be estimated through slope failure mechanisms. The breaching process may be modelled as a landslide, where the materials would not flow, but block sliding or slow creep deformation could occur in advance of the failure (as shown in Table 2). The residual angle in the TSF is expected to be much steeper than in Case 2A, and probably closer to the angle of repose for the deposited tailings material.

2.5 *Hydrologic analysis*

The hydrologic analysis involves determining the starting elevations and volumes for the supernatant pond in the TSF, and the discharges in the upstream and downstream drainage networks for the fair weather and flood induced dam breach events. These key hydrologic parameters are used to determine the breach outflow volumes and to conduct the downstream flood routing.

The maximum normal supernatant pond elevation and the corresponding pond volume are typically selected for assessing fair weather failure scenarios. For operating dams, it is necessary to assess whether overtopping is a possible credible scenario based on the past management and operation of the TSF. If overtopping due to inadequate operations, and insufficient storage volume and freeboard is considered credible, a pond level coincident with the top of the dam may need to be selected for the fair weather scenario. The maximum normal pond elevation or the spillway invert elevation (if applicable) can be selected as the initial supernatant pond elevation at the onset of a flood event for assessing flood induced failures. It is important to consider the duration of the inflow design flood (IDF) that was used in the TSF design, as it can have a profound impact on the storm inflow volume, and consequently on the magnitude of the dam breach outflow volume.

The hydrologic conditions upstream of the TSF that can provide inflows to the TSF may impact the volume of free water in the supernatant pond, and subsequently the volume of mobilized tailings in the breach outflow. For fair weather failures, the runoff volume from the upstream drainage network is typically either diverted or included in the normal operational supernatant pond range. For flood induced failures, however, the flood runoff from the catchment upstream of the TSF needs to be accounted for when determining the additional volume of free water in the TSF, which can mobilize additional tailings. Diversion structures located upstream of the TSF should be assumed to be non-operational for flood induced failures, if they were designed for smaller return period flood events than the TSF itself.

The assessment of hydrologic conditions downstream of the dam have a profound impact on the breach flood wave routing, which is similar to the flood routing for a breach of water retaining dams. For fair weather failures, the downstream flows are typically assumed to be equivalent to the mean annual discharge (MAD). For flood induced failures, it is typically assumed that the storm causing the flood being considered for the breach analysis is centered over the TSF. Pre-breach flood flows in the drainage network immediately downstream of the facility should then be equal to the same flood event that was assumed for the breach and then prorated with distance from the facility depending on the extent of the model.

2.6 *Breach analysis*

In the breach analysis, the following breach characteristics are determined/estimated:

- The volume of free water in the pond and the volume of mobilized tailings, which define the breach outflow volume.
- The dam breach parameters (width, shape/side slopes, breach formation time).
- The peak discharge and the outflow flood hydrograph.
- The sensitivity range for various breach parameters.

2.6.1 *Volume of free water and volume of mobilized tailings*

For modelling purposes, it can be assumed that the volume of tailings discharging with the initial flood wave would be similar or higher for Case 1A compared to Case 1B for facilities with similarly sized supernatant ponds, but the amount of additional tailings discharging in Process II would be different and likely considerably higher in Case 1A than in Case 1B, due to the flow of liquefied tailings.

The tailings outflow volume in case of liquefiable tailings (Case 1A, Case 2A) could be determined from the liquefaction analysis if it was available for the TDBA. Alternatively, a liquefaction failure surface could be approximated as a plane with a constant angle based on the tailings geotechnical information, in which case the volume of liquefied tailings could be estimated assuming a cone of depression. Based on past failures, it has been estimated that the post-liquefaction tailings angle (or the angle for the cone of depression) in the TSF varies between at 3.5°-5°, or 6%-9% (Lucia et al. 1981, Blight and Fourie 2003). The volume of the slumped tailings in Process II for Case 1B can be estimated by assuming a residual angle in the TSF steeper than in Case 1A, and likely closer to the angle of repose for the deposited tailings material (e.g., 24° or 45% for wet sand).

A methodology for estimating the mobilized tailings volume in Process I of a dam breach event based on the amount of available water in the facility was proposed by Fontaine&Martin (2015). The analysis considers the pond volume, the solids density for the tailings mass, and the degree of saturation. The percent solids mixed with the available water in the TSF (or the solids content in the breach outflow) is an assumed value and requires professional judgement. The impacts of the selection of this parameter should be evaluated through sensitivity testing. As an example, the methodology was applied to the Mount Polley incident, which was assessed as a Case 1B failure without substantial flow of liquefied tailings (Small 2017). The following assumptions were used: average dry density of 1.4 t/m^3, tailings solids density of 2.65 t/m^3, the degree of saturation of 100% in consideration of the tailings beach being under water cover at the time of the breach; and the volume of free water in the supernatant pond of 10.6 Mm^3. Assuming the average solids content in the initial flood wave was 40-50%, this method would result in a volume of tailings solids of 3.3-5.6 Mm^3 and a volume of interstitial water of 2.5-4.2 Mm^3.

The officially reported total breach outflow volumes contained 7.3 Mm^3 of tailings solids, 6.5 Mm^3 of interstitial water, and 10.6 Mm^3 of free water (http://www.imperialmetals.com/s/Mt_Polley_Updates.asp?ReportID=717253). To obtain these values, the average mixing ratio with water would need to be at 53% solids by weight, where the total water volume that mobilizes the tailings includes both pond and interstitial water. Assuming that the tailings were mobilized in sequential phases for simplification purposes, not all of these solids and interstitial water would have been discharged in Process I (the initial flood wave), but some additional tailings would have been discharged in Process II as the slopes steepened and the tailings slumped following the erosive removal of the dam. The difference between the calculated volumes using the Fontaine&Martin (2015) method and the actual reported volumes may have been due to Process II in which tailings slumping occurred. These tailings were also transported through the breach, but then likely deposited closer to the dam due to a low water content.

Determining the tailings outflow volume for Case 2A requires further research. It is recommended that the professionals conducting the TDBA apply judgement on the lateral extent of the breach, and assume the width of the breach based on that. A conservative assumption may be made that the breach extends to the foundation of the dam; however, professional judgement needs to be utilized here too, and a final decision made based on the assumed tailings trigger, the dam construction method, the height of the dam, or the depth of the tailings that would have a potential to liquefy and flow (e.g., consideration if the tailings below a certain depth would be flowable considering consolidation and lower moisture content). From the assumed breach geometry, a tailings release cone (or a cone of depression) could be established by projecting the anticipated post liquefied residual shear strength angles upward from the base of the breach. The outflow volume would then be estimated based on the volume of tailings contained in the cone.

For Case 2B the same approach as described for Case 2A could be used, but the slope angles of the cone of depression would be steeper (e.g., 24° or 45% for wet sand). Alternatively, the dam failure analysis could be conducted as a slope failure analysis, which is not discussed in detail in the draft TDBA Bulletin.

2.6.2 *Breach parameters*

Dam breach parameters define the initial and final shapes of the breach, the breach development time (or time to fail), and how the breach develops over time (e.g., linear or nonlinear breach growth over time). The initial and final shapes of the breach are a function of the material and type of construction of the tailings dam (e.g., upstream, downstream, centerline, rockfill, etc.), the dam height, the runout volume, as well as the failure mechanism (e.g., overtopping, slope failure, foundation failure, internal erosion, or piping; noting that typical dam breach software can only simulate piping and overtopping type failures).

Similar to water retaining dams, the breach parameters define the peak flow and the shape of the breach outflow hydrograph that is routed downstream. Consequently, breach parameters have a significant effect on the resulting wave speed and the extent of inundation, particularly in areas closer to the dam. Most of the research related to the breach formation is based on past failures of water retaining dams. There are no comprehensive and reliable models available that can simulate the formation of a breach of a tailings dam. Rico et al. (2008) provided empirical relationships for the volume of tailings runout, but not for breach parameters that are specific to tailings dams. Engineered embankments of tailings dams are significantly different from water dams, which can either result in a faster breach if the embankment extends over top of liquefiable and flowable tailings (i.e., upstream construction method), or in a slower breach due to the presence of an extensive tailings beach upstream of the dam, or the presence of a more erosion resistant rockfill shell on the downstream side of the dam.

Table 3 provides the general range of breach parameters based on previous research and case studies of water retaining dam failures. Additional empirical equations for estimating the breach parameters are provided in Wahl 1998, Wahl 2014, and other literature. A sensitivity analysis on breach parameters is highly recommended, where the range of selected breach parameters should be carefully determined. Ranges of breach parameters for water dams shown in Table 3 were developed for relatively small dams in comparison to some of the modern tailings dams that may reach well over 100 m in height.

As shown in Table 3, breach development time for water retaining dams may vary between 0.1 to 4 hours (USACE 2007). This could be unrealistic and not fast enough for tailings dams, particularly if the dam was built using an upstream construction method, as was recently demonstrated in the videos of the Feijão dam failure that occurred in January 2019 near Brumadinho, Brazil. Furthermore, a one hour breach development time (as proposed in FERC 1993) for a 50 m high dam would indicate a dam down-cutting/erosion rate of 50 m/h, while for a 200 m high dam with the same one hour development time, the erosion rate would be four times higher, or 200 m/hr. This may not be realistic for well-engineered large tailings dams constructed using a downstream or centerline method with shallow slopes and developed tailings beaches. In such cases a more realistic development time based on possible dam erosion rate and well documented case studies of similar tailings dams would need to be considered. Walder&O'Connor (1997) reviewed the mean erosion rate for past water retaining dam failures and showed that the erosion rates were typically slower than 100 m/h.

Table 3. Typical breach parameters for water retaining dams

Parameters	Engineered embankments	Non-engineered embankments
Breach average width	1 to 5 times the height of the dam – FERC 1993 0.5 to 5 the times height of the dam – USACE 2007	0.8 times the crest length – FERC 1993
Side slope	0.25 to 1 – FERC 1993 0 to 1 – USACE 2007	1 to 2 – FERC 1993
Bottom elevation	Ground level	Ground level
Breach formation time	0.1 to 1 hour – FERC 1993 0.1 to 4 hours – USACE 2007	0.1 to 0.5 hour – FERC 1993

2.6.3 *Peak discharge, breach outflow hydrograph and sensitivity range*

This part of the TDBA does not differ substantially from the analysis of breaches of water retaining dams. The peak discharge and the breach outflow hydrograph play an important role in mapping the inundated areas and determining the downstream impacts. The magnitude of the peak and the shape of the outflow hydrograph depend on the runout volume, the breach size and shape, and the breach formation time.

Breach models can simulate the erosion of the embankment and estimate the flow through the developing breach using orifice and weir equations, or momentum and continuity equations to compute the outflow hydrograph (e.g. Fread 1988). The outflow hydrograph is created based on the breach parameters (width, side slopes, and development time), and the magnitude of the peak flow. As part of the sensitivity analysis, a range of possible breach parameters (e.g., breach width, side slopes, and breach formation time) should be tested to establish the impact these parameters may have on the final results.

2.7 *Runout analysis*

The two breaching processes described in Section 2.4.1 are not independent and do not necessarily occur in sequence; however, different modelling tools may need to be utilized to simulate each process more adequately, and a phased approach may need to be adopted for the analysis. For modelling purposes, these processes could be referred to as Phase I and Phase II. For typical TSFs with supernatant fluids and tailings (Cases 1A and Case 1B), both hydrodynamic modelling tools that can model flow of water and/or fluid tailings, and geo-mechanical modelling tools that capture the flow of solid to semi-solid tailings may be required to model the runout. Conversely, for TSFs with no impoundment of supernatant fluids, or TSFs with large beaches and surface ponds situated far from the dam (Case 2A and Case 2B), the failure runout could be analyzed using geo-mechanical modelling tools only, or using hydrodynamic modelling tools for Case 2A failures.

The initial flood wave that develops during Process I of the tailings dam breach could be modelled as Phase I using hydrodynamic modelling tools to establish the flood wave propagation and attenuation. The inundation extents, peak flow magnitudes and arrival times, depths and velocities, or depth-velocity products indicating flood severity can be determined from this analysis at different downstream locations of interest. The models typically extend as far downstream as there are identifiable differences compared to the concurrent natural flows. Modelling is conducted for failure scenarios with and without a dam breach, to establish a basis for quantifying incremental consequences.

Phase II is modelled to establish the extent and depth of tailings deposition that develops during Process II of the tailings dam breach, where the geotechnical and rheological properties of the tailings mass need to be considered. This is further discussed in the next section.

The type of hydrodynamic model to be used for Case 1A, Case 1B, and Case 2A primarily depends on the input information available and the type of terrain downstream of the dam. One-dimensional (1D) models should be limited to areas with well-defined lateral confines, while two-dimensional (2D) models should be used for flat topography and for densely populated areas. Flows can be modelled as Newtonian for solids contents below 40-50% by weight (20-30% by volume), which may represent a reasonable starting point for certain cases. This approach may be applied for Cases 1A and 1B for modelling the propagation of the initial flood wave; however, the modelling tool would need to change in the Phase II of the breaching process as the solids concentration increases. A non-Newtonian model needs to be used for higher solids contents (e.g., Case 2A, or Case 1A when modelling the entire event as one phase). When compared to a Newtonian flood routing analysis, a non-Newtonian analysis will likely compute a slower initial flood wave arrival time and different inundation extents (i.e., width, length, and maximum depth of inundation). Common to all dam breach assessments, the flood wave from a tailings dam breach needs to be routed downstream to the point where the incremental effects of a failure no longer represent a threat to life, or to properties and the environment. A cascading failure may need to be evaluated if there are other dams located downstream.

Computational models used in state-of-practice tailings dam breach analysis are continually evolving. Depending on the type of flow and solids content, some of the modelling tools that can be used for runout assessment include:

- Case 1A and 1B: 0 to 30% solids by volume (water floods and some mud floods) – HEC-RAS 1D and 2D, Telemac-Mascaret, MIKE 11/21
- Case 1A, 1B, 2A: 0 to 55% solids by volume (water floods, mud floods, mudflows) – FLO-2D, FLD-WAV
- Case 2A and 2B: 45% to over 70% solids by volume (mudflows, landslides, debris flows) – DAN-3D, MADFlow-3D (neither available commercially yet)
- Case 1A, 1B, 2A and 2B: 0 to over 60% solids by volume (all flow types) – FLOW-3D

2.8 *Deposition analysis*

To predict the tailings deposition resulting from Process II (sometimes modelled as Phase II) of the TDBA, a number of methods are available such as Lucia et al. (1981), Jeyapalan et al. (1983), McDougall&Hungr (2004), McDougall (2006), Chen&Lee (2002), Chen&Becker (2014), or Wang et al. (2010). Some of these methods were originally established for runout assessment of debris flows, landslides, and flow slides; however, they can be advanced to model tailings runout due to a dam breach. Rheological models and associated parameters are required as inputs for these models to simulate non-Newtonian behavior of the mobilized tailings.

The tailings runout volume and distance may increase due to a steep topography. If the terrain downstream of the dam is at an angle that is steeper than the post liquefaction residual shear strength angle (i.e., >4°, or 7%, as discussed in Section 2.4.1), then the runout distance could be extensive. Numerical models based on continuum mechanics are suitable for this kind of tailings runout assessment. Models that incorporate the failure mechanism, the tailings properties, the complicated 3D terrain, and the entrainment of material in the flow path should be considered (e.g., FLOW-3D, MADFlow-3D, and DAN-3D).

In cases when the topography downstream of the dam is at an angle that is flatter than the post liquefaction residual shear strength, the runout could be estimated using simplified tailings deposition models. The rheological parameters can be determined via laboratory testing, field testing, or empirical analog data. Reasonable assumptions and subjective judgement can be made to estimate the rheological properties from historical rheological studies. The key parameters for a simplified tailings deposition analysis include the undrained shear strength, or the equivalent angle of the internal friction angle of the tailings, the released volume, and the deposition angles. The undrained shear strength of liquefied tailings can be back-calculated from tailings flows, while the released volume can be estimated from slope stability analysis. The deposition angle can be estimated based on the tailings beach angle, or based on the expected undrained liquefied strength of the consolidated tailings. The deposition extent could be mapped based on tailings outflow volume using 3D volumetric modelling tools.

2.9 *Sensitivity analysis*

Various uncertainties are inherent in every step of TDBA, and consequently, sensitivity analysis must be undertaken to account for some of these uncertainties and to evaluate the impact on the results as discussed above. The sensitivity of the results should be evaluated with respect to the factors that have the largest impact on the downstream runout analysis (e.g., inundation and tailings deposition extents). Some of the factors that have the largest impact on the results are: the total breach outflow volume including the volume of mobilized tailings, the breach parameters (i.e., the breach geometry and development time), the peak discharge, the shape of the breach outflow hydrograph, the rheological properties of the breach outflow, the type of the flood wave routing analysis, and the roughness parameter (e.g., Manning's n) used to represent the resistance to flow.

The sensitivity of most of these factors has been discussed throughout this paper. Additional comments are made here in terms of rheology, because the rheology of the mobilized tailings are often not known. As part of the sensitivity analysis, the rheological properties of the tailings material should be varied over the typical reported range, because the yield stress and viscosity of the material in the breach outflow affect the downstream flow velocity and depth. Additional consideration should be given to the source of the tailings material (Small et al. 2017), as tailings from hard rock mines (e.g., copper, lead, zinc, molybdenum, gold, silver, nickel or uranium) may behave quite differently than tailings from soft rock mines (e.g., potash or coal). For example, tailings from hard rock mines with a relatively low solids entrainment level may have a low yield stress and behave like Newtonian fluids (e.g., up to about 40-50% solids concentration by weight, or 20-30% solids by volume). Higher solids concentrations and/or tailings from soft rock mines are not likely to behave as Newtonian fluids and the assessment/modelling should be conducted assuming non-Newtonian flow properties.

2.10 *Inundation and deposition mapping*

Inundation and deposition maps should be prepared for selected scenarios to achieve the study objectives. The resolution and accuracy depends on the available input information and flooded area at risk, as well as the purpose of the study (e.g., emergency preparedness planning vs. dam consequence classification). The information provided on inundation maps should be consistent with the intended use(s) of the maps and meet applicable dam safety and environmental regulations.

Basic information should include all the information that would be included for water retaining dams: flood inundation extents; flood front and peak flow arrival times; peak flow depths and velocities; ground surface elevation contours; background orthophoto or satellite images; locations of key landmarks and critical infrastructure/facilities (e.g., roads, bridges, hospitals, firefighting stations, etc.). Separate maps could be included showing the depth-velocity (DV) product that indicates the flood severity, if the flood wave passes through populated areas and population at risk and loss of life needs to be estimated.

Additional information specific to tailings dam breaches could be presented on separate maps and may include: tailings solids deposition extents and depths; types and concentrations of contaminants within the mapped inundation limits; and potential for tailings and/or contaminants to be transported outside of the mapped inundation extents.

2.11 *Documentation and reporting*

A systematic approach should be undertaken as agreed between the dam owner and the dam breach professional to document the TDBA that is in line with the objectives of the assessment. The report should include information related to the breach analyses methodology, inputs and results, including key assumptions, approximations, uncertainties, sensitivities tested, and applicable limitations. The typical outcomes of TDBA are inundation and deposition maps that could be prepared for different end users and used for dam breach consequence assessment.

3 CONCLUSIONS

The Working Group of the CDA's MDC is nearing completion of a Technical Bulletin specific to tailings dam breaches. The manuscript is intended to provide dam safety professionals with guidance on the general process and scope of these types of analyses. Reliable TDBA are critical for tailings dam design and safety management as they help identify and characterize threats to public safety and the environment. In this paper, the major differences between breaches of tailings dams and water retaining dams were discussed and the key steps for conducting TDBA were presented. The presence of a supernatant pond and the potential of the tailings mass to liquefy and flow, are considered to be the key parameters influencing the runout potential and the outflow volume. The physical processes occurring during a TDBA were discussed, including estimating the volume of released tailings materials during a breach.

The results of the TDBA can be used for various purposes including dam consequence classification, emergency planning, dam safety management, failure mitigation planning, and closure planning.

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