Challenges with conducting tailings dam breach assessments

Violeta Martin[a], Anna Akkerman[b]

Power and Water Resources, Knight Piésold Ltd., Vancouver, BC, Canada

[a]vmartin@knightpiesold.com
[b]aakkerman@knightpiesold.com

ABSTRACT

Following the recent tailings dam breaches at Mount Polley, Canada, and Samarco, Brazil, the mining industry and regulatory agencies worldwide increased the demand for tailings dam breach analyses and flood inundation mapping. The results of such studies are used to determine the hazard classification of a dam through the assessment of dam failure consequences, to support emergency preparedness and response planning, and to inform environmental assessments. Dam breach studies involve the selection of a dam failure mode and appropriate hydrologic conditions, the approximation of the breach size, the estimation of the volumes of released tailings and water, and the modelling and mapping of the runout pattern of released materials. There is considerable uncertainty in each step of the analysis, which combined with the lack of a standardized approach for completing such studies, necessitates that practitioners rely on experience and sound professional judgement to conduct the studies and assess the results. In this paper, we review some of our recent experiences with tailings dam breach assessments and discuss challenges encountered and lessons learned for various case studies, including selecting credible failure modes, selecting appropriate hydrologic parameters, determining the range of possible breach parameters, and estimating the volumes of released tailings.

1. INTRODUCTION

Tailings dam breach assessments are commonly expected and required for operating and planned Tailings Storage Facilities (TSFs). These studies are primarily used to determine the hazard classification for a dam, for the preparation of emergency preparedness and response plans, and sometimes for environmental impact assessments and alternatives assessments for newly proposed or expanding facilities. Various dam breach guidelines are available to help direct such studies, but they were originally developed for water retaining dams and are not specific to, nor fully applicable for tailings dams (e.g. FEMA 2013, CDA 2007a, CDA 2007b, ICOLD 1998). The Technical Bulletin *Application of Dam Safety Guidelines to Mining Dams* issued by the Canadian Dam Association (CDA 2014) would appear to address this situation, but rather than prescribing procedures for conducting tailings dam breach analyses, it is limited to identifying "some specific issues that should be considered during the design and safety evaluation of mining dams." The CDA subsequently formed a working group for developing guidelines specific to tailings dam breach assessments, and the first draft is expected in the fall of 2017. In the interim, practitioners must largely rely on their own initiative, judgment and experience to frame a TSF dam breach assessment, although useful information is available in a few recent conference proceedings, such as those by Martin et al. (2015) and Strauss et al. (2016).

The key differences between a water retaining dam failure and a tailings dam failure are the volume of outflow and the solids contained in that volume. A breach of a water dam typically results in the discharge of the entire impounded volume of water above the breach, and the outflow has a relatively low solids content, which originates from the embankment material and the mobilization of settled sediments from the reservoir. A breach of a tailings dam, in contrast, often results in the discharge of the entire supernatant pond volume, but does not consistently result in the full discharge of the impounded tailings volume. The outflow, however, typically has a high solids content due to the mobilization of stored tailings solids.

A dam breach of a TSF that stores a sizeable supernatant pond typically results in two discharge mechanisms: (1) initial flood wave, and (2) tailings slumping and/or flow of liquefied tailings. These mechanisms occur in sequence following a catastrophic failure of a TSF dam for all cases where there is a supernatant pond present, and are distinctly different in terms of the potential risk they pose to the downstream environment. The initial flood wave is caused by the discharge of the supernatant pond, which erodes and mobilizes the stored tailings solids and embankment construction materials. The flood wave typically propagates far downstream causing extensive erosion and large inundation. Following the initial flood wave, additional mobilization/slumping of tailings material occurs due to the loss of confinement and local steepening of slopes created by the initial discharge. The flow of slumped tailings has a much lower water content than the initial flood wave, and though it can have extensive deposition in areas immediately downstream of the facility, it typically results in a considerably smaller inundation footprint farther downstream. For cases where the entire tailings mass has a potential to undergo liquefaction, discharge of even larger tailings volumes could be expected, which could result in a substantially larger tailings inundation footprint.

This paper discusses specific challenges encountered while conducting tailings dam breach assessments for several case studies. These challenges included insufficient topographic information, uncertainty in the selection of adequate hydrologic conditions, selection of credible failure modes or appropriate breach parameters, and the selection of downstream boundaries of hydrodynamic models. Some of the case studies presented are in the public domain, while others are discussed in more general terms due to confidentiality agreements with our clients.

2. BREACH PARAMETERS

The quantitative assessment of potential consequences caused by the initial flood wave from a breach of a tailings facility requires estimates of the volumes of water and tailings released during the breach. The total volume of the breach outflow is a key piece of information used to estimate the peak discharge, the physical characteristics of the breach (width and side slopes) and the time of failure (an estimate of how quickly the breach would develop). These characteristics are used to develop a dam breach hydrograph, which is subsequently routed through the downstream drainage network to estimate the inundation limits of the flood.

The volume of the breach outflow includes the volume of tailings that would mobilize due to the discharge of supernatant pond from the breached TSF. The volume of mobilized tailings can be estimated assuming full mixing of water with tailings solids, as discussed in Fontaine and Martin (2015). This approach is based on the potential of the available free water in the TSF to entrain and mix with tailings solids, while considering the physical characteristics of the deposited material (total mass of deposited solids, density of the tailings mass, degree of saturation, and average dry density). If the volume of stored tailings is small relative to the volume of water in the facility, this approach tends to result in estimates of all tailings solids being mobilized, and in turn, if the volume of stored tailings is large relative to the volume of water, it results in estimates of small volumes of tailings solids being mobilized. An alternative and commonly applied approach is to use an empirical relationship developed by Rico et al. (2007), which predicts that approximately 37% of the impounded volume comprised of tailings solids, supernatant water and interstitial water, constitutes the breach outflow volume. This approach may at times result in unrealistic estimates, particularly in cases where the volume of water in the TSF is small relative to the volume of stored tailings, or when liquifaction is a known risk. It should be noted that the above two approaches do not explicitly consider the tailings mass rheology (viscosity and yield stress), which would play a significant role in the case when liquefied tailings behave like a Bingham plastic fluid (Jeyapalan et al. 1983; Seddon 2010; Kulesza 2011).

The other breach parameters are similarly challenging to define. There are no industry standards for tailings dams, and the typically referenced equations are in most cases empirical and largely based on past failures of water retaining dams less than 30 m high, and as such they are not particularly applicable to large tailings dams. The selected parameters, however, have a considerable impact on the final results. Several equations should therefore be considered to determine a possible range of values for various breach parameters, especially considering that various breaching software packages, in our experience, often produce values closer to the low end of the range that may not be sufficiently conservative for dam safety purposes. A number of commonly used equations that are used to determine the range of peak flows, breach widths, side slopes and times of failure have been summarized by Wahl (1998): Johnson and Illes (1976), Singh and Snorrason (1982, 1984), MacDonald and Langridge-Monopolis (1984), Costa (1985), Bureau of Reclamation (1988), Von Thun and Gillette (1990), FERC (1993), and Froehlich (1995a, 1995b). Other common approaches are found in Rico et al. (2007), Froehlich (2008), and Pierce et al. (2010). Most of these empirical equations are based on dam height and estimated outflow volume. Further discussion on methods for predicting the breach parameters, the range of values obtained, and the physical constraints that should be considered is provided in Martin et al. (2015).

3. CASE STUDIES

Our recent experience with various tailings dam breach assessments indicates that a high level of professional judgement and experience is required in order to make reasonable assumptions and overcome the uncertainties that are encountered in every step of the process. Three case studies are presented and specific challenges are discussed, including the selection of appropriate hydrologic parameters, selection of credible failure modes, determination of study extents, estimation of volumes of released tailings, and determination of the possible range of breach parameters. All these considerations have substantial impacts on the results and study outcomes.

3.1 Afton TSF Dam Breach Assessment

3.1.1 Project Description

The Afton TSF is located 12 km west of the City of Kamloops, BC, Canada. The facility was designed in accordance with the Extreme dam hazard classification to withstand the Maximum Credible Earthquake (MCE) and pass the Probable Maximum Flood (PMF). It was constructed in 1976-1977 and has been under care and maintenance since mining operations ceased in 1997. Production at the Afton Mine began in 1977 and the embankments were progressively raised throughout the operating period. Additional information about the project can be found in Akkerman and Martin (2015) and Adams et al. (2017).

The Afton TSF incorporates two two-zoned earthfill/rockfill dams with engineered filter zones, riprap lined spillway, two seepage collection ponds, and upstream diversion structures sized for a 1 in 200 year peak flow event (Figure 1). The Afton Mine ceased operations before reaching the full mine life and the dams were never raised to their ultimate design height; however, the dams were constructed to their

ultimate design width. Consequently, the East and West Dams were overbuilt for conditions when operations ceased, and the crests of the dams were left at approximately 100 m wide. A portion of the East Dam was buttressed by a waste rock dump that is higher than the East Dam itself, while the West Dam was constructed with relatively shallow downstream slopes (shallower than 2H:1V). The spillway is designed to pass the PMF and has an invert constructed 2 m below the crest of the East Dam. The spillway consists of a 50 m wide riprap lined channel (Figure 2) that transitions to an unlined earth channel, which curves along the toe of the East Dam and leads to a haul road located along the perimeter of the Historic Afton Open Pit. The sand tailings beaches have been capped and revegetated, and the TSF pond is mostly dry (Figures 1 and 3).

Figure 1. General arrangement of the Afton TSF

Figure 2. Riprap lined spillway entrance with reclaimed tailings beach in the foreground and waste rock dump on the right side of the frame; looking downstream (northeast)

The climate in the project area is typical of the dry BC Interior Region, with generally low total precipitation and high evaporation, and correspondingly low streamflow rates. Located in the rain shadow of the Coast Mountains, this area has a semi-arid steppe climate characterized by generally cool, dry winters and hot, dry summers, with low humidity. Temperature and precipitation records for the mine area indicate mean annual temperature and precipitation values of 7.3°C and 305 mm, respectively, while the annual potential evapotranspiration (PET) was estimated using the Thornthwaite equation at approximately 565 mm.

Figure 3. TSF pond on July 9, 2013; looking northeast

3.1.2   Challenges with Defining Credible Failure Modes

A tailings dam breach study was completed in 2014 according to the Canadian Dam Association (CDA) "Dam Safety Guidelines" (CDA 2007a), which specify that "To assess the potential consequences [of a dam breach], the potential failure modes for the dam and the initial condition downstream from the dam should be determined…". Defining credible modes of failure for the Afton TSF proved to be rather challenging; it was hard to envision the possibility of any substantial dam failure given the dryness of the local climate, the large capacity of the spillway, the robustness of the embankment design, and the current embankment condition. The challenges were specifically related to selecting the breach locations and the initial pond water levels for plausible failure scenarios.

Breaching through the deepest dam section represents a common conservative modelling approach, as it results in the largest outflow volume and the highest peak discharge. The highest dam section is the West Dam at its north end, which is 75 m high; however, because a large area along this end of the West Dam has a reclaimed tailings beach developed to the crest of the dam, a pond cannot form adjacent to the dam. Accordingly, a potential failure through this deepest section would likely result in a deformation of the dam crest and possible slumping of tailings, but would not result in the largest possible flood wave and associated downstream inundation that could potentially result from the discharge of free water.

The West Dam at the south end is 30 m high through the deepest section, and has a tailings beach developed to approximately 6 m below the dam crest. A pond may develop adjacent to the dam in this area, and consequently, a catastrophic failure in this location is credible and could result in the discharge of stored water. However, the outflow volume and the peak outflow discharge would be considerably less for a 30 m high dam compared to a 75 m high dam. On the opposite side of the Afton TSF, the south end of the East Dam is buttressed by a waste rock dump that is higher than the dam itself, and the north end has a reclaimed tailings beach developed to the crest of the dam, so these are not realistically probable breach locations. The only credible location for a potential breach of the East Dam is through the unlined portion of the earth spillway, however, consideration of this is contrary to the common practice of disregarding the spillway as a potential breach location.

Setting the initial pond volume proved to be equally challenging to selecting the breach location. The actual annual variation of the water level in this facility is not known since water levels have not been continuously monitored during the care and maintenance period. However, it is anticipated that the water level in the TSF remains several metres below the spillway invert at all times for the following reasons: (a) this is a non-operating facility and there is no requirement for water storage; (b) the natural inflow from the majority of the upstream catchment is diverted around the facility; and (c) the historic climatic conditions indicate that the annual evaporation is higher than the annual precipitation, leaving the facility in a natural deficit condition.

The maximum normal operating water level is typically used for a sunny day dam breach assessment. The Afton TSF is in care and maintenance, and hence, such a condition does not apply. Based on LiDAR surveys, the maximum water storage volume available from the tailings surface to the spillway invert is estimated at 3.3 Mm^3 (million cubic meters); however, the observed pond volume is much smaller and on the order of 0.2 Mm^3. Given this small volume of water and the relatively large embankments with shallow slopes and 100 m wide crests, sufficient erosion and material mobilization to scour the

embankments all the way down to the existing ground elevation is not likely to occur in a realistic sunny day dam breach scenario. Rather, it is more reasonable to expect that the amount of released tailings volume would be reduced compared to a breach eroding through the full height of the embankment, resulting in substantially less downstream inundation. In fact, with only a small pond volume present in the Afton TSF, it is likely that a sunny day failure would only result in an embankment deformation followed by localized slumping of tailings, with essentially no downstream inundation.

In a flood induced dam breach scenario, and if prior to the onset of a PMF the initial water level was set at the maximum observed level, the peak water level in the facility during the PMF event would be 0.8 m below the dam crest, assuming a functioning spillway. In the case where the initial water level is assumed to be at the invert of the spillway, the facility would still retain 0.4 m of freeboard during the PMF. Overtopping of either the East or West Dams would require that the 50 m wide, 2 m deep spillway is fully or partially blocked, which is unlikely for the current conditions of this facility considering the large size of the spillway, the sparse ground cover in the drainage basin, and the active nature of the neighbouring mine site that results in opportunities to observe and correct any potential blockage. As such, it is difficult to conclude that arbitrarily increasing the volume of water stored in the facility and/or blocking the spillway to force overtopping during a flood event represents a credible failure scenario.

3.1.3   Results of the Conducted Dam Breach Assessment

Despite the above discussion on credible failure modes and considering the current state of practice of dam breach and inundation studies for mining dams, the authors of the Afton TSF dam breach study found themselves having to proceed with conservative but unrealistic assumptions, which required ignoring the realities of very dry climate conditions and current low pond water levels. In the sunny day failure scenarios, the pond water level was assumed to be at the spillway invert, since the true variation of the pond level was unknown and this represented the most conservative assumption. The observed small pond and the dry climate, however, make the occurrence of a large flood wave in a sunny day breach quite improbable. In the flood induced failure scenarios, the starting pond water level was also assumed at the spillway invert, and the West and East Dams were assumed to breach when the pond was at its maximum level during the PMF flood.

Setting the initial water level at the spillway invert for both the sunny day and flood induced scenarios resulted in modelling a release of an excessive volume of water (approximately 3 Mm^3 above current volume). This additional volume of water resulted in larger outflow volumes, greater peak discharges, and higher downstream inundation levels than would have been predicted with a smaller and more realistic pond volume. The modelled failure of the West Dam for sunny day and flood induced scenarios resulted in large inundation areas from the dam to Kamloops Lake, located 12 km downstream, and flooding of a mobile home park and numerous farmlands and associated human dwellings.

In summary, a flood induced scenario would not cause overtopping, but would likely result in discharge through the large spillway in the East Dam with flows directed into the Historic Afton Open Pit located a short distance downstream, while the areas downstream of the West Dam would not be impacted. For a sunny day scenario, foundation or embankment slope failures are not probable due to buttressing and shallow dam slopes. Internal erosion and piping are unlikely considering the dry facility, while a catastrophic earthquake would not results in significant dam crest deformation thus discharge of tailings is also unlikely, but if it occurred the impacts downstream would be limited due to the lack of water in the facility.

3.2   Dam Breach Assessment for a Proposed Project

3.2.1   Project Description

A dam breach assessment was undertaken for a proposed project in Northern Canada to aid in determining the hazard classification of the dam and support the environmental impact assessment of the project. The proposed project is a hard rock mine with a high throughput and a mine life of over 20 years. The proposed TSF is a large facility designed to store tailings, waste rock, and potentially acid generating (PAG) material, which requires subaqueous deposition. The normal operating pond volume is estimated to be substantial at approximately 20 Mm^3.

The TSF is located in a remote area, in the headwaters of a small creek in a V-shaped valley between the mountains. The outflow from the breached dam would flow down a small creek, which drains into another watercourse, followed by meandering and braided rivers ever increasing in size. There are no

lakes or reservoirs along these rivers, the first larger populated area is approximately 300 km away, and the ocean is over 2,200 km away.

3.2.2 Challenges with Flood Wave Routing

One of the challenges with this dam breach assessment was determining the downstream boundary of the one-dimensional model for flood wave routing. The initial downstream boundary set at 80 km from the dam proved to be insufficient, as the incremental water depth at this location was still between 2 and 3 m high, depending on the modelled scenario. This finding led to the need to extend the model for another 110 km to the confluence with another large river.

For much of the modelled river system, only coarse topographic data was available which made river channel definition challenging. 1 m and 5 m LiDAR contours were available for the first 20 km downstream of the dam, but only 30 m contours were available from NTS (National Topographic System) mapping for the remaining area. Combining the two types of data resulted in two issues. The first was that the contours did not align well. The second was that the crude 30 m contours did not define the topography of the large braided river valleys well and the GIS software was not able to interpolate between the river contours correctly (Figure 4a, b). Good river valley definition was needed for "cutting" the cross-sections for the flood routing model that were set 250 m apart. Conducting field surveys to validate such a large number of cross-sections along the 190 km modelling reach was not practical for this level of assessment. These issues required considerable time for computer manipulation in order to adequately define the cross-sections of river channels and adjacent floodplains along the wide U-shaped river valleys.
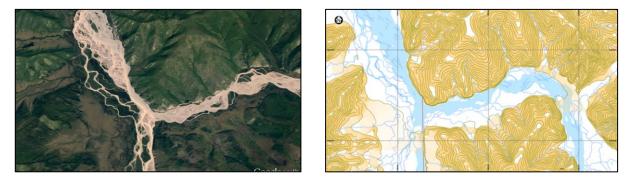

Figure 4. Confluence of two rivers: (a) Google Earth image; (b) 30 m contours for the same area

3.2.3 Results of the Dam Breach Assessment

For the sunny day scenario, the modelled front of the flood wave arrived to the first downstream confluence 11 km downstream of the dam in 0.7 hours following the breach, with an incremental increase in flow depth of 10 m. The flood wave arrived to the end of the model 190 km downstream, approximately 32 hours after the breach occurred, with an incremental flow depth of less than 1 m. The peak of the breach flood wave was estimated to be approximately equal to the mean annual flood at this location. Given that river channels can typically contain the mean annual flood within their banks, the sunny day breach flood wave was assumed to be contained within the natural river channel at this location.

For the flood induced scenario, it was assumed that the PMF event centered over the mine site was coincident with a 200 year flood in the larger rivers in the downstream drainage network. The modelled front of the flood wave arrived downstream at the first confluence point in 0.8 hours following the breach, with an incremental increase in flow depth of 13 m. The flood wave arrived at the end of the model approximately 18 hours after the breach, with an incremental flow depth above the 200 year flood level of about 1 m.

The results of the study indicate that a flood wave caused by a major dam breach of this TSF storing a large amount of tailings and water would be considerable and would propagate tens or hundreds of kilometres downstream, likely causing extensive erosion and floodplain deposition along the way. Considering the 30 m contour spacing and the assumed shape of river channels and their adjacent floodplains in the model, there is considerable uncertainty associated with the accuracy of the inundation mapping and the estimates of flow depths. The inundation results need to be viewed critically when trying to assess impacts to fisheries and wildlife, and may not be adequate for highly detailed

quantification of such impacts. Any assessment of environmental impacts based on these results should be completed at a comparable level of effort and detail. However, the results of this study are considered useful as they prompted further discussion related to the design and size of the TSF, the placement of waste rock within the facility, the separation and placement of PAG tailings, as well as the amount of water stored in the facility.

3.3   Dam Breach Assessment for an Operating Mine

3.3.1   Project Description

A preliminary dam breach model and inundation assessment were conducted for an existing mine in the USA that is located upstream of a densely populated area. The TSF is a facility with large volumes of stored tailings and water, and with embankments that were raised over several decades. The tailings beach in the TSF is up to 2 km long and the supernatant pond is positioned far away from the embankments except in one corner of the facility. The open pit is located downstream of the TSF, and it is anticipated that in case of a dam breach the outflow would primarily discharge into the open pit. In order to assess the flood wave pathways, map the inundation limits, and determine whether the flood wave would potentially bypass the open pit and travel beyond the mine property, a two-dimensional hydrodynamic model was developed for the mine site. A risk assessment conducted for the facility indicated that a sunny day piping scenario represents a credible failure mode and the most likely dam breach scenario for the current condition of the TSF. This scenario was the only scenario modelled during the preliminary dam breach assessment.

3.3.2   Challenges with Defining Dam Breach Parameters

As discussed in Section 2, breach parameters are challenging to define, with peak flows being particularly important considering the impacts they have on the final results. In this study, the outflow volume in the initial flood wave was determined using the approach outlined by Fontaine and Martin (2015), and a range of mixed tailings solids of 25-65% by weight was used to determine a range of potential outflow volumes. This range represents sediment laden flows with solids contents observed in water floods, mud floods, and hyperconcentrated flows (e.g. Pierson and Costa 1984, O'Brien 1986, Gusman 2011). Figure 5 illustrates the calculated range of outflow volumes for saturated beach conditions, a range of observed historic pond volumes from 18.5 Mm^3 - 37.0 Mm^3, and a range of 25-65% mixed solids by weight.

The maximum observed supernatant pond volume of 37 Mm^3 was used to determine the breach parameters in combination with 50% mixing of solids with free water, which resulted in a total outflow volume of 76.8 Mm^3. The range of values for peak discharge, average breach width, breach side slopes, and time to fail was then determined using various empirical equations, as discussed in Section 2. The results are shown in Table 1, with the lowest value shown in green and the highest value shown in red.
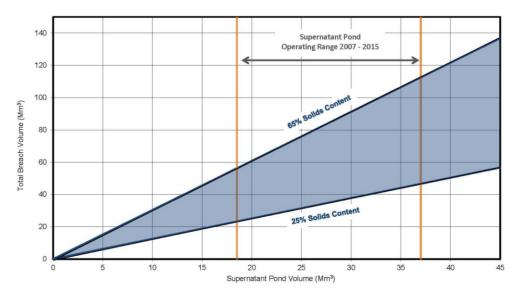

Figure 5. Relationship between supernatant pond volume and total breach outflow volume

Table 1. Breach parameters based on empirical relationships by various authors

Methodology	Peak Flow m³/s	Time to Fail hours	Average Width m	Side Slope Ratio H:1V
Johnson and Illes, 1976	-	-	4 - 251	-
Singh and Snorrason, 1982, 1984	-	0.25 - 1.0	168 - 419	-
Macdonald, 1984	12,296 - 40,110	2.59	73	0.50
Costa, 1985	9,735	-	-	-
Bureau of Reclamation, 1988	60,021	2.56	233	-
Von Thon and Gillette, 1990	-	1.17	249	0.33 - 1.0
FERC Guidelines, 1993	-	0.1 - 1.0	84 - 419	0.25 - 1.0
Froehlich, 1995	28,413	0.71	140	0.9 - 1.4
Rico et. al., 2007	12,523	-	-	-
Froehlich, 2008	-	0.59	108	0.7 – 1.0
Pierce et al., 2010	14,781 - 24,321	-	-	-
Mean	**26,076**	**1.26**	**184**	**0.76**

The main challenge during this assessment was the selection of the peak flow, as the model outcomes are very sensitive to this parameter. Without guidelines or strong research to suggest which empirical equation or breach modelling software better predicts dam breach peak flows, this significant decision is left up to the practitioner. Considering the large range of peak flows and other breach parameters (Table 1), three peak flows covering this range were selected to conduct flood routing modelling: 14,000 m³/s, 28,000 m³/s, and 48,000 m³/s. The breach width and time to fail were selected such that the outflow hydrographs would result in the selected peak flow value, while the breach side slopes were kept the same at 0.7 for all three scenarios. The selected failure mode was modelled as piping. The ultimate breach bottom width and time to fail ranged from 67 m and 2.5 hours for the low peak flow of 14,000 m³/s, to 187 m and 0.8 hours for the high peak flow of 48,000 m³/s.

3.3.3 Results of the Dam Breach Assessment

The flood routing results indicate that most or all (in case of the low peak flow scenario) of the breach outflows end up in the open pit, 3.3 km downstream of the breach location. The start of the flood wave reaches the open pit in 15 minutes for the high peak flow scenario, and a much longer 40 minutes for the low peak flow scenario due to its much flatter hydrograph. None of the outflow volume reaches the mine property, 5.5 km downstream, for the low peak flow scenario, and only 0.1% and 2.8% of the total outflow volume does for the medium and high scenarios, respectively. The mine property boundary is reached in approximately 25 minutes and 60 minutes for the medium and high scenarios, with respective maximum flow depths and velocities of 0.5 m and 0.75 m/s and 2.5 m and 2.25 m/s.

The results of this assessment indicate that the downstream inundation extent is very sensitive to the method selected for determining the peak flow, which in turn depends on the estimate of the volume of mobilized tailings solids and total outflow volume. Considering the uncertainty in selecting any of these values, this assessment demonstrates the importance of evaluating a range of equally possible scenarios. The downstream populated area would not experience any breach effects in the low peak discharge scenario and only minor impacts in the medium peak discharge scenario, but possible loss of life conditions in the high peak discharge scenario. The results of this study prompted discussions related to the volume of stored water in the TSF and emphasised the importance of storing as little water as practicable to limit possible outflow volumes in the case of a breach. Furthermore, the study

highlighted the value of using multipoint tailings discharge locations to develop extensive beaches across the full embankment perimeter, so as to ensure that supernatant water is as far from all points of the embankment as possible.

4.   DISCUSSION AND CONCLUSIONS

Dam breach and inundation studies are an important aspect of dam safety procedures, and all efforts should be made to produce conservative yet credible results for the protection of the public and the downstream environment. However, inundation results based on unrealistic modes of failure do not offer any real value to the owner, regulators, or the public, because they provide little insight into the actual risk posed by the facility. A major difficulty with dam breach assessments is due to the considerable uncertainty involved in each step of the analysis. This situation, combined with the lack of any standardized or mandated approach for completing such analyses, leads to the need for the practitioners to make assumptions and choices that may substantially impact the modelled results. Practitioners must rely on good professional judgement and experience when carrying out and interpreting their work. Furthermore, simply applying an empirical relationship can result in unrealistic or impossible results, and physical constraints need to be considered throughout the process (e.g. mixing too high of a solids content with free water may result in a non-flowable tailings mass). It is important that all dam breach modelling results be viewed in this context.

The major benefit of dam breach studies, no matter how improbable the results may be, is that they trigger discussions on various possible measures to reduce the risk of a breach. One possible measure includes reduction of pore water from the tailings mass, which can improve the rheological characteristics so that the stored tailings solids are non-flowable as described by Adams et al (2017). Another measure that seems to be frequently evaluated in the post Mount Polley and Samarco era is related to the size of the supernatant pond. The current trends are to reduce the supernatant pond size to the extent practicable, while considering the geochemical and climate constraints for each project, as it is recognized that large ponds can increase the risk of breaches and the extent of downstream impacts. For each of the presented case studies, it was the large volume of water in the TSF that exaggerated the downstream inundation extent. In the recent Mount Polley tailings dam breach incident, it has been acknowledged that the foundation failure of the dam would have resulted in a dam crest deformation and potentially some tailings slumping, but not in a catastrophic breach and release of the stored TSF content, which would not occur if the tailings beaches were adequately developed and the facility had less stored water (KCB 2015). It was the overtopping and discharge of supernatant pond in the deformed crest area that led to the downcutting of the embankment and the subsequent massive release of water and tailings solids. The reduction of stored water, along with sound construction and operational practices, followed by good closure and reclamation measures, all contribute to minimizing the potential risk that TSF embankments pose to society and the environment.

5.   ACKNOWLEDGEMENTS

The authors gratefully acknowledge the opportunity to conduct these tailings dam breach assessments and learn from these experiences. They wish to thank their clients and colleagues for their valuable advice and support during the actual dam breach assessments and preparation of this manuscript.

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