



TAILINGS AND MINE WASTE 2015



PROCEEDINGS OF TAILINGS AND MINE WASTE 2015 CONFERENCE



Assessing credible modes of failure: Afton TSF dam breach study

Anna Akkerman, P.Eng, Violeta Martin, P.Eng, Ph.D,
Knight Piésold Ltd., Vancouver, BC, Canada

ABSTRACT

The Afton Tailings Storage Facility is located in the semi-arid Interior Region of British Columbia and has been in care and maintenance since 1997, after approximately 20 years of operation. In response to the British Columbia Chief Mine Inspector's orders issued in August 2014, following a dam breach incident at the Mount Polley Mine, dam breach analysis and inundation studies for the Afton Tailings Storage Facility were conducted. Defining realistic and credible modes of failure that were consistent with the Canadian Dam Association Dam Safety Guidelines for conducting these studies proved challenging due to the hydrologic conditions and certain features of the Tailings Storage Facility dam design. The selection of initial hydrologic conditions and breach locations has a considerable effect on the predicted volume of tailings mobilized, the characteristics of the flood wave, and the extent of the downstream impact. Inundation results based on modes of failure that are not credible do not provide real value to the owner, regulators, or the public because they offer little insight into the actual risks posed by a facility. This paper examines the challenges in defining credible modes of failure used in dam breach and inundation studies for mining dams, and presents a case study based on the Afton Tailings Storage Facility.

1 INTRODUCTION

Dam breach analyses and inundation studies were conducted for the Afton Tailings Storage Facility (TSF) in response to orders from the British Columbia (BC) Chief Mine Inspector, which were issued in August 2014 for all HIGH, VERY HIGH and EXTREME classification tailings dams following a dam breach incident at the Mount Polley Mine. Knight Piésold (KP) completed the studies according to the Canadian Dam Association (CDA) "Dam Safety Guidelines" (2007a). These studies required the identification of credible modes of failure for the Afton TSF, which proved challenging because of the site hydrologic conditions and certain features of the Tailings Storage Facility dam design.

The Afton TSF dam breach evaluation was completed for two initial hydrologic conditions, known as sunny day and flood induced conditions, as recommended in CDA (2007a, 2007b).

- Sunny day failure – a sudden dam failure that occurs during normal operations, which may be caused by internal erosion, piping, earthquakes, mis-operation leading to overtopping, or another event.
- Flood induced or rainy day failure – a dam failure resulting from a natural flood of a magnitude that is greater than what the dam can safely pass.

The downstream inundation and the resulting impacts from an outflow flood wave were evaluated for both of these failure scenarios. The studies were done for the facility as it existed in early fall

2014. However, it should be noted that in late fall 2014 and early winter 2015 the pond in the Afton TSF was largely dewatered, which further reduced the likelihood of a catastrophic dam failure and associated downstream effects.

Dam breach and inundation studies are typically completed for Emergency Preparedness and Response Planning purposes. These studies are also used to determine the dam hazard classification based on the incremental consequences to downstream socio-economic and environmental values and loss of life. It is important that these studies be based only on credible modes of dam failure. Inundation results based on modes of failure that are not credible do not provide value to the owner, regulators or the public, since they offer little insight into the actual risks posed by a facility.

2 AFTON TAILINGS STORAGE FACILITY

2.1 Facility Location

The Afton TSF is located 12 km west of the City of Kamloops between Highway 5 and Highway 1, as shown on Figure 1.

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 (Demarchi 2011). A discontinued Environment Canada climate station (Kamloops Afton Mines) was located near the Afton TSF at an elevation of 700 masl. Temperature and precipitation records for this station for the period of 1977 to 1993 indicate mean annual temperature and precipitation values of 7.3°C and 305 mm, respectively (Environment Canada 2015). Evaporation records are not available for this site, but the annual potential evapotranspiration (PET) was estimated to be approximately 565 mm (KP 2013) using the Thornthwaite equation (Thornthwaite 1948).

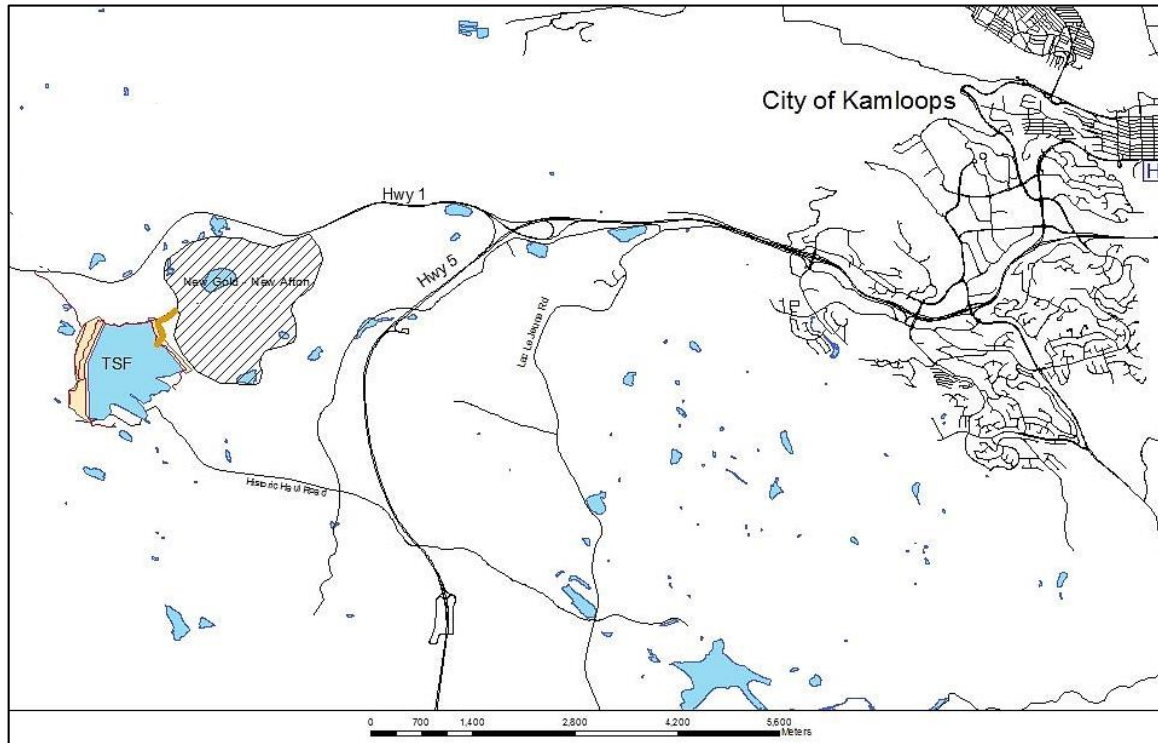


Figure 1: Afton TSF Location Map

2.2 Facility History

The Afton TSF was constructed in 1976 and 1977 by Teck Resources Ltd (Teck). Production at the Afton Mine began in 1977 and the TSF’s embankments were progressively raised throughout the operating period to store the increasing volume of tailings and water generated from milling the Afton, Ajax, Crescent, and Pothook ore reserves. An estimated 37 million tonnes of tailings solids were deposited into the TSF between 1977 and 1997.

The facility has been under care and maintenance since mining operations ceased in 1997. Ownership of the TSF was transferred to Abacus Mining Inc. upon Abacus Mining’s acquisition of the Ajax Project from Teck in 2002. KGHM subsequently acquired a controlling interest in the Ajax Project and the Afton TSF in 2011.

New Gold Inc. (New Gold) acquired the rights to the New Afton Copper-Gold Project from Teck in January 2007, and the New Afton Mine began commercial production in July 2012. The project area is located directly to the east of the existing Afton TSF and consists of process plant facilities, a new TSF (shown as New Afton TSF on Figure 2), and an underground mining operation. The New Afton Mine has a projected mine life of 12 years (New Gold 2012).

2.3 Facility Overview

The general arrangement of the Afton TSF is shown on Figure 2. The Afton TSF consists of the following major components:

- Two zoned earthfill/rockfill dams with engineered filter zones. The two dams are referred to as the East Dam and the West Dam. The East Dam is classified as HIGH hazard and the West Dam as EXTREME (KP 2014a). The West Dam is further divided into the north section and the south section.
- The tailings solids and the surface water pond.
- The spillway channel, which is located near the north end of the East Dam.
- Two seepage collection ponds located downstream of the West Dam that are referred to as the Northwest Seepage Pond and the Southwest Seepage Pond.
- Diversion structures located at the south side of the TSF that divert Alkali Creek around the TSF to Cherry Creek. The diversion scheme is comprised of the East Diversion Dam across Alkali Creek, the West Diversion Dam across a smaller valley, and the Alkali Creek Diversion Channel. The diversion structures are sized to divert the 1:200 year peak flow event.

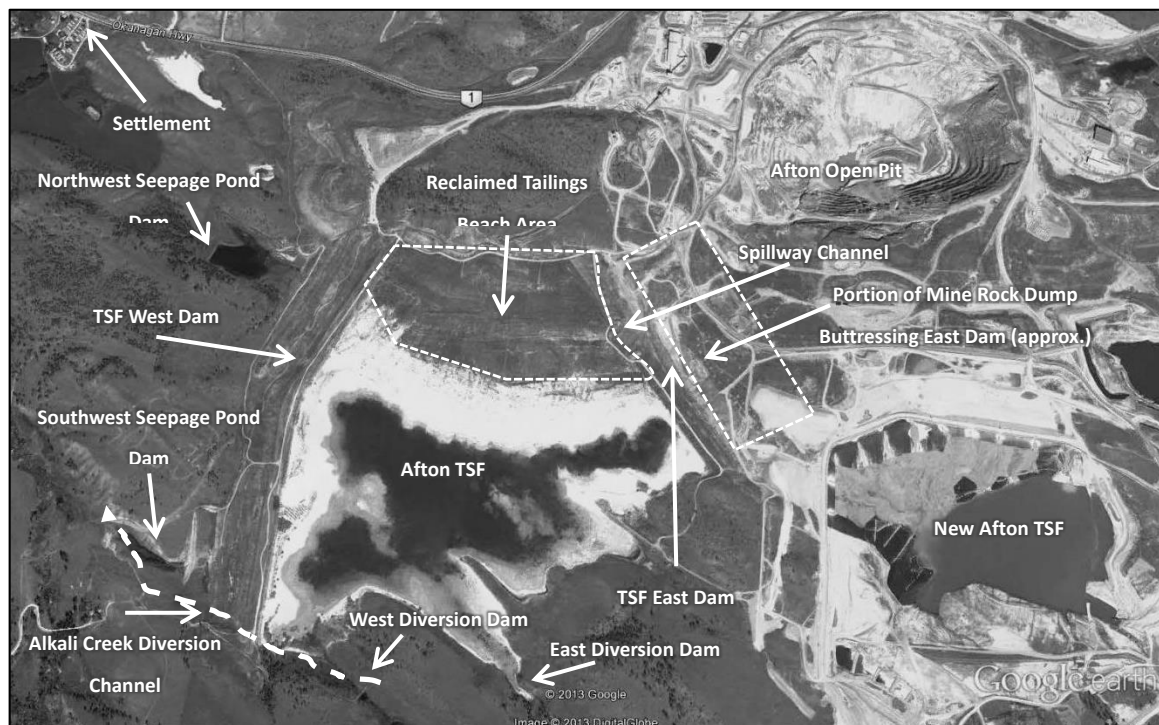


Figure 2: Afton TSF – General Arrangement

The area downstream of the West Dam drains into an 11 km long section of Cherry Creek that discharges into Kamloops Lake. There is a settlement located about 1.4 km downstream from the West Dam, as well as a number of farms farther downstream. The population inhabiting these areas may be at risk should the West Dam breach. The East Dam is located adjacent to New

Gold's New Afton Mine. Any runoff in the area downstream of the East Dam drains through a portion of the New Afton Mine site and ultimately discharges into the historic Afton Open Pit.

3 PHYSICAL CHARACTERISTICS AND HYDROLOGY FOR THE TSF

3.1 TSF Embankments

A layout and schematic cross section of the Afton TSF are presented on Figure 3. The Afton Mine ceased operations before reaching the full mine life and the dams were never raised to their ultimate design height. Consequently, the dams were overbuilt in terms of crest width, which is approximately 100 m at an elevation of 706 m. Table 1 outlines the TSF embankment parameters for each dam and the spillway. A portion of the East Dam is buttressed by a mine rock dump that is higher than the East Dam itself, as shown in the section on Figure 3, which makes the dam particularly stable in that location. Furthermore, it is worth noting that the West Dam was constructed with relatively flat downstream slopes (flatter than 2H:1V).

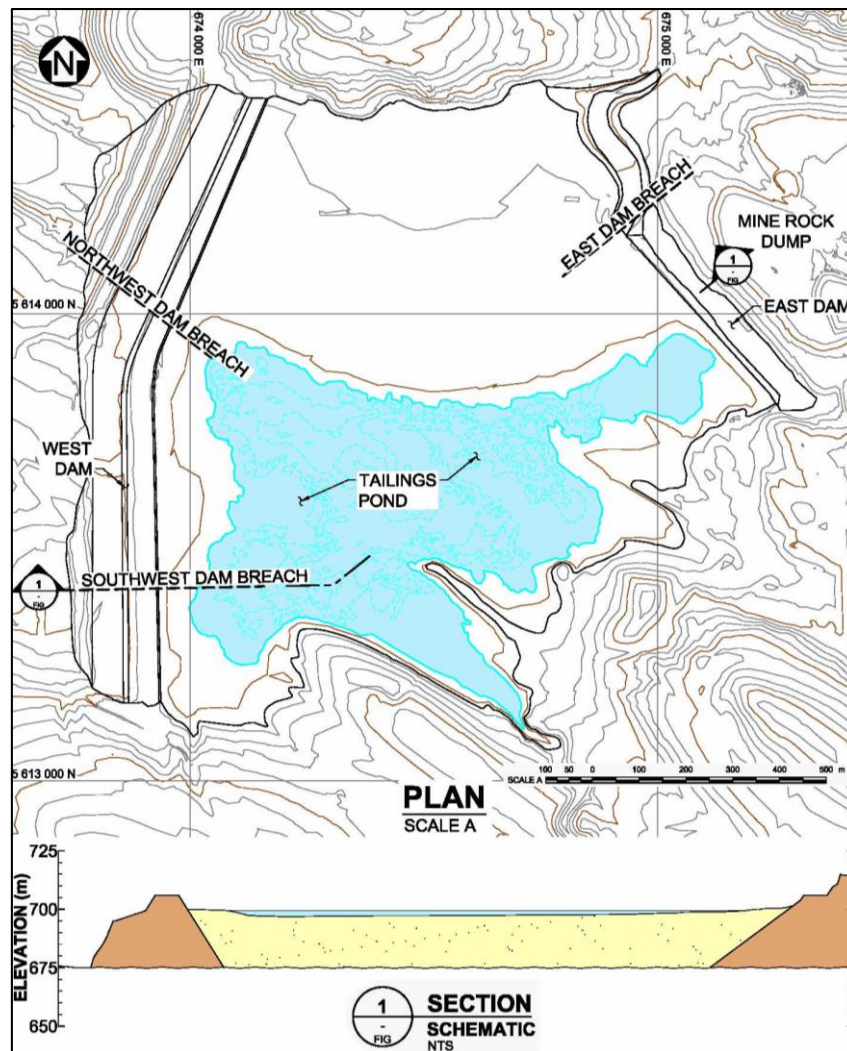


Figure 3: Afton TSF Plan and Section

Table 1: TSF Embankment Parameters

Parameter	Value
TSF dam crest elevation	706 m
TSF dam crest width	100 m
TSF dam maximum height	
Northern end of the West Dam	75 m
Southern end of the West Dam	30 m
East Dam	Buttressed
East Dam at spillway location	16 m
Spillway	
Invert elevation	704 m
Width	50 m

The spillway invert was constructed 2 m below the dam crest in the East Dam and was designed to pass the Probable Maximum Flood (PMF). The spillway consists of a 50 m wide riprap lined opening in the East Dam that transitions to an unlined earthen channel, as shown on Figures 4 and 5. The spillway channel curves along the toe of the East Dam and leads to a set of five culverts that discharge onto a haul road that runs along the perimeter of the Afton Open Pit. The tailings beach at the entrance to the spillway has been reclaimed.



Figure 4: Riprap lined spillway entrance with reclaimed tailings beach in the foreground and mine rock dump on the right side of the frame, looking downstream (northeast)



Figure 5: Spillway channel with roadway crossing in background, looking downstream (northeast)

The north end of the Afton TSF has beaches developed to the dam crest elevation of 706 m with no potential for water storage in that area of the TSF. This beach area, as shown with a polygon on Figure 2, has been reclaimed. Part of this reclaimed area is shown on Figure 6.



Figure 6: Reclaimed tailings beach, looking southwest from the north end of the East Dam

3.2 Tailings Volume in the Afton TSF

The TSF is estimated to hold approximately 37 Mt of tailings from the former Afton Mine. Assuming a dry density of 1.4 tonne/m³, the approximate volume of stored tailings is 27 Mm³, which includes solids and interstitial water.

3.3 TSF Pond Water Levels

The water levels in the tailings pond have not been monitored during the care and maintenance period and the actual annual variation of the water level in this facility is not known. It is anticipated that the water level has been several metres below the spillway invert at all times for the following reasons: (a) the Afton TSF is a non-operating facility, and as such, there is no requirement for water storage; (b) the natural inflows from Alkali Creek are diverted around the facility; (c) the upstream catchment area of the TSF is minimal; and (d) the historical climatic conditions indicate that the annual evaporation is higher than the annual precipitation, leaving the facility in a natural deficit condition.

The 2013 Dam Safety Review estimated the pond water level to be at elevation 699.5 m based on 2013 LiDAR topography (KP 2014a) as shown on Figure 7. This level equates to a freeboard of 6.5 m to the dam crest and 4.5 m to the spillway invert. In 2014, the pond level was assessed to be at an elevation of between 699.5 m and 700.0 m (KP 2014b). The slightly higher water level in 2014 was attributed to the Alkali Creek Diversion Channel construction program, which included the temporarily diverted flow from the diversion channel into the TSF during the channel upgrades (KP 2014b). Given the observed water levels, the facility layout and the local climate, the authors estimate that a freeboard of about 4 m to the spillway invert and 6 m to the dam crest will likely be available throughout most of the year.



Figure 7: TSF pond on July 9, 2013, looking northeast.

The depth area capacity relationship for the Afton TSF was developed using the 2013 LiDAR data. This relationship defines the available volume above the stored tailings that is potentially available for water storage. The TSF capacity between the tailings surface and the spillway invert is approximately 3.3 Mm^3 ; the capacity to the dam crest is approximately 5.6 Mm^3 .

3.4 PMF Hydrograph Development

The CDA guidelines (CDA 2007a, 2013) require all dams to contain or pass the Inflow Design Flood (IDF) without an uncontrolled release of the reservoir. Considering the EXTREME hazard classification of the West Dam, the IDF for the Afton TSF is the PMF, and hence, the TSF and the spillway were designed to pass the PMF.

It was assumed in the dam breach study that if the PMF were to occur, the upslope Alkali Creek diversion structures would fail and runoff from the entire catchment area would flow into the TSF. For this situation, the TSF has an upslope catchment area of 55.6 km^2 (KP 2014b). A PMF hydrograph for Alkali Creek was developed using a unit hydrograph rainfall-runoff modelling approach and an estimated 24-hour Probable Maximum Precipitation (PMP) of 221 mm (KP 2013). The modelled PMF hydrograph resulted in an estimated flood volume of 7.6 Mm^3 .

4 DEFINING CREDIBLE MODES OF FAILURE

CDA Guidelines 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...” (CDA 2007a). Defining credible modes of failure for the TSF proved to be challenging because it was hard to envision the possibility of a dam failure given the aridness of the local climate, the large capacity of the spillway, and the apparent robustness of the embankment design. The challenges related to selecting the breach locations and the initial pond water levels for plausible failure scenarios are discussed in the following sections, along with a summary of the credible failure modes that were ultimately selected and assessed for this study.

4.1 Challenges with Selecting Credible Dam Breach Locations along the Embankments

Locations for a hypothetical and worst case dam breach were assessed for each dam. Breaching through the deepest dam section is a conservative and common approach, as it usually results in

the largest outflow volume and the highest peak discharge, and therefore represents the worst case scenario. However, failure through the deepest dam section does not represent the worst case breach location for the Afton TSF. The highest dam wall for the Afton TSF is the West Dam at its north end. A large area along this end of the West Dam, including the deepest dam section, has a reclaimed tailings beach developed to the crest of the dam. A pond cannot form adjacent to the dam in this area because of this reclaimed tailings beach area. Considering that the pond water cannot reach this area, a failure of the dam through this deepest section would not result in the largest possible outflow flood wave and associated downstream inundation in either the sunny day or the flood induced scenario. For that reason, a hypothetical failure location was selected closer to the middle section of the West Dam in an area where the tailings beach is not developed to the dam crest elevation. This hypothetical failure location is identified as the Northwest Dam Breach on Figure 3.

The south end of the West Dam is located across a tributary catchment to Cherry Creek. This section of the West Dam has a tailings beach developed to approximately 6 m below the dam crest, and a pond may develop adjacent to the dam. Accordingly, a hypothetical breach location was chosen through the deepest section of this part of the West Dam, which is identified as the Southwest Dam Breach on Figure 3.

The East Dam is largely buttressed by a mine rock dump that is higher than the dam itself (Figure 3), while the north end of the East Dam has a reclaimed tailings beach developed to the crest of the dam. Therefore, the only credible location for a potential breach of the East Dam is the spillway location, which is identified as the East Dam Breach on Figure 3.

4.2 Challenges with Credible Failure Modes for the Sunny Day Dam Breach Scenario

The initial pond volume selected for the TSF affects the estimates of volumes of water and tailings that would be released in a dam breach, which in turn impacts the extent of the downstream inundation. The discharge can occur through two mechanisms: 1) an initial flood wave forming as the pond water from the facility is released; and 2) a slumping of liquefied tailings as a result of containment loss (Martin et al. 2015). A larger pond volume generally mobilizes a larger volume of tailings than a smaller pond.

The CDA guidelines recommend using the maximum normal water level as the initial pond conditions for a sunny day failure scenario (CDA 2007b). As discussed in Section 3.3, the annual TSF pond water level fluctuations are unknown. However, given the dry climate and relatively small catchment area of the facility (with diversions operating), a small pond volume is expected year-round for this facility. A fairly standard and conservative initial condition assumption would be to select the initial pond water level at the spillway invert, but this would not be consistent with observed and expected conditions. Such an unsupported assumption (water level set at the spillway invert elevation of 704 m) would correspond to an estimated pond volume of more than 3.3 Mm³, and would result in an unrealistic estimate of the breach outflow volume of water and tailings.

As mentioned in Section 3.1, the Afton TSF embankments are relatively large with approximately 100 m wide crests and relatively flat side slopes. The expected small pond volume associated with a sunny day dam breach scenario is unlikely to provide sufficient erosion potential and material mobilization to scour the embankments down to the existing ground elevation. Therefore, it is reasonable to expect that the amount of tailings volume released would be smaller compared to a breach that eroded through the full height of the embankment, resulting in substantially less downstream inundation. In fact, with only a small pond volume present in the TSF, it is likely that a sunny day failure would only result in an embankment failure followed by localized slumping of liquefied tailings.

4.3 Challenges with Credible Failure Modes for the Flood Induced Dam Breach Scenario

The CDA Guidelines indicate that a flood induced failure is a failure “occurring coincident with a flood of magnitude greater than the dam can safely pass” (CDA 2007b). Considering that the West Dam classification is EXTREME and the IDF for the facility is the PMF, the facility has been designed to safely pass the PMF. As there is no theoretical basis for the occurrence of a flood larger than the PMF, it is difficult to conceive of a flood induced dam breach unless the spillway is blocked or the dam fails through collapse rather than overtopping.

If the initial water level was set at the maximum level of 700 m observed during the 2014 Dam Safety Review (KP 2014b) prior to the onset of a PMF, the peak water level in the facility during a PMF event would be 0.8 m below the dam crest assuming a functioning spillway. If the initial water level was set at the invert of the spillway prior to the onset of the PMF, 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 be fully or partially blocked, or that there was a lower elevation section present somewhere along the embankments, which was not identified in the LiDAR survey or dam inspections conducted in 2013 and 2014. Overtopping is therefore very unlikely. Furthermore, considering the large size of the spillway, the sparse ground cover in the drainage basin, and the active nature of the neighbouring site, it is not expected that there would be an unobserved blockage of the spillway under the current conditions of this facility. 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.

4.4 Credible Modes of Failure Analysis

A credible mode of failure analysis was completed for the Afton TSF to identify the worst failure mode for each scenario for each dam. This analysis is summarized in Table 2. This analysis did not take into consideration whether the failure is likely, but only considered the mechanisms that would lead to a catastrophic breach. Any hypothetical failures that were considered even remotely possible were assigned the YES ranking, while failures that cannot occur under any circumstances were given a NO ranking.

Table 2: Credible Modes of Failure

Dam	Dam Section	Dam Failure Mode	
		Sunny Day	Flood Induced
West Dam	North End Deepest section	YES (due to reclaimed tailings beach area does not result in worst case failure)	NO (due to reclaimed tailings beach area)
	Alternate dam section	YES (assumed initial pond elevation at spillway invert)	YES (assumed initial pond elevation at spillway invert and dam collapses at maximum water elevation)
	South End Deepest section	YES (assumed initial pond elevation at spillway invert)	YES (assumed initial pond elevation at spillway invert and dam collapses at maximum water elevation)
East Dam	Deepest section	NO (buttressed by Mine Rock Dump)	NO (buttressed by Mine Rock Dump)
	Unlined spillway	YES (assumed initial pond elevation at spillway invert)	YES (assumed initial pond elevation at spillway invert)

The spillway was assumed to be functioning properly during all failure modes

The recent Technical Bulletin *Application of Dam Safety Guidelines to Mining Dams* (CDA 2014) does not prescribe procedures for selecting credible failure modes for inundation studies for mining dams. Without clearly defined guidelines, it is difficult for practitioners to exclude certain scenarios that do not appear to be credible, while making sure they are sufficiently conservative in their approach to account for the potentially serious outcomes of a dam failure.

Considering the current state of practice of dam breach and inundation studies for mining dams, the authors of the Afton Dam Breach study found themselves having to proceed with conservative but unrealistic assumptions, which required them to ignore the realities of very dry climate conditions and current low pond water levels. For the sunny day failure scenarios, the pond water level was assumed to be at the spillway invert, since the true variation of the pond was unknown and this represented the most conservative assumption. However, the very small pond in the facility and the dry climate make the occurrence of a large flood wave after a sunny day collapse improbable. For the flood induced failure scenarios, the starting pond water level was also assumed to be at the spillway invert and the dams were assumed to collapse 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 and rainy day scenarios resulted in the modelling of an excessive volume of water (approximately 3.3 Mm³ above current levels) being released from the facility. This additional volume of water resulted in larger outflow volumes, greater peak discharges, and higher downstream inundation levels than what would have been predicted with a smaller and more realistic pond volume.

5 DISCUSSION AND CONCLUSIONS

Dam breach and inundation studies are an important part of dam safety procedures, and all efforts should be made to produce conservative yet credible results. These results may ultimately lead to decisions and designs that will strive for the protection of the public and the downstream environment. 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.

Challenges in selecting credible modes of failure exist for some facilities, and the authors found that providing a definitive rationale for excluding unrealistic failure modes was difficult given the current state of guidelines and practice. Mitigation measures implemented during the design, construction, operation and closure phases of a tailings dam should be considered when conducting dam breach and inundation studies. Such measures may include buttressing, shallow downstream dam slopes, large storage volumes, extensive freeboard, well developed tailings beaches, and small supernatant ponds. Ignoring such conditions and modelling dam breaches using unrealistic scenarios produces excessively conservative results, which could lead to unjustified safety concerns, unwarranted regulatory and stakeholder constraints, and unnecessary safety measures and costs. For instance, the flood management plan during operations of a tailings facility often involves maintaining sufficient freeboard to store the IDF volume. Accordingly, in situations where the IDF is the PMF and the climate ensures a water deficit condition, practitioners should be able to rule out overtopping as a credible mode of failure, rather than using it to produce excessively improbable results.

Many mitigation measures have been included in the Afton TSF, as detailed in earlier sections of this paper. The extensive storage and a properly designed spillway in the Afton TSF makes overtopping highly improbable; therefore, the authors elected to model the dam as failing during the PMF at the time of maximum pond level due to an unknown mechanism. The authors question whether a facility that was designed to safely pass the PMF with adequate freeboard should be modelled as failing due to overtopping. By creating unrealistic dam breach scenarios in order to satisfy guidelines developed for water retaining dams, practitioners may be simulating improbable inundation conditions and unrealistically predicting potential harm to the public and the environment.

Inundation and predicted impacts caused by a non-credible event do little to inform the public about the true risks posed by these facilities by predicting outcomes that are already specifically mitigated. In the Afton TSF case, the inundation maps that were created based on unrealistically conservative assumptions, indicate that the settlement located downstream of the West Dam would be inundated if this dam were to breach. If the population of that settlement were to only consider this final result and not understand the unrealistic antecedent conditions, this population would be unduly concerned. Considering the current conditions in the facility, the authors expect that there would be no flood wave reaching this settlement. A sunny day failure would not have sufficient water for a flood wave, while a flood induced failure would see the flood wave travelling down the spillway into the Afton Open Pit.

The perceived conflict between dam design studies and dam breach analysis studies could leave the public with the impression that some practitioners believe that an event could occur while others argue the opposite. Dam designers may argue that a specific failure mechanism could not occur due to mitigation measures already in place; however, the use of such a failure mechanism for dam breach studies, regardless of credibility, would contradict this position, and the public would understandably be confused and ultimately lack confidence regarding the safety of a facility.

The authors understand that future conditions at a facility may be different than those designed or predicted, and as such, dam breach studies need to be updated if operational or closure practices change. In the case of the Afton TSF, for instance, if the facility was used for future operations to store water, the assumptions outlined in this paper would need to be revisited. Given its current status, however, the likelihood of a failure occurring according to the modelled scenarios is extremely remote.

The potential devastation driven by the failure of a dam requires practitioners to provide thoughtful consideration of such an event in their design and analyses. Dam breach assumptions should focus on credible modes of failure for the facility in question and guidelines should be developed to support the exclusion of unrealistic failure modes for mining dams. Dam breach and inundation studies that use only credible failure modes provide useful results that are constructive tools for mining dam design, dam classification, and emergency preparedness and response planning.

6 REFERENCES

- Canadian Dam Association (CDA). 2007a, Revised 2013. *Dam Safety Guidelines*.
- Canadian Dam Association (CDA), 2007b. *Technical Bulletin: Inundation, Consequences, and Classification for Dam Safety*.
- Canadian Dam Association (CDA), 2014. *Technical Bulletin: Application of Dam Safety Guidelines to Mining Dams*
- Demarchi, D. A., 2011. *The British Columbia Ecoregion Classification*. Third Edition. Ecosystem Information Section, Ministry of Environment. Victoria, BC.
- Environment Canada. Climate. Available at: <http://climate.weather.gc.ca/>. (Accessed: July 2015)
- Knight Piésold (KP), 2013. Ajax Project: 2012 Hydrometeorology Report. Ref. No. VA101-246/8-8. Vancouver, British Columbia
- Knight Piésold (KP), 2014a. Afton Tailings Storage Facility: Dam Safety Review. Ref. No. VA101-246/16-2. Vancouver, British Columbia
- Knight Piésold (KP), 2014b. Afton Tailings Storage Facility: Report on 2014 Annual Inspection. Ref. No. VA101-246/39-1. Vancouver, British Columbia
- Martin, V., D. Fontaine and J. Cathcart, 2015. Practical Tools for Conducting Tailings Dam Breach Studies. Canadian Dam Association Annual Conference, Mississauga, Ontario. October 5-8, 2015.

New Gold (2012) Properties: New Afton Project Summary. Available at: www.newgold.com/properties/operations/new-afton/project-summary/default.aspx. (Accessed: November 2014)

Thornthwaite, C.W., 1948. An approach towards a rational classification of climate. *Geographical Review*, Vol. 38. pp. 55-94