

The Risks of Excess Water on Tailings Facilities and Its Application to Dam-break Studies

H Rourke & D Luppnow

This paper was first presented at Tailings and Mine Waste Management for the 21st Century, Sydney, NSW, 27–28 July 2015

Abstract

Recent disasters such as the failure of the Mount Polley tailings embankment remind us of the risks that tailings facilities pose. It is widely recognised that dam-break assessments are a vital tool in identifying the consequences of the failure of a facility, which in turn can be used to develop emergency action plans. A typical assessment includes an estimation of breach parameters and outflow volume, followed by the preparation of an inundation map to illustrate potential flow extents and downstream impacts. This paper focuses on the estimation of outflow volumes, which is an area that the authors feel can be improved. Presently, many types of analyses assume that the volume of tailings released is only a function of the storage volume and dam height. After a review of several documented tailings failures, it has been found that the extent and depth of the supernatant pond needs to be considered as it is just as important, if not more so, as the storage volume and dam height. Tailings facilities with excess water storage have a higher risk of failure as they are more susceptible to overtopping, piping and liquefaction failures. In addition, they pose greater failure consequences as the saturated conditions will lead to more material being mobilised.

This paper has reviewed available information on a number of tailings dam failures and proposes an alternative estimation of potential tailings release volumes as a function of supernatant water stored on the facility for use in dam-break analyses. In a broader sense, the paper seeks to shift the current risk paradigm from tailings dam heights to volumes of water stored and provides a basis for continuing research and discussion.

Introduction

Tailings storage facility (TSF) failures have been occurring for as long as TSFs have been in use. The consequences of failure range from minor to catastrophic and, in some cases, involve the loss of lives. Dam-break assessments are an important safety tool used to identify the potential consequences of a facility failure and develop emergency response plans. They are an integral part of dam safety as proactive planning can greatly reduce the consequences of failure. As a direct response to the Mount Polley tailings dam failure in August 2014, the Chief Inspector of Mines for British Columbia issued an order that all tailings dams with a failure classification of high, very high or extreme must have completed a dam-break inundation study and emergency action plan by December 2014. The guidelines provided by the Australian National Committee on Large Dams (ANCOLD, 2012a, 2012b) and the International Committee on Large Dams (ICOLD, 1998) recommend that dam-break assessments be used to estimate the population at risk for determining the risk/ consequence category classification of a tailings facility. Dam-break assessments are not a new practice, but were mostly only undertaken for water dams until relatively recently. It is expected that more assessments will be undertaken for tailings facilities now that it is a requirement of many regulatory bodies and international best-practice guidelines.

This paper reviews current practice for undertaking dam-break assessments and identifies an area that needs improvement.

Review of Current Practice

Overall protocol

A typical protocol for undertaking a dam-break assessment for a TSF includes the following steps:

1. *Identify potential breach location(s)*. The breach locations selected for assessment are typically identified as critical areas where the potential for impacts on downstream environment or infrastructure is greatest. This is based on site-specific topographic, environmental and social impact criteria and can be readily determined when suitable data are available.
2. *Determine breach parameters*. There are numerous empirical relationships available for predicting breach parameters, including breach geometries and formation times. These parameters are generally based on the embankment configuration, failure mechanism (i.e. piping or overtopping) and construction materials and, in some instances, the height of the water. As a number of studies and comparisons have already been made between these relationships, they will not be replicated here. The literature on

this topic is extensive, and an appropriate method can be selected based on the information that is available, the level of detail of the assessment and the discretion of the engineer.

3. *Estimate the volume of tailings and water that will be released.* Methods to estimate the release volume range from those based on embankment heights and impoundment volumes to assuming a post-failure slope. These are discussed in more detail in the following sections.

4. *Route the breach flood downstream and prepare inundation maps.* Routing of the flood can be done using simple, one-dimensional water flow models or complex, two-dimensional, non-Newtonian models, depending on the level of study required. Inundation maps can be prepared using drafting or geographic information system tools based on the results of the breach flood routing.

Identifying potential breach locations, determining breach parameters, routing the flood downstream and preparing inundation maps are areas that are either practised well or are currently undergoing extensive research. However, estimating the volume of tailings and water that will be released is an area that the authors feel can be improved.

Criticism of common volume estimation methods

Some of the more commonly used methods to predict the release volume associated with a failure include 'rule of thumb' estimates, assumed post-failure final slopes and storage- and height-based formulae developed from experience data.

'Rule of thumb' estimates that have been presented in dam-break reports include the assumption that 50 per cent, 100 per cent or another arbitrary percentage of the total stored volume is released. Past tailings facility failures show that anywhere from 1 to 100 per cent of the stored volume can be released in the event of a failure, with the average around 20 to 40 per cent.

Unlike water dams, where a breach spanning the full height of the embankment will result in the entire storage volume being released, it is widely accepted that TSFs are more likely to retain some solids due to the viscous nature of the tailings. Applying this principle, some dam-break studies have assumed a post-failure tailings surface sloping at an angle of about 3 to 10° from the downstream toe, as illustrated in Figure 1.

The empirical approximation proposed by Rico, Benito and Diez-Herrero (2007) is one of the most commonly used methods for estimating baseline outflow run-out distances and volumes. In their paper, data from 29 historic tailings dam failures is used to define a relationship between outflow characteristics and embankment heights and storage volumes. Such relationships had previously been developed for and applied to water-storage dams; however, a specific relationship was needed to account for tailings breaches generally retaining more storage. The outflow volume was plotted against storage volume and the resulting regression had a correlation of $r^2 = 0.86$. The run-out distance was plotted against a dam factor (the product of the embankment height and storage volume) and had a regression of $r^2 = 0.57$. The regression relationships imply that the larger the impoundment or embankment height, the greater the risk associated with a facility failure. It is true that larger facilities have more material available to release, but if they are well-designed and operated, the failure outflow volume is likely to be less than that of a smaller, poorly operated facility or a facility storing a large surplus of water.

All of these methods are limited as none consider the influence of the supernatant water pond. Intuitively, large water volumes stored on the TSF not only increase the risk of failure, but also the consequence of failure as more material will be mobilised. Many tailings dam failures have occurred following a storm event or from poor operation resulting in a large supernatant pool prior to the breach. It is therefore proposed that empirical relationships to predict breach outflow volumes should incorporate the effect of water.

Tailings Facility Failures and Water

While it is recognised that some TSFs are designed as water-retention facilities and are capable of storing surplus water, most are not. Because of this, poor pool control leading to large water volumes on a TSF is a high-risk practice that has historically been one of the main causes of embankment instability and breach failures.

Intuitively, large water volumes can be directly linked to many failure modes. For example, large ponds reduce freeboard and increase the potential for overtopping and reduced beach areas generate high phreatic surfaces through embankments that can lead to seepage and/or piping failure. ICOLD and UNEP (2001) collected data from over 200 reported tailings dam incidents and failures and concluded:

Lack of control of the hydrological regime is one of the most common causes of failure. Of the cases reported here, the majority of failures were due to overtopping, slope instability, seepage and erosion; all caused by a lack of control of the water balance within the impoundments.

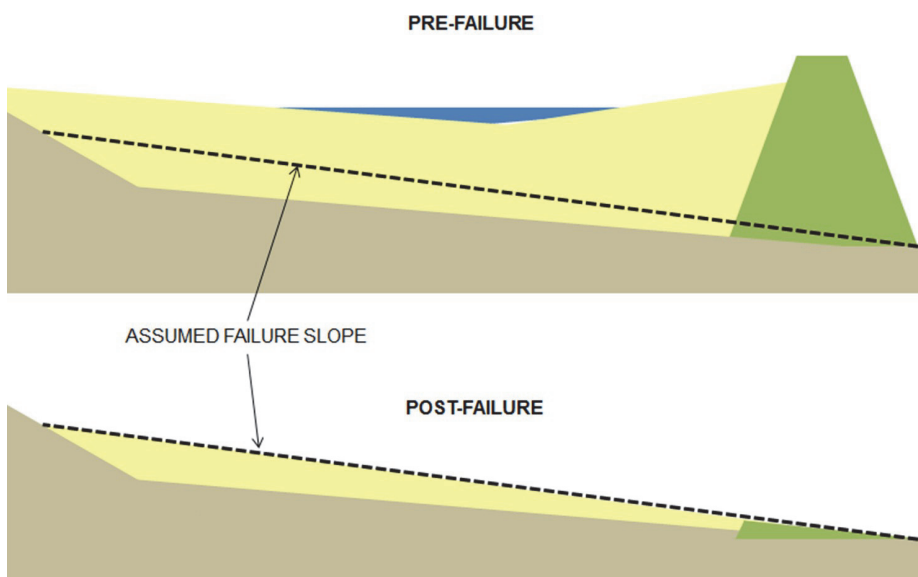


FIG 1 – Estimating release volume based on an assumed post-failure slope.

Even if it is not the direct cause of failure, the water volume has a significant influence on the amount of material mobilised following a failure. Therefore, water is an important parameter that cannot be ignored.

Case Studies

One of the greatest difficulties in developing dam-break relationships for TSFs is the lack of information available on historical failures. Various researchers have endeavoured to collate case histories of tailings failures using the limited data available. Some of the most noteworthy include Lucia, Duncan and Seed's (1981) report on 25 tailings and water dam failures, the United States Commission on Large Dams' report (USCOLD, 1994) on 187 incidents, ICOLD and UNEP's (2001) report on 221 incidents and Rico et al.'s (2008) report on 29 failures.

The descriptions of the incidents/failures in these reports generally include information on the released volume of water and tailings, stored volumes, embankment heights and failure modes. Details on operational aspects such as the pre-failure water pond volume are scarce. In order to demonstrate the influence of water on release volumes, case studies where the degree of pre-failure water storage could be inferred were needed. A limited number of case studies where either the pre-failure water surface area was reported or pre- and post-failure photographs or satellite imagery were readily available were selected. The pre-failure images were used to estimate the amount of water stored on the facility prior to failing (see Figure 2). This was then used to calculate the ratio of pool area to the total TSF surface area so that a relationship to represent the influence of water on release volumes could be developed. The six selected case studies are presented in the following sections.

Merriespruit, South Africa

On the evening of 22 February 1994, one of the Merriespruit tailings facility embankments failed, releasing approximately 0.6 Mm³ towards downstream residences. The flood wave destroyed 80 houses, killed 17 people and caused extensive environmental damage. ICOLD and UNEP (2001) classified the Merriespruit disaster as an overtopping failure. Deposition practices had pushed the operating pond away from the decant and toward the embankment, reducing freeboard. The failure was preceded by a rain event of 30 to 55 mm the night before the breach, which led to the embankment overtopping.

The pre-failure pool area from the day before the breach is reported in Blight (2010) from an aerial image taken two weeks before the failure.

Bafokeng, South Africa

On the morning of 11 November 1974, approximately 3 Mm³ of liquefied tailings escaped through a breach in the embankment at the Bafokeng facility, covering a mine shaft and killing 12 mine workers, destroying mine buildings and travelling 45 km.

The Bafokeng failure has been classified as a seepage/piping failure. While the exact mechanism of the failure is debatable, it was likely triggered by a combination of heavy rain the night before the failure and vibration-induced liquefaction from a loader working on the crest.

The pre-failure pool area was sourced from Blight (2010) based on satellite images taken the day before the failure on 10 November 1974.

Mount Polley, Canada

The 4 August 2014 failure of the Mount Polley tailings dam in British Columbia resulted in the release of 24.4 Mm³ of tailings and water (Wise Uranium Project, 2015). The flood wave inundated salmon- and trout-inhabited rivers.

The independent review report by Morgenstern, Vick and Van Zyl (2015) found that the foundation was the principal cause of the embankment failure and noted that the sizeable volume of water stored on the dam contributed to the large release of tailings.

The prefailure pool area was estimated using Google Earth™ satellite imagery from 18 July 2012, approximately two years before the breach.

Kolontár, Hungary

The failure of an embankment of Basin X of the red mud reservoir on 4 October 2010 released approximately 0.7 Mm³ of red mud toward the nearby villages of Devecser and Kolontár, killing ten people and injuring 120 others.

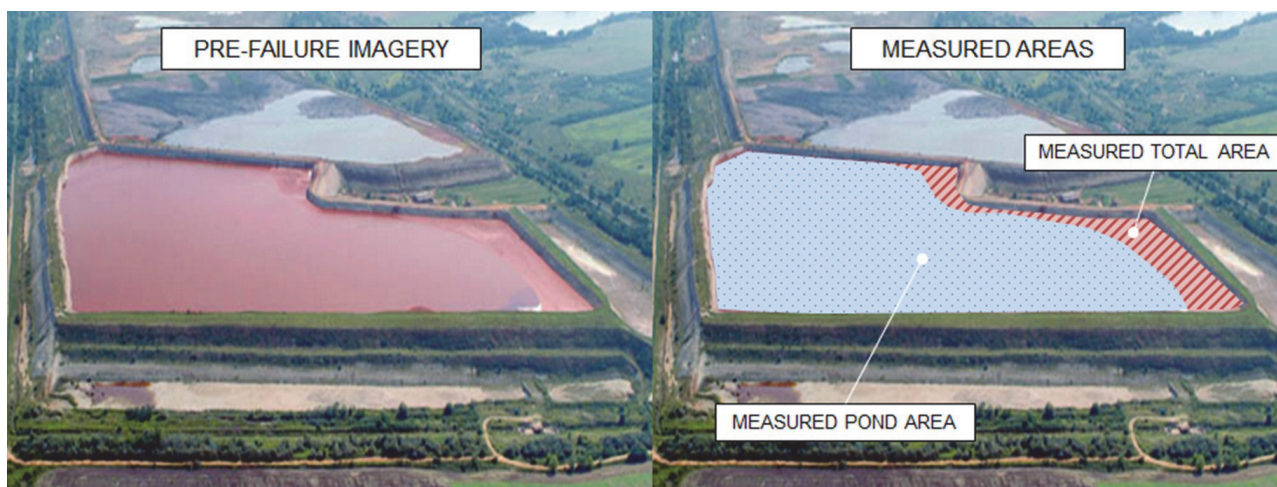


FIG 2 – Prefailure imagery and area measurements of the Kolontár tailings dam (imagery taken in June 2010 by Hungarian aerial photography company Interspect).

An investigation of the failure mechanism found that seepage initially triggered a shear failure in part of the embankment. A combination of improper foundations and high pore pressures culminated in a failure at the corner of the embankment, where stresses are highest (Wise Uranium Project, 2015).

The prefailure pool area was estimated using an aerial image taken in June 2010; a few months before failure (see Figure 2).

Stava, Italy

The 1985 Stava tailings dam failure in Italy is the most devastating tailings dam failure in history. The TSF was located on a steep slope immediately upstream of the village of Stava. On 19 July 1985, an embankment failed and released 0.2 Mm³ downstream, killing 268 people and destroying 62 buildings (Wise Uranium Project, 2015).

The failure has been attributed to a poor design with an extremely low factor of safety. The triggering mechanism was the blockage of a decant pipe, which led to an excessively large amount of water being stored on the facility.

The prefailure pool area was estimated using photographs of the facility that showed the pool covering the entire surface area (Wise Uranium Project, 2015).

Summary

A summary of the data collected for these five case studies is presented in Table 1. These data were then plotted in Figure 3, which shows the volume ratio (release volume to storage volume) versus the pond ratio (pond area to TSF area) and provides the following regression equation:

$$VR = 0.6533 PR + 0.0136 \quad r^2=0.996 \quad (1)$$

where:

VR is the volume ratio representing the percentage of the total volume that is released

PR is the pond ratio expressed as a percentage

This equation provides a surprisingly good correlation for the five case studies analysed and serves as a starting point for incorporating the influence of water in estimating potential failure volumes. It is acknowledged that this is a simplistic relationship that has been developed from limited data. It is expected that a reasonable correlation will still be achieved when additional data are incorporated, but that the r2 value will likely decrease.

Going Forward

Equation 1 demonstrates a linear relationship that shows that the percentage of volume released is approximately equal to the per cent ratio of the pool to total TSF area. While this relationship shows a good correlation for the small number of case studies, more data is needed to increase confidence. Adding more case studies to the analysis may indicate that the relationship is steeper (more dependent on pond volume), shallower or even non-linear. It would also be worthwhile incorporating other parameters, such as embankment height, into the analysis.

TABLE 1 Summary of case study data used in the analysis.

Name	Impoundment storage volume (Mm ³)	Release volume (m ³)	Ratio of release volume to stored volume (%)	Ratio of pool area to total area (%)
Merriespruit	7.0	0.6	9	14
Bafokeng	13.0	3.0	23	30
Mount Polley	50.0	24.4	49	72
Kolontár	1.2	0.7	58	88
Stava	0.3	0.2	67	100

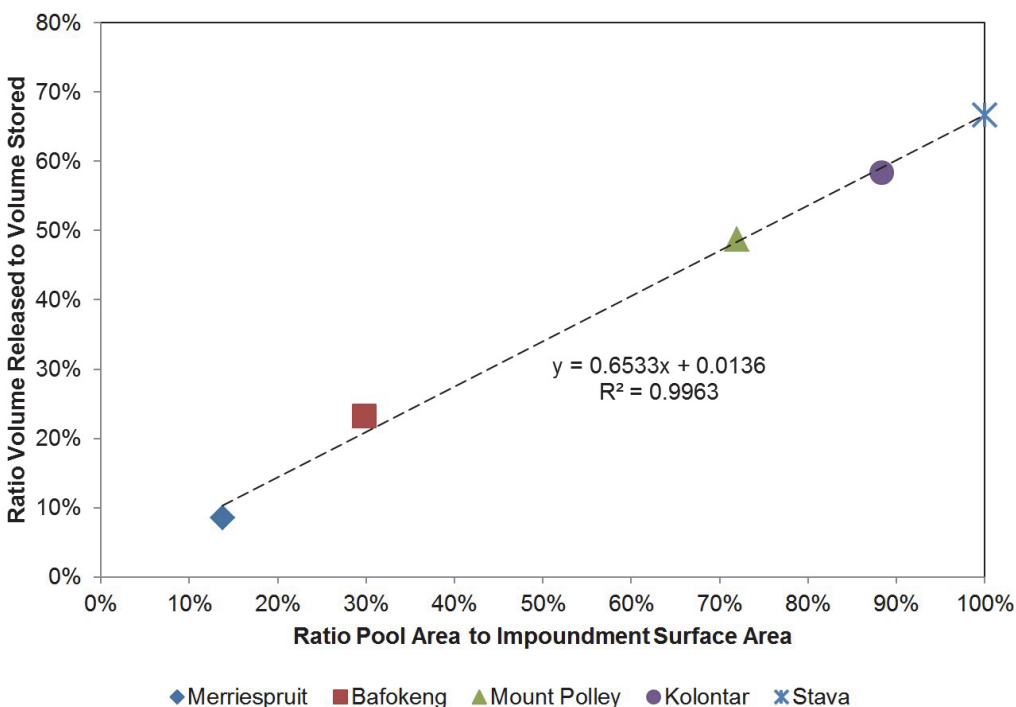


FIG 3 – Graph of the volume ratio (volume released to volume stored) versus pool ratio (pool area to impoundment surface area) with regression.

The principal theme is that stored pond water has a major influence on the volume of material that will be released during a breach and is a parameter that should be considered in estimations.

It is envisaged that when the relationship becomes more robust, it could be used to predict volume releases as part of dam-break assessments and for operational audits. Auditors can quickly relate the observed pool size to the potential breach volume and can make recommendations regarding pool management and ongoing monitoring if required.

Conclusions

This paper has identified an area of improvement in the current methods for estimating failure release volumes, which is one of the first and most influential steps in performing a dam-break assessment. Despite historical evidence showing that poor water control during operations is one of the most common causes of tailings dam failures, current methods do not consider the influence of water.

Five case studies have been used to develop a preliminary relationship between potential failure release volumes and water by considering approximate pre-failure pool sizes. This is a simple approximation that can be used as a starting point for further study.

The main objective of this paper is to generate a discussion around shifting the risk focus away from the size of a TSF only and towards a more inclusive approach that considers water. TSFs are not typically designed as water-retaining structures, and poor operational pool control is likely to either directly cause or increase the potential and/or consequence of a failure. Therefore, water is arguably the most critical parameter in estimating potential release volumes and cannot be ignored. This is emphasised in the review of the recent Mount Polley TSF breach, where Morgenstern, Vick and Van Zyl (2015) conclude:

... overtopping did not cause the breach ... However, the high water level acted in other ways that influenced both the failure and its effects ... The high water level was the final link in the chain of failure events ... Had the water level been even a metre lower and the tailings beach commensurately wider, this last link might have held until dawn the next morning, allowing timely intervention and potentially turning a fatal condition into something survivable. Finally, the quantity of water had a great deal to do with the quantity of tailings released after the breach developed. It was water erosion that transported the bulk of the tailings, and these fluvial processes ended when the supply of water was exhausted. Had there been less water to sustain them, the proportion of the tailings released from the TSF would have been less than the one-third that was actually lost.

Acknowledgements

The authors would like to thank Caroline Holmes for her critical review and feedback in preparing this paper.

References

- Australian National Committee on Large Dams (ANCOLD), 2012a. Guidelines on tailings dams – planning, design, construction, operation and closure, May 2012.
- Australian National Committee on Large Dams (ANCOLD), 2012b. Guidelines on the consequence categories for dams, October 2012.
- Blight, G, 2010. Geotechnical Engineering for Mine Waste Storage Facilities, 652 p (Taylor and Francis: London).
- International Commission on Large Dams (ICOLD), 1998. Dam- break flood analysis – review and recommendations, bulletin 111.
- International Commission on Large Dams and United Nations Environment Programme (ICOLD and UNEP), 2001. Tailings dams: risk of dangerous occurrences – lessons learnt from practical experiences [online], bulletin 121. Available from: <<http://www.unep.fr/shared/publications/pdf/2891-TailingsDams.pdf>> [Accessed: 7 May 2015].
- Lucia, P C, Duncan, J and Seed, H B, 1981. Summary of research on case histories of flow failures of mine tailings impoundments, in Proceedings Mine Waste Disposal Technology: Technology Transfer Workshop, pp 46–53 (US Environmental Protection Agency and US Department of the Interior: Washington DC).
- Morgenstern, N R, Vick, S G and Van Zyl, D, 2015. Independent expert engineering investigation and review panel report on Mount Polley tailings storage facility breach [online]. Available from: <<https://www.mountpolleyreviewpanel.ca/sites/default/files/report/ReportonMountPolleyTailingsStorageFacilityBreach.pdf>> [Accessed: 7 May 2015].
- Rico, M, Benito, G and Diez-Herrero, A, 2007. Floods from tailings dam failures, Journal of Hazardous Materials, 154:79–87.
- Rico, M, Benito, G, Salgueiro, A R, Diez-Herrero, A and Pereira, H G, 2008. Reported tailings dam failures: a review of the European incidents in the worldwide context, Journal of Hazardous Materials, 152:846–852.
- US Committee on Large Dams (USCOLD), 1994. Tailings Dam Incidents, 82 p (US Committee on Large Dams: Denver).
- Wise Uranium Project, 2015. Chronology of major tailings dam failures [online]. Available from: <<http://www.wise-uranium.org/mdaf.html>> [Accessed: 6 February 2015].