Comparing geometric TSF breach volumes with case histories

C. Cilliers & J.R. Collins
BEAL Consulting Engineering, Pretoria, South Africa

ABSTRACT: The safety of Tailings Storage Facilities (TSFs) has received increased attention due to past failures. As per industry guidelines it is required to conduct dam breach assessments to determine the potential areas affected in the event of failure. These assessments fundamentally depend on estimating the volume of tailings likely to be released during a dam failure. Various approaches have been proposed for determining these volumes, with the geometric method being a widely used technique. This method involves modelling a potential dam breach using the physical parameters of the breach. This study examines past TSF failures to evaluate the accuracy of the geometric method. The guidelines provided by the Canadian Dam Association (CDA) were used alongside observed breach dimensions post failure. The geometries were modelled using Autocad Civil 3D software, incorporating historical records such as incident reports and aerial imagery. The findings indicate that the geometric method provides a conservative estimate of probable breach volumes. These results can assist in dam breach assessments to support compliance with safe tailings management practices by enabling a more accurate determination of breach geometry for various types of TSFs. This study offers a more robust approach to estimating the volume of tailings released during a potential dam failure.

1 INTRODUCTION

1.1 *Background*

The safe design and operation of tailings dams are critical components of modern mining operations. Tailings dams, constructed to store waste materials left over from mining processes, present significant safety risks, especially in the event of a breach or failure. A breach in a tailings dam can lead to catastrophic consequences, including loss of life, environmental degradation, and significant economic damages (ICOLD 2001). Due to the potential severity of such events, dam breach assessments have become an essential aspect of tailings dam safety management, and one of the key elements of these assessments is the estimation of breach volume.

As regulatory frameworks evolve globally, the importance of ensuring compliance with safety standards has grown. One such framework is the Global Industry Standard on Tailings Management (GISTM), which was developed to address the need for more stringent and consistent safety measures in the design, operation, and monitoring of tailings dams (ICMM 2020). Breach volume estimation serves as the basis for flood modelling, which in turn informs emergency response plans, evacuation strategies, and environmental protection measures. Without an accurate estimate of breach volume, it is impossible to determine effective mitigation measures or to fully assess the risks posed by tailings dams (Chen et al. 2021). Thus, determining the correct breach volume is not only a technical requirement but also an essential component of overall dam safety and regulatory compliance.

In the context of GISTM compliance, the geometric approach to estimating breach volume has garnered attention as one of the most widely used methods. This approach relies on the assumption that the geometry of the breach can be approximated, allowing for a geometric specific volume calculation. By employing this method, engineers and safety experts can estimate the breach volume based on the dam's physical characteristics, such as its height, slope, and the dimensions of the breach itself (MacDonald & Langridge-Monopolis 1984). However, while the geometric approach offers a relatively straight-forward means of estimating breach volume, it is not without its limitations, and there remain gaps in the literature regarding the precision and accuracy of this method.

The general methodology relies on simple geometric shapes, such as trapezoids, triangles, or more complex combinations of these shapes, to approximate the shape of the breach and the resulting flow of tailings

(USACE 2009). The key assumption behind this approach is that the breach will form a specific geometric profile, which can be used to estimate the total volume of material released.

One of the most common ways to model the breach geometry is as a cone of depression, where you calculate the volume by dividing the area of the breach into slices, estimating the area of each slice based on its elevation and finally determining the total of the volumes of the slices to obtain the breach volume. Modelling software such as Civil 3D enables these calculations (Schoeman 2018). This method assumes that the breach will propagate in a manner that preserves certain geometric characteristics, such as a constant breach width or a fixed slope of failure. In some cases, more advanced geometric modelling may be employed to account for variations in the breach profile, such as irregularities in the slope or other factors that could influence the breach's size and shape by way of using trapezoidal or parabolic properties (West, Morris & Hassan 2018). These models can help to provide a more detailed estimate of the volume of material re-leased, considering factors such as the type of tailings, the structure of the dam, and the rate of failure. Additionally, the breach volume can be influenced by the type of failure mechanism that is expected to occur. For example, an overtopping failure may result in a different breach shape compared to a structural failure or internal erosion. In such cases, engineers must account for the specific failure mode when applying the geometric approach, as different failure mechanisms can produce varying breach geometries and, consequently, different breach volumes (Morgenstern et al. 2023).

Despite the relatively straightforward nature of the geometric approach, challenges remain in ensuring that the estimated breach volume accurately reflects the complexities of real-world dam failures. A key limitation of this method is that it relies heavily on simplified assumptions about breach geometry, which may not always be applicable to all types of dams or failure scenarios (Fell et al. 2008).

While the geometric approach to estimating breach volume has been widely adopted, there is a notable lack of comprehensive studies that assess the accuracy of this method. Most existing literature focuses on theoretical models, assumptions, or case studies based on limited data, but there is insufficient empirical evidence to support the claimed accuracy of the geometric approach in a wide range of tailings dam scenarios.

2 REVIEW OF HISTORIC TSF FAILURES

This study focused on notable tailings dam failures, specifically analysing breach geometries, dam types, associated mining activities, and key technical aspects.

The Brumadinho dam failure shown in Figure 1, occurred on January 25, 2019, in Brumadinho, Minas Gerais, Brazil. This upstream iron ore tailings dam released approximately 9.7 Mm^3 of tailings. The embankment on which the breach occurred was approximately 720 m long. The breach geometry included a base width of approximately 100 m and a height of 80 m, forming quickly and causing complete failure within seconds. The tailings travelled over 9 km downstream, severely impacting the Paraopeba River. Investigations revealed that static liquefaction, caused by insufficient compaction of tailings and high pore water pressures, caused by poor drainage caused the failure (Robertson & Wilson 2019). Inadequate design and management, including insufficient monitoring systems, further worsened the situation (Robertson & Wilson 2019).

Figure 1. Brumadhino dam failure (Pearson & Lewis 2021)

The Mount Polley dam failure occurred on August 4, 2014, in British Columbia, Canada, presented in Figure 2. This centreline copper and gold tailings dam released approximately 25 Mm^3 of water and tailings. The embankment length at the site of the breach was approximately 1800 m. The breach geometry included a base width of approximately 42 m and an initial height of 36 m. The failure developed over several hours, depositing tailings over an 8 km stretch into Polley Lake and Quesnel Lake. Investigations identified weak glacial till foundation material and undetected subsurface failure as the primary causes. The Independent Expert Engineering Investigation and Review Panel concluded that design flaws and foundation instability were key contributors (Mount Polley Expert Panel Report 2015).

Figure 2. Mount Polly dam failure (Parsons 2016).

The Merriespruit tailings dam failure occurred on February 22, 1994, in Merriespruit, Virginia, Free State, South Africa. This upstream tailings dam as seen in

Figure 3, used in gold mining, released approximately 650 000 m^3 of tailings. The embankment length at the breach site measured around 1000 m. The breach geometry included a base width of 55 m and a height of 27 m. The failure occurred abruptly, with tailings traveling over 2 km and inundating the nearby suburb of Merriespruit, resulting in 17 fatalities and extensive property damage. Investigations revealed that the dam's failure was primarily due to overtopping caused by heavy rainfall, compounded by poor design, inadequate freeboard, and insufficient drainage systems. The lack of emergency preparedness further worsened the disaster's impacts as indicated by ICOLD (ICOLD 2001).

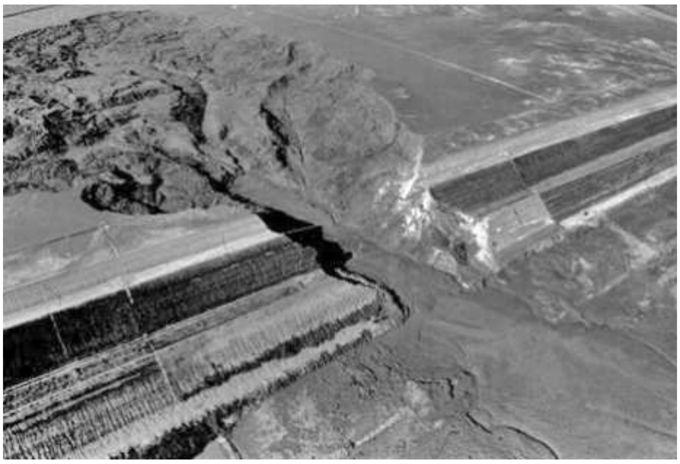

Figure 3. Merriespruit dam failure (Schoeman 2018)

3 METHODS

A short literature review, supplemented by the work of Adria et al. (2023), was conducted to analyse and document the geometric properties of three historical tailings dam breaches. This review drew upon publicly available resources, including academic journals, industry reports, and regulatory investigations. Key breach parameters studied included breach width, depth, side slopes, and recorded volumes.

Using the compiled data, a geometric model of each dam and the associated conical breach was developed in AutoCAD Civil 3D. The methodology involved the following steps:

- Data collection: Gathered all relevant information about each dam failure.
- Parameter summary: Extracted and summarised key breach parameters for modelling purposes.
- Surface data acquisition: Retrieved surface data for each dam site using FABDEM v1.2 (Forest and Buildings Removed Copernicus DEM), available at https://data.bris.ac-.uk/data/dataset/s5hqmjcdj-8yo2ibzi9b4ew-3sn.
- Breach modelling: Constructed breach models in Civil 3D based on collected data and applicable engineering standards.
- Volume validation: Compared the calculated breach volume in Civil 3D against recorded failure volumes to assess model accuracy.

3.1 *Breach Geometry*

The standards most relevant to this part of the study are those outlined by the Canadian Dam Association (CDA) and the Federal Energy Regulatory Commission (FERC). These two resources provide critical guidelines and methodologies that were incorporated into this study, particularly for modelling breach parameters

3.1.1 *Relevant Guidelines*

The CDA and FERC guidelines for water retaining dams, are summarised in Table 3 below:

Table 3. Breach Parameters for Water Retaining Dams (CDA)

Parameter	Engineered dam	Non-Engineered dam
Average Breach Width	1 to 5 x height of the dam (FERC 2015) or 0.5 to 5 x height of the dam (USACE 2007)	Equal or larger than 0.8 times the crest length (FERC 2015)
Breach Side Slopes	1V:0.25H to 1V:1H (FERC 2015) or 1V:0H to 1V:1H (USAGE 2007)	1V:1H to 1V:2H (FERC 2015)
Breach Bottom Elevation	Ground level	Ground level
Breach Development Time	0.1 to 1 hour (FERC 2015) or 0.1 to 4 hours (USACE 2007)	0.1 to 0.5 hours (FERC 2015)

The guidelines indicate a wide range of possible parameters and choosing between the options would rely on the definitions of both engineered and non-engineered dams. Engineered Tailings Dams are designed using engineering principles, considering geotechnical, hydrological, and environmental factors. Non-Engineered Tailings Dams, are constructed with minimal or no formal engineering input. They often develop incrementally over time without proper stability assessments, controlled construction methods, or adherence to modern safety standards (ICOLD 2001).

3.1.2 *Breach Volume Calculations*

An additional key recommendation by the CDA involves the use of geometric methods to calculate breach volumes.

Figure 4a) and 4b) illustrate the theoretical breach geometry as defined by the CDA standards:

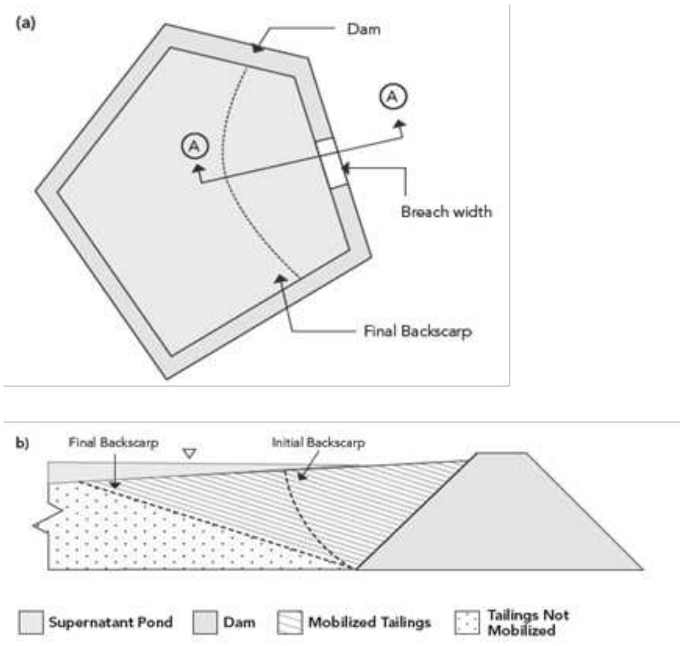

Figure 4. Schematic of the Failure Surface for a TSF: a) Plan View b) Cross Section A-A as per the CDA standards

From the figures, the concept of modelling the breach as a cone shaped structure was developed. The figures of the past failures described in Section 2 was observed and it was decided to apply a 30° angle to each side of the breach outlet as opposed to how the CDA represents the cone geometry in Figure 4. The rationale to this decision was made to mimic the actual geometry of the breaches. Furthermore, the CDA states that the outflow slope typically ranges from 3.5% to 9%, depending on the characteristics of the tailings. As the rheological parameters of the tailings in this study is not readily available, the angles would be determined interactively.

3.1.3 *Breach Modelling*

A schematic representation of the breach geometry utilised in this study is provided in Figure 5 below:

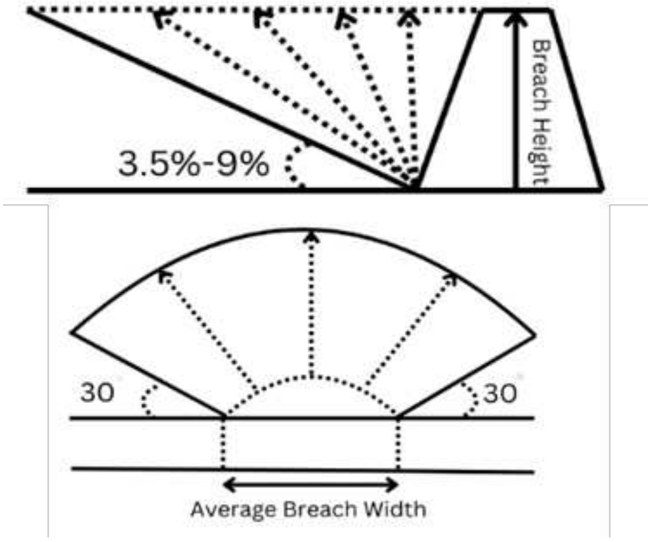

Figure 5. Simplified Model for breach geometry

This figure illustrates the geometric cone model applied to the breaches, incorporating the 30° angle and slope guidelines. The schematic ensures consistency with CDA standards while allowing for adjustments based on observed real-world data.

3.1.4 *Application of Guidelines*

The steps outlined above were combined with real-world data observed for each failure event. This approach allows for the validation of the geometric cone method and ensures that the model provides realistic and usable results.

4 RESULTS

The publicly available FABDEM data for each site was acquired and utilised to model the dams prior to their breaches, as well as to construct the models for each breach. The specifications for each dam were obtained from existing literature (Adria et al. 2023) and are summarised in Table 4 below.

Table 4. Dam Specifications adapted (Adria, et al., 2023)

ID	Year	Arrangement	Ore	Dam Raises	Failure Mode
1*	2019	Cross-valley and side hill	Iron	Upstream	Collapse
2*	2014	Side hill	Copper and Gold	Centreline/Upstream hybrid	Collapse followed by overtopping
3*	1994	Ring-Dyke	Gold	Upstream	Overtopping followed by collapse

*Note:(1) Brumadinho Dam (2) Mount Polley Dam (3) Merriespruit Dam

The breach and dam characteristics of significance are detailed in Table 5 below.

Table 5. *Breach Specifications adapted (Adria et al. 2023)*

ID	VS*	VI*	VP*	VOut*	HB*	BT*	BB*	ZL*	ZR*
1*	5.6	4.1	0	9.7	80	560	100	2.9	2.9
2*	7.9	6.5	10.6	25	36	260	42	1.75	3.9
3*	0.3	0.3	0.09	0.6	27	150	55	1.75	1.8

**Note:(1) Brumadinho Dam (2) Mount Polley Dam (3) Merriespruit Dam, VS= Volume of Solid tailings released (106 m), VI= Volume of pore water released (106 m), VP= Volume of supernatant pond (106 m), VOut= Total volume of tailings material released (106 m), HB= Breach Height (m), BT = Top Breach Width (m), BB = Bottom Breach Width (m), ZL = Left Breach Side Slope V:xH, ZR = Right Breach Side Slope V:xH*

The breaches for the three failures were modelled using the bottom breach geometry as well as side slopes post event, alongside outflow slopes determined in accordance with the CDA standards. The Civil 3D representations of all three dams are shown in Figure 6 to Figure 8 below.

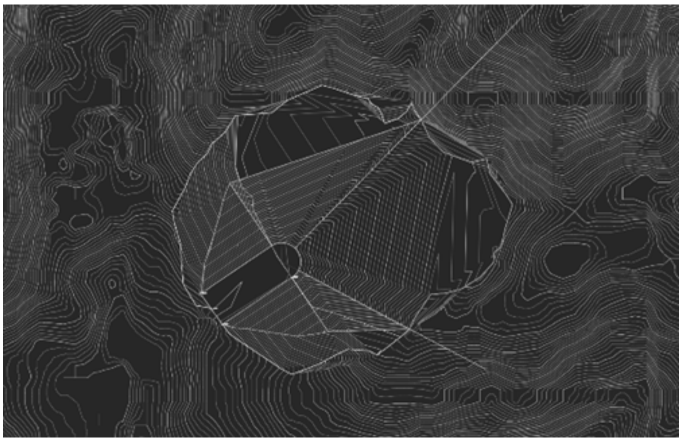

Figure 6. *Brumadinho Dam Breach model*

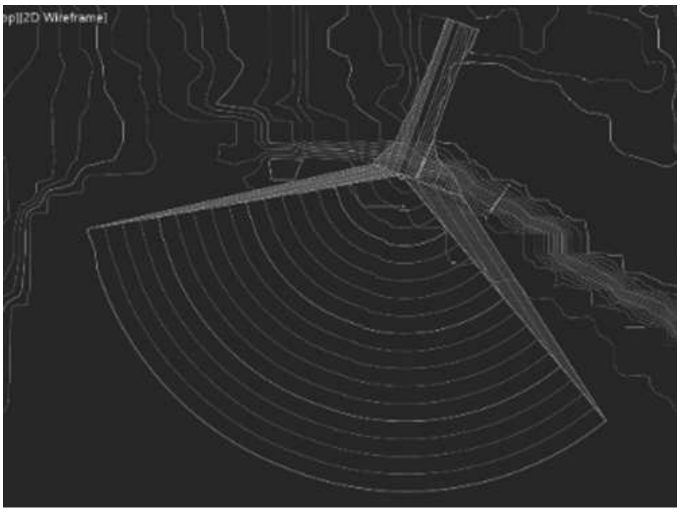

Figure 7. *Mount Polley Dam Breach model*

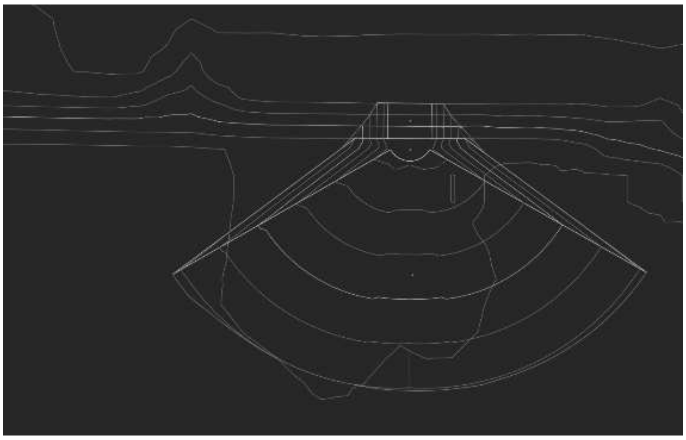

Figure 8. *Merriespruit Dam Breach model*

4.1 *Model parameters and volumetric results*

The model specifications used, and final volumes calculated are presented in Table 6 below.

Table 6. Model specifications and volumetric results

ID	BB (m)	Cone Slope	Total Breach Volume (m^3)	Recorded Total Breach Volume (m^3)
1*	100	9%	7 916 861	9 651 000
2*	42	5%	7 225 312	25 000 000
3*	55	9%	1 206 510	615 000

*Note: (1) Brumadinho Dam (2) Mount Polley Dam (3) Merriespruit Dam

The maximum angle was used for both the Brumadinho and Merriespruit dams (9%). Brumadinho was modelled with a steep angle due to the facility's natural incline. For Merriespruit, the angle was determined iteratively to match the actual breach size observed during the event. Similarly, the angle for Mount Polley was determined using the same iterative approach as Merriespruit.

For a dam breach assessment, in-situ soil tests specifically CPTu tests are essential. The residual angle should be derived from the CPTu results or laboratory testing, as this would represent the failure angle used in the conic model. However, since this data is not publicly available, assumptions were necessary for this study.

5 DISCUSSION

The findings indicate that the estimated volume for the Brumadinho Dam breach closely matched the recorded breach volume. Since no supernatant pond was present, the outflow primarily consisted of tailings (both solid and interstitial water). The results showed an 18% difference between the calculated geometric volume and the recorded volume.

The Mount Polley Dam results showed a significant difference between the calculated and recorded volumes. This difference can largely be attributed to the presence of a large supernatant pond (10 600 000 m^3 of the total 25 000 000 m^3). The geometric method does not account for the supernatant pond's contribution to the breach outflow. It was estimated that approximately 20% of the pond's area was covered by the breach cone, leaving 8 480 000 m³ of supernatant water beyond the cone area.

The amount of eroded tailings was estimated as equal the volume of supernatant water present on a tailings dam:

$$V_{ET} = V_P \quad (1)$$

This gives a total of remaining eroded tailings excluding that in the cone as 8 480 000 m^3. The available tailings for the cone can thus be calculated as follow and compared to the modelled theoretical value:

$$V_{Cone} = 25\,000\,000 - 2 \times 8\,480\,000 = 8\,040\,000 m^3 \quad (2)$$

This means that the results obtained using the geometric modelling indicated only an 11% difference.

In contrast, the Merriespruit Dam breach, which resulted from overtopping, did include a supernatant pond. Here, the calculated geometric volume was approximately 50.9% higher than the recorded release volume. The reason for this could be attributed to the failure mode of Merriespruit which was overtopping followed by embankment collapse, which did not occur in the foundation. This would mean that only the pool and erodible tailings had been released as opposed to other failures such as Mount Polley which was a foundation failure and therefore encapsulated additional materials beyond only the tailings in the failure mechanism.

6 CONCLUSIONS

Guidelines on dam breach assessments often lack detail, and this study aimed to provide insights into one key aspect, namely breach volume estimation. The geometric method applied in this study proved to be a reasonable and conservative approach for estimating breach volumes. The preliminary investigation, based on three historical dam failures, revealed that the calculated results for the Brumadinho and Mount Polley failures were within a 10% – 20% margin of error when compared to recorded volumes. However, the Merriespruit results were significantly overestimated using this method as the failure mode resulted in only eroded tailings being released.

The limitations of this study include the reliance on publicly available data, limited information on tailings rheology, and the lack of detailed survey data. Future research should focus on incorporating more historical case studies and obtaining comprehensive technical datasets to refine the methodology.

This study underscores the practical applicability of the geometric method for breach volume estimation in conjunction with CDA standards. The results provide a foundation for tailings dam breach modelling in the industry and highlight the importance of accounting for factors such as supernatant ponds in future assessments.

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