

# **A CONCEPTUAL ELEVATION VERSUS VOLUME CURVE DETERMINATION METHOD FOR TAILINGS DAM BREACH STUDIES**

JL Schoeman<sup>1</sup>

1. Knight Piésold, Pretoria, South Africa

**PRESENTER: VICCI SCHOEMAN**

## **ABSTRACT**

Most of the theory used in tailings storage facility breach studies was developed for water dams and are not fully applicable to tailings storage facility failures. This paper describes a conceptual alternative formulation of the elevation versus volume curve of the cone of depression that forms during a tailings dam breach. It is the intention that the alternative elevation versus volume curve formulation method be used in conjunction with the hydrologic reservoir routing method to generate more realistic tailings dam failure outflow hydrographs. Only an overview of the method is given here, with more research being required to fully validate the method.

## **1. INTRODUCTION**

Various methods exist to determine the potential zone of influence for the breach of a tailings storage facility (TSF). These methods range from reasonably simple methods such as the SABS 0286 Code of practice for mine residue method (SANS, 1998) to full hydrodynamic modelling using non-Newtonian flow models that are informed by rheological studies, liquefaction analyses and LiDAR survey data. More and more inputs are required with increasing analysis methodology complexity. Some of these inputs can be quantified by investigation and testing, but ultimately a lot of uncertainty remains, and numerous assumptions are required to execute a TSF breach analysis. These assumptions are based on engineering judgement, where engineering judgement is defined as “the ability to interpret factual information in light of one’s own experience.” The inevitable consequence of the high degree of uncertainty and the subjective nature of engineering judgement is a wide range of possible results generated for the same problem by different practitioners.

The problem of variability of results is compounded in the case of TSF failures when compared to normal embankment dams, as most of the theory developed for dam breach studies was developed for embankment dams and are not fully applicable (Martin et al., 2015). The application of embankment dam theory to TSF breach studies leads to even more engineering judgement being required, as the fundamentally different conditions under which the calculation methods were developed versus what they are being used for needs to be considered. By implication theories developed specifically for TSF breach studies should reduce the variability in the results generated by different practitioners.

A technique inherited from embankment dam breach theory is the hydrologic (or level pool) reservoir routing method (SANCOLD, 1990). The elevation versus volume curve (EV-curve) of the impoundment is one of this method’s key input parameters, along with breach parameters such as breach formation rate, final bottom width and side slopes. Such EV-curves have traditionally been calculated using the (horizontal) method of slices, or other similar techniques. The author’s experience in generating TSF breach hydrographs based on traditionally calculated EV-curves led to the realisation that this approach overestimates the volume tailings that is available to mobilise through the breach section in the top portion of the impoundment. This in turn leads to an overestimation of the outflow peak.

This paper outlines a conceptual methodology to determine the EV-curve of the assumed tailings failure volume based on the assumption that the shape of the failure volume will remain congruent to the final shape of the cone of depression during the progression of the breach. The ultimate motivation for the development of an alternative EV curve calculation method is to produce more realistic TSF breach outflow hydrographs and secondly to simplify the engineering judgement-based assumptions that need to be made during a TSF breach analysis due to the non-applicability of water dams breach theory.

Martin et al. (2015) intended that their paper titled “Practical tools for tailings dam breach studies” be a starting point for ongoing discussion about what approaches and methods are best suited to specific aspects of tailings dam breach and inundation studies. The objective of this paper is to continue the discussion by describing the starting point of the development of another practical tool that can aid practitioners in the development of tailings dam breach outflow hydrographs. Formal validation of the method will be the subject of future research.

**2. DETERMINATION OF THE ELEVATION VERSUS VOLUME CURVE**

**2.1 Conceptual dam breach characteristics**

Small et al. (2017) suggest that the fraction of impounded tailings that will be released during a breach is a function of (a) the presence of a pond near the breach and (b) the potential for liquefaction of the tailings. The authors propose that tailings dam failures be categorised into the four distinct classes illustrated in Figure 1.

		Potential for tailings to runoff of the breach area as a result of liquefaction (seismic or static)	
		Yes	No
Presence of free water in area of breach	Pond near crest of dam	<b>1A: Dam break method with flow of liquefied tailings contributing additional volume of material released</b>	<b>1B: Dam break method with tailings eroded, transported and deposited by flow of water</b>
	No pond or pond far from crest	<b>2A: Slope failure with debris flow or mud flow (degree of saturation)</b>	<b>2B: Slope failure</b>

Liquefaction of tailings – could be induced by (i) a seismic event associated with a dam breach (either causing or following) and/or (ii) by shear strains in the tailings as a result of the dam breach.

**Figure 1. Tailings breach classes based on the presence of free water and liquefaction potential.**

Rico et al. (2007) and Haumán et al. (2015) report that the volume of tailings mobilised during historic tailings dam failures vary between 1% and 100% of the stored tailings. Several sources (Martin et al., 2015, Rico, 2007 and Haumán et al. 2015) recommend taking the fraction of released tailings between 37 % to 40 % of the total impounded tailings volume as a first order estimate. The logical consequence of the paper by Small et al. (2017) is that the initial mobilisation estimate of between 37 % to 40 % should be adjusted upwards or downwards by the analyst based on factors such as liquefaction potential, pool position and other site-specific considerations.

**2.2 Shape of the failed tailings volume**

Regardless of the actual volume of tailings released during a dam breach, some form of residual failure surface, also termed a cone of depression, will form during a TSF breach event. Two examples of such failure surfaces are illustrated in Figures 2 and 3.



**Figure 2. Aerial view indicating the cone of depression after the failure of the Merriespruit TSF in 1994 (Engels, n.d.)**



**Figure 3. Cone of depression visible after the failure of the Kolontár dam (Oszvald, 2015 in Martin et al., 2015)**

The shape of the cone of depression can be approximated as a cone or any other applicable well-behaved piecewise continuous function. For simplicity of illustration only a simple cone is considered in this paper.

The ultimate shape selected for the cone of depression by the analyst will be influenced primarily by the height and assumed residual slope of the tailings impoundment. The total volume and shape of the assumed cone of depression should be critically evaluated in the light of the expected dam breach characteristics outlined in the preceding sub-section.

### **2.3 Description of an alternative formulation of the elevation versus volume curve**

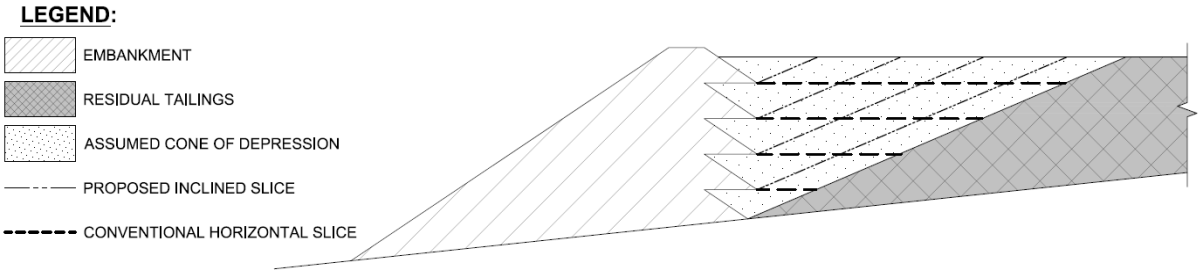
A conventional EV-curve of a tailings failure volume can be calculated using the method of slices:

- Slice the assumed failure volume horizontally at discrete elevations.
- Determine the surface area of each slice.
- The volume between two slices is equal to the average of the bounding slices' areas times the height difference between the slices. This inter-slice volume can be visualised in 3-D as a flat disc.
- The conventional EV-curve is calculated by taking the cumulative sum of the inter-slice volumes.

An alternative formulation of the method of slices for the calculation of the EV-curve of a cone of depression approximated by a cone is as follows:

- Slice the volume at an angle equal to the assumed residual slope of the tailings at discrete elevations. Each slice will form a smaller version of the final cone of depression when viewed in 3-D\*.
- The volume of the top-most slice is calculated directly based on its conical shape.
- The volume between any other two slices is calculated by taking the difference between two consecutive cone-shaped volumes.
- The EV-curve is the cumulative sum of the inter-slice volumes.

The difference between the conventional horizontal method of slices and the alternative described above is illustrated graphically for a hypothetical cross section in Figure 4.



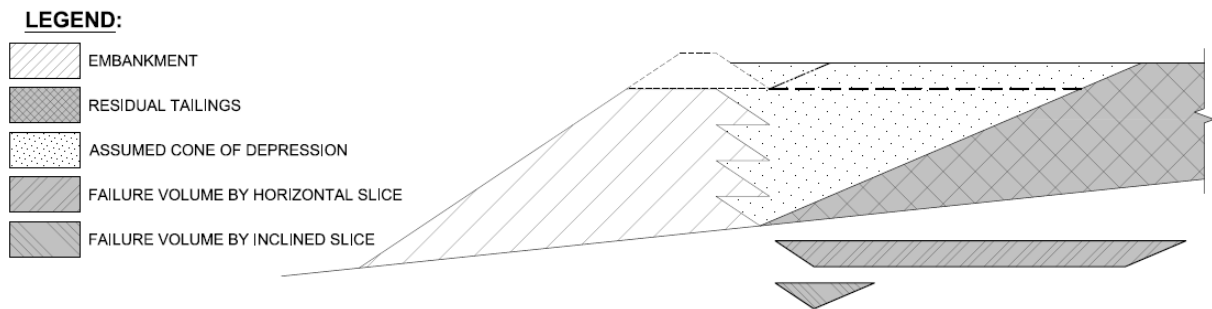
**Figure 4. Inclined versus horizontal slices for determining an elevation versus volume curve for an assumed cone of depression.**

Consider the case where the dam in Figure 4 is breaching, with the breach having developed to the level of the top-most slice's bottom elevation. What is the maximum conceivable volume of tailings that could be mobilised up to this point in time? This author's view is that the maximum cone of depression at this point should have a similar shape to the final cone of depression. This assumption is essentially an extension of the widely accepted assumption that is made when considering the temporal change in the geometry of the breach outflow section. This is more in line to the routing which can be performed with HEC-RAS using one-dimensional unsteady flow routing (using Saint Venant equations) or two-dimensional unsteady flow routing (using Saint Venant or Diffusion Wave equations) compared with level pool routing. The unsteady flow routing can capture the water surface slope during the dam breach (US Army Corps of Engineers, 2014).

The difference between the maximum volume of tailings that can be mobilised by the top-most horizontal or inclined slices indicated in Figure 4 are illustrated in Figure 5. A moment's consideration should convince the reader that the alternative EV-curve intuitively provides a more realistic representation of the volume of tailings that is available to mobilise, either due to erosion during the initial flood wave or due to the ensuing paste-like outflow resulting from static liquefaction.

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\* This principle should hold true for other than cone-shaped approximations for the shape of the final cone of depression as well. Each slice, when viewed in 3-D, should be a smaller but congruent version of the final failure surface.

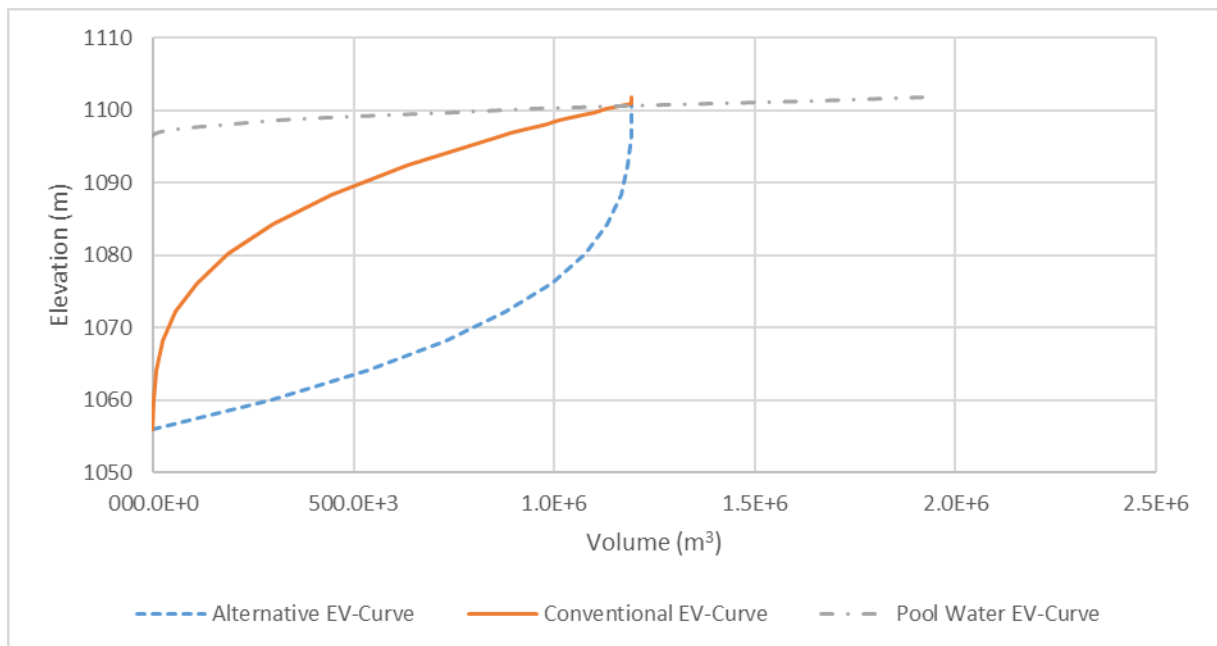


**Figure 5. A comparison between the volume of tailings available to breach as calculated by the standard and proposed methods.**

### 3. A HYPOTHETICAL CASE STUDY

#### 3.1 Comparative EV-curves

The practical implications of adopting the alternative EV-curve calculation method is illustrated below by a hypothetical example. EV-curves for an assumed conical failure surface from a Class 1A type failure of a 45 m high TSF are illustrated in Figure 6. The volume of pond water to the volume of tailings assumed to liquefy is in the order of 1,5 : 1.



**Figure 6. EV-curves for the assumed cone of depression and the pool water.**

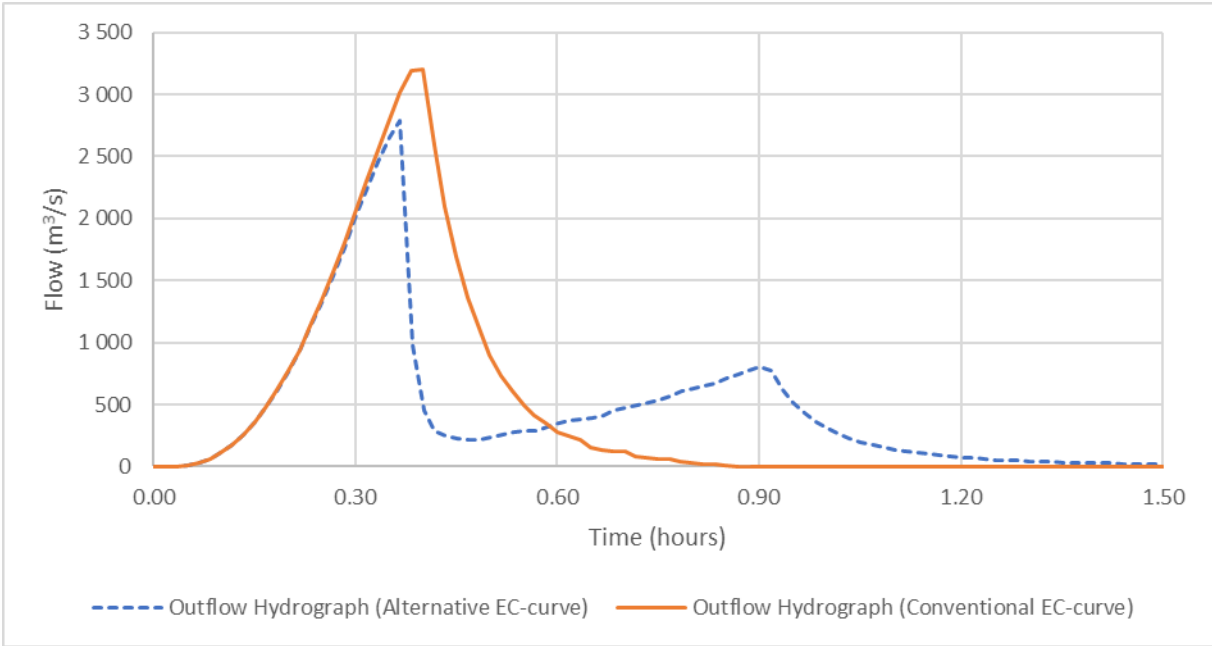
Note that the two EV-curves for the failure volume converge at the maximum tailings level. This is expected, as the total assumed failure volume remains the same regardless of the method selected to calculate the EV-curve. The main difference between the two curves is that the conventional EV-curve is top-heavy: A 10 m reduction in elevation from the highest embankment level would release over 50 % of the stored volume. In contrast to this only a small portion of tailings would be mobilised for the same 10 m reduction in elevation when considering the alternative EV-curve.

#### 3.2 Hydrologic reservoir routing

There is ongoing debate on the topic of the appropriate solids concentration to assume for the initial flood wave. This is an important parameter, as it could potentially have a significant influence on the volume of water that is used to model the initial flood wave. A higher assumed solids concentration for the same pool volume leads to a higher volume of material contained in the initial flood wave, likely causing a higher calculated peak flow (Fontaine & Martin, 2015). This debate will be side-stepped for the moment by simply assuming that the entire volume will flow like water (i.e. Newtonian behaviour)

and taking the EV-curves used as input in the breach analysis as the sum of the volume of the pool and the respective EV-curves for the entire failure volume. While this approach is obviously technically flawed from a hydraulics perspective, the current purpose of illustrating the effect that the alternative EV-curve can have on the shape of the outflow hydrograph is not hindered.

Figure 7 illustrates the difference between outflow hydrographs produced using the hydrologic reservoir routing method with different EV-curves as input but keeping the other breach parameters the same. The breach was modelled as an overtopping failure with the water level at the top embankment level at the start of the analysis. A constant breach rate of 50 m per hour, final bottom width equal to the height of the wall and side slopes of 1 : 1 were assumed. No inflows were considered. The downstream terrain had a slope of -0,9 %.

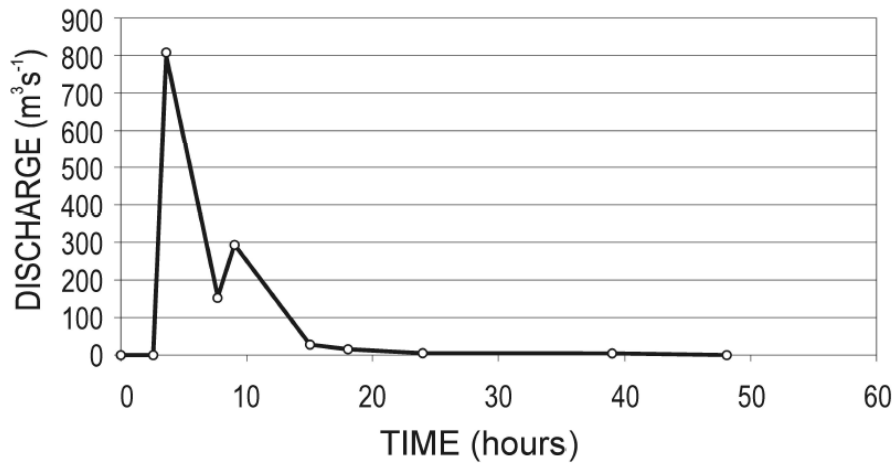


**Figure 7. Breach outflow hydrographs generated using the hydrologic reservoir routing method**

Figure 7 illustrates the difference between the hydrograph shapes and peak values calculated by respectively using the alternative or conventional EV-curves. The following observations are made:

- The use of the EV-curve determined using the alternative method described in this paper as input to a hydrologic reservoir routing dam breach analysis yielded an outflow hydrograph with two peaks. The first peak can be associated with the initial flood wave, and the second peak with the ensuing slumping-style tailings outflow.
- The peak of the initial flood wave was likely modelled theoretically correctly, as the sediment concentrations expected during the initial flood wave should be low enough not to alter the flow behaviour significantly. Further study is required to confirm this assertion.
- The calculated slumping-style outflow peak is too high due to the non-Newtonian behaviour of the liquefied tailings not being considered.
- The initial peak calculated using the alternative EV-curve is lower than the peak calculated using the conventional one. This is the result of there being less volume available in the EV-curve at high elevations, causing the level in the impoundment to drop quicker.

The obvious question to ask at this point is whether the results obtained by incorporating the alternative EV-curve in the analysis reflects reality. Little data exists or is available on tailings dam breach outflow hydrographs to verify the conceptual approach described in this paper. An example of such a hydrograph that is available is the slurry flood hydrograph that was measured at the El Guijo gauge station, 11 km downstream of the Los Frailes tailings dam, in the Guadiamar River (Ayala-Carcedo, 2004 in Rico, 2007). This hydrograph is presented in Figure 8.



**Figure 8. Hydrograph from the Los Frailes TSF failure measured 11 km downstream at the El Guijo gauge indicating the initial flood wave peak and the ensuing tailings slurry flow peak.**

At face value there appears to be some merit to the adoption of the alternative EV-curve: The general shape of the hydrograph calculated using the alternative EV-curve and the historic hydrograph presented in Figure 7 are similar. The initial flood wave and ensuing slumping-style tailings outflow portions of the flow can easily be distinguished on both hydrographs, something that is not possible with the hydrograph obtained when using the conventional EV-curve.

### 3.3 Limitations

The hydrologic reservoir routing method is limited when compared to other routing methods such as hydraulic reservoir routing. In cases where rapid, near instantaneous breaching occurs, a negative wave may propagate upstream into the impoundment with consequent effects on the outflow rate. The effects of this phenomenon are likely to be more prevalent for TSF failures than for water dams due to the higher viscosity of the slumping-style tailings flow. Hydrologic routing cannot take this effect into account.

The comparison between the shapes of the hydrographs presented in Figures 6 and 7 is not meant to be a full verification of the described method.

## 4. FUTURE RESEARCH

What was presented in this paper is a conceptual idea for defining a more realistic EV-curve, but it is only a starting point. More research is required before the alternative EV-curve calculation method should be incorporated as part of TSF breach studies:

- The non-Newtonian nature of the slumping-style tailings flow should be considered in the determination of the breach outflow hydrograph. The effects of this aspect require further investigation.
- The alternative EV-curve method has not been adequately verified against past failure cases or other TSF breach hydrograph calculation methods.
- A Class 1A failure mode was modelled in this paper. Other failure classes also need to be considered.
- The potential of the method to influence the selection of the assumed solids concentration during the initial flood wave needs to be studied.
- The fundamental assumption on which the alternative EV-curve method is based is that the failure volume will maintain a congruent shape to the final failure surface over time. In reality the development of the failure volume over time will be a function of hydraulics, rheology and soil mechanics. The failure volume congruency assumption therefore also requires validation.

## 5. CONCLUSION

The objective of this paper was to serve as a starting point for the development of a practical tool that can be used as part of TSF breach studies. This was achieved in three steps:

- A conceptual method to determine the elevation versus volume curve of the cone of depression that is formed during a TSF failure was described. The alternative EV-curve method is based on the principle that the failure volume will maintain its shape over time. If a conically shaped cone of depression is assumed, then the failure volume will start as a small cone and will get progressively larger until the bottom breach elevation is reached.
- Elevation versus volume curves were generated for an example case using both a conventional method and the method described in this paper. These were used as inputs in a hypothetical breach scenario. It was found that the alternative elevation versus volume curve formulation enabled the identification of two distinct peaks: Both the initial flood wave and the ensuing slumping-style tailings outflow peaks could be identified in the breach outflow hydrograph. The initial peak calculated using the alternative elevation versus volume curve was slightly lower than the single peak calculated using the conventional one.
- The limitations of the method and future research required to complete the described method's development were highlighted.

## 6. ACKNOWLEDGEMENTS

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