

TAILINGS AND MINE WASTE 2015


PROCEEDINGS OF TAILINGS AND MINE WASTE 2015 CONFERENCE

Colorado State University

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Tailings mobilization estimates for dam breach studies

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ABSTRACT

Quantitative assessment of potential consequences caused by a flood from a dam breach of a tailings facility requires an estimate of the volume of water and tailings released during the breach. A methodology for estimating the volume of tailings mobilized by the free water stored in the pond and the resulting initial flood wave following a dam breach is presented. Tailings mobilization can be estimated as a function of the stored water volume and the physical characteristics of the tailings deposit. The result is an estimate of the total outflow consisting of volumes of free water, and tailings and interstitial water that could be potentially mobilized. This approach indicates that a larger operating pond would mobilize more tailings than a smaller pond. Similarly, a tailings deposit that is more consolidated or only partially saturated would result in a smaller volume of tailings being released in a breach. These are the primary attributes of stored tailings affecting the potential consequences of a breach. An understanding of these attributes allows the practitioner to use the results of the analysis as a decision making tool for decreasing the consequences of failure.

Key words: dam breach, methodology, solids content, outflow volume, risk

1 INTRODUCTION

Tailings dam breach studies are often expected and required for operating and planned Tailings Storage Facilities (TSFs). The Technical Bulletin *Application of Dam Safety Guidelines to Mining Dams* issued by the Canadian Dam Association (CDA) does not prescribe procedures for conducting tailings dam breach analyses, but is rather limited to identifying "some specific issues that should be considered during the design and safety evaluation of mining dams" (CDA 2014). The guidelines (CDA 2007a, CDA 2007b, FERC 1993, FEMA 2013) that are typically followed for tailings dam breach analyses were originally developed for water retaining dams, and as such, are not fully applicable to tailings dams.

The key difference between a water retaining dam failure and a tailings dam failure is in the outflow volume and the solids contained in that volume. A breach of a water retaining structure typically results in the discharge of the entire impounded volume of water above the breach. The outflow has a relatively low solids content originating from the embankment material and mobilization of settled sediments from the reservoir. A breach of a tailings retaining structure, in contrast, could result in the discharge of the entire supernatant pond volume, but does not have to result in the full discharge of the impounded tailings volume. A dam breach of a TSF that has a supernatant pond typically results in two discharge mechanisms: (1) an initial flood wave, and (2) slumping or flow of liquefied tailings. These mechanisms occur in sequence following a catastrophic failure of a TSF dam for all cases where there is a supernatant pond present, and are distinctly different in terms of the potential risk they pose to the downstream environment. The initial flood wave would propagate much farther causing extensive erosion and larger inundation downstream, while the flow of liquefied tailings would cause deposition in the areas immediately downstream of the facility with a smaller inundation footprint. This paper focuses on estimating the volume of tailings released from the facility with the initial flood wave. More tailings may be released in addition to the tailings released with the initial flood wave, which is further discussed in a companion paper (Martin et al., 2015).

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

The volume of water in the facility can be estimated reasonably accurately with an understanding of pond volumes for both sunny day (normal operating level) and rainy day (flood induced) failure scenarios. The approach to estimating the volume of tailings released in a breach is not clearly defined in available literature. A common approach is to estimate the volume of released tailings as a percentage of the stored tailings in the facility at the time of the breach, which is largely based on the judgement of the practitioner. Estimates ranging between 10% and 100% are not uncommon. While useful for high level studies, this approach does not take into consideration the physical mechanisms controlling the volume of tailings released.

Rico et al. (2007) developed an empirical relationship (Equation 1) which predicts that approximately 37% of the impounded volume (V_T in Mm^3) comprising tailings solids, supernatant and interstitial water, is released in the breach outflow volume (V_{OUT} in Mm^3). This approach is quite commonly used by practitioners to estimate outflow volumes, but may at times result in unrealistic estimates. About 250 known cases of tailings dam failures worldwide have been compiled; however, the basic information is often incomplete. Relationships developed by Rico et al. (2007) are based on 28 historic tailings dam failures for which complete data on runout distances and outflow volumes were available.

$$V_{OUT} = 0.354 \text{ x } V_T^{1.01} \quad (1)$$

The approach proposed in this paper is to consider the available free water in the supernatant pond that, through the process of solids entrainment and mixing, has a potential to mobilize a certain mass of tailings and embankment construction material. Tailings mobilization can be estimated as a function of the volume of stored water and the physical characteristics of the tailings deposit, such as the total mass of deposited solids, density of the solids, degree of saturation, and average dry density. The mass of mobilized tailings is estimated as a function of the water volume by assuming full mixing of the free water with the tailings solids and interstitial water at a selected solids content limit. The result is an estimate of the total outflow volume which consists of the initial supernatant pond volume, tailings solids, and interstitial water that would be potentially mobilized.

2 METHODOLOGY

The estimate of tailings mobilization should follow a repeatable methodology that considers the physical characteristics of the tailings facility. The proposed methodology includes four key steps:

1. Define the Tailings Deposit Characteristics
2. Define the Supernatant or Storage Pond Volume
3. Estimate the Solids Content of the Breach Outflow
4. Predict the Breach Outflow Volume

The approach for each step and the equations used to develop an estimate are provided in the sections that follow.

2.1 Define Tailings Deposit Characteristics

The first step is to establish an estimate of the characteristics of the tailings deposit at the time when the consequences of a breach are going to be examined. The storage volume and characteristics of the tailings deposit will change throughout operations and closure, and an estimate of tailings mobilization is limited to a representative point in time. The tailings deposit characteristics should initially include estimates of the following:

- mass of tailings solids stored,
- average dry density of the tailings deposit,
- tailings solids density, and
- degree of saturation of the tailings.

Estimates of the above parameters are usually readily available as design basis criteria during evaluation of a new project or from actual characterization data for an existing facility. The remainder of the tailings deposit characteristics can be calculated using first principles and these initial estimates. Various calculated parameters include:

- volume of the tailings deposit,
- volume of tailings solids,
- volume of voids,
- porosity,
- void ratio,
- volume and mass of interstitial water,
- moisture content, and
- tailings bulk density.

A hypothetical project is defined for the purpose of this paper to demonstrate the methods presented. This project has a tailings facility sized based on a mill throughput of 20 million tonnes per year (20 Mt/yr) with a mine life of 10 years. The total mass of tailings solids ($M_{S\text{-}INIT.}$) retained at the end of mine life is 200 Mt. The average dry density (ρ_D) of the deposit is 1.4 tonnes per cubic metre (1.4 t/m^3). The tailings solids density (ρ_S) is 2.7 t/m^3 (specific gravity of solids multiplied by the density of water). The degree of saturation (S) of the tailings deposit is 100%. These initial characteristics can be used to calculate other tailings deposit characteristics as presented below.

The total volume of the tailings deposit:

$$V_T = M_{S\text{-}INIT.} / \rho_D \tag{2}$$
$$V_T = 143 \text{ Mm}^3$$

The volume of the tailings solids:

$$V_S = M_{S\text{-}INIT.} / \rho_S \tag{3}$$
$$V_S = 74 \text{ Mm}^3$$

The volume of the tailings voids:

$$V_V = V_T - V_S \tag{4}$$
$$V_V = 69 \text{ Mm}^3$$

The porosity of the tailings deposit:

$$n = V_V / V_T \tag{5}$$
$$n = 0.48$$

The void ratio of the tailings deposit:

$$e = V_V / V_S \tag{6}$$

$e = 0.93$

The volume of the tailings interstitial water:

$$V_{IW} = S \times V_V \qquad \text{where } S = 1.0 \text{ for this example} \tag{7}$$

$$V_{IW} = 69 \text{ Mm}^3$$

The mass of the tailings interstitial water:

$$M_{IW} = V_{IW} \times \rho_W \qquad \text{where } \rho_W = 1.0 \text{ t/m}^3 \tag{8}$$

$$M_{IW} = 69 \text{ Mt}$$

The moisture content of the tailings deposit:

$$\%_W = M_{IW} / M_{S\text{-}INIT.} \tag{9}$$

$$\%_W = 0.34 = 34\ \%$$

The bulk density of the tailings:

$$\rho_{BULK} = (M_{S\text{-}INIT.} + M_{IW}) / V_T \tag{10}$$

$$\rho_{BULK} = 1.9 \text{ t/m}^3$$

2.2 Define Supernatant Pond Volume

The second step is to establish an estimate of the volume of supernatant water stored within the impoundment. This estimate may also include concurrent storm water storage if applicable for the chosen scenario. The estimated volume should be consistent with the representative point in time used to develop the tailings deposit characteristics. This volume is referenced as the amount of free water throughout this paper. Testing a range of values may be appropriate for facilities with fluctuating water storage. The mass of water is required for the tailings mobilization estimates; a density of water of 1 t/m^3 is used in the following calculations.

The hypothetical project for this paper considers a tailings facility with an operating pond storage volume (V_W) of 10 Mm^3.

The mass of the free water in the operating pond is:

$$M_W = V_W \times \rho_W \qquad \text{where } \rho_W = 1.0 \text{ t/m}^3 \tag{11}$$

$$M_W = 10 \text{ Mt}$$

2.3 Estimate the Solids Content of Breach Outflow

The mobilization of tailings during a breach can be calculated using first principles by estimating the gravimetric solids content of the resulting outflow. The selected solids content estimate is up to the practitioner and should be developed on a case by case basis. A rationale for the selected solids content of the breach should be provided and should be consistent with the purpose of the study. The practitioner conducting the study should specify the ratio at which mixing would occur. A solids content of 50% is one part water and one part solid, by mass. A solids content of 35% is two parts water and one part solid.

The simplifying assumption is that the free water mixes instantaneously with the tailings deposit during breaching until the resulting slurry reaches the specified solids content. A solids content

(%s) limit can be applied with an understanding of the “flowability” of the resulting breach outflow. This is a key parameter for the proposed methodology and the practitioner should use the available resources to make a reasonable and defensible estimate (or estimated range of values). For example, lab test data may be available from process test work, rheology testing, or geotechnical lab testing. This information may provide a basis for the solids content estimates.

A solids content of 55% was selected for the hypothetical project considered in this paper, which represents a typical solids content of a thickened slurry.

$$\%s = 0.55$$

The solids content of the resulting breach outflow is a value defined by the practitioner and is directly used to estimate the tailings mobilization volume. The solids content of the outflow can be calculated as a ratio of the mass of mobilized solids in the outflow ($M_{S\text{-}MOB}$) to the total mass of the outflow that includes solids and water. This ratio is defined in Equation 12 as follows:

$$\%s = M_{S\text{-}MOB} / (M_{S\text{-}MOB} + M_{IW\text{-}MOB} + M_W) \tag{12}$$

where $M_{IW\text{-}MOB} = M_{S\text{-}MOB} \times \%w$

2.4 Predict the Dam Breach Initial Flood Wave Outflow Volume

The volume of tailings mobilized by the initial flood wave is estimated as a function of the free water in the supernatant pond and the tailings (including solids and interstitial water) that can mix with this free water. First, the mass of mobilized tailings solids ($M_{S\text{-}MOB}$) is determined by reorganizing Equation 12 to derive Equation 13. The mass of mobilized tailings solids for the hypothetical project used in this paper is:

$$M_{S\text{-}MOB} = M_W / ((1 / \%s) - 1 - \%w) \tag{13}$$

valid for $\%w < (1 / \%s) - 1$

$$M_{S\text{-}MOB} = 21 \text{ Mt}$$

The estimate of the tailings solids mobilized by the initial flood wave must be compared with the total solids stored within the tailings facility as a limiting condition. More tailings than existing within the facility cannot be mobilized. The estimate of mobilized tailings should be adjusted to the lower of the two values. Consequently, facilities with large volumes of stored water may result in 100% tailings released in a breach, while facilities with smaller volumes of water would result in partial release of stored tailings. The hypothetical project used in this paper would result in a partial release of stored tailings:

$$M_{S\text{-}MOB} \leq M_{S\text{-}INIT}$$

$$21 \text{ Mt} < 200 \text{ Mt}$$

The resulting breach outflow volume can then be determined using the mass of mobilized tailings solids. The breach outflow volume includes free water, tailings solids and interstitial water. The mass of the mobilized tailings interstitial water is:

$$M_{IW\text{-}MOB} = ((M_{S\text{-}MOB} / \rho_D) - (M_{S\text{-}MOB} / \rho_S)) \times S \times \rho_W \qquad (14)$$

$$M_{IW\text{-}MOB} = 7 \text{ Mt}$$

The volume of the mobilized tailings is:

$$V_{T\text{-}MOB} = (M_{S\text{-}MOB} + M_{IW\text{-}MOB}) / \rho_{BULK} \qquad (15)$$

$$V_{T\text{-}MOB} = 15 \text{ Mm}^3$$

The resulting breach outflow volume is:

$$V_{OUT} = V_W + V_{T\text{-}MOB} \qquad (16)$$

$$V_{OUT} = 25 \text{ Mm}^3$$

The resulting percentage of volume of the impoundment released in the breach is:

$$\%V_{OUT} = V_{OUT} / (V_W + V_T) \qquad (17)$$

$$\%V_{OUT} = 0.16 = 16 \%$$

The conclusion of the tailings mobilization estimate for this particular analysis is that this hypothetical tailings facility containing 200 Mt (143 Mm^3) of tailings and a supernatant pond of 10 Mm^3 has the potential to mobilize 15 Mm^3 of tailings during a breach of the facility under normal operating pond conditions and assuming that the tailings will mix to a 55% solids content. The mobilized tailings volume would consist of approximately 21 Mt of tailings solids and 7 Mt of interstitial water. The total breach outflow is estimated to be approximately 25 Mm^3, which represents 16% of the total volume of the impoundment (stored tailings and free water). The estimated breach volume in this case is approximately 2.5 times the pond volume at the time of the breach (bulking ratio).

3 SENSITIVITY

Estimating the volume of mobilized tailings is subject to uncertainty. There are a number of physical attributes of stored tailings that will affect the flowability in the event of a dam breach; the three basic parameters considered in this methodology are:

- volume and location of stored water,
- density of the tailings, and
- degree of saturation of the tailings.

These three physical attributes, together with the estimated solids content of the breach outflow, play a controlling role in the tailings mobilization estimate. The following sections discuss the sensitivity to these key parameters.

3.1 Sensitivity to Supernatant Pond Volume

The volume and location of the supernatant water has a direct impact on the resulting breach outflow volumes. The location of the pond is not a specific topic of this paper; however, it is noted that the storage of water away from tailings dams is preferred in the majority of cases to minimize the likelihood and potential consequences of a breach developing. Water that is unavailable to develop a breach would have no impact on the potential breach outflow if that condition is maintained (e.g. water separated by a significant tailings beach, stored in a separate location in or external to the facility, stored below the breach invert).

The initial flood wave outflow volume is predicted to have a linear relationship with the initial volume of supernatant water. More water storage is a direct indicator of increasing breach outflow volume as demonstrated on Figure 1, which shows the relationship of the supernatant pond volume and the predicted initial flood wave outflow volume at solids contents between 25% and 65% in 10% increments. The comparison assumes the same initial tailings deposit characteristics as described in Section 2.1.1. The ratio between the pond volume and the outflow volume can be estimated from Figure 1 for the tailings facility considered in this paper. This represents a bulking ratio that appears to range from 1.3 to 4.7 for outflow solids contents of 25% and 65%, respectively. There is a significant jump in bulking ratio between 55% and 65% solids, which is attributed to the non-linear relationship between the mass of mobilized solids and the assumed solids content.

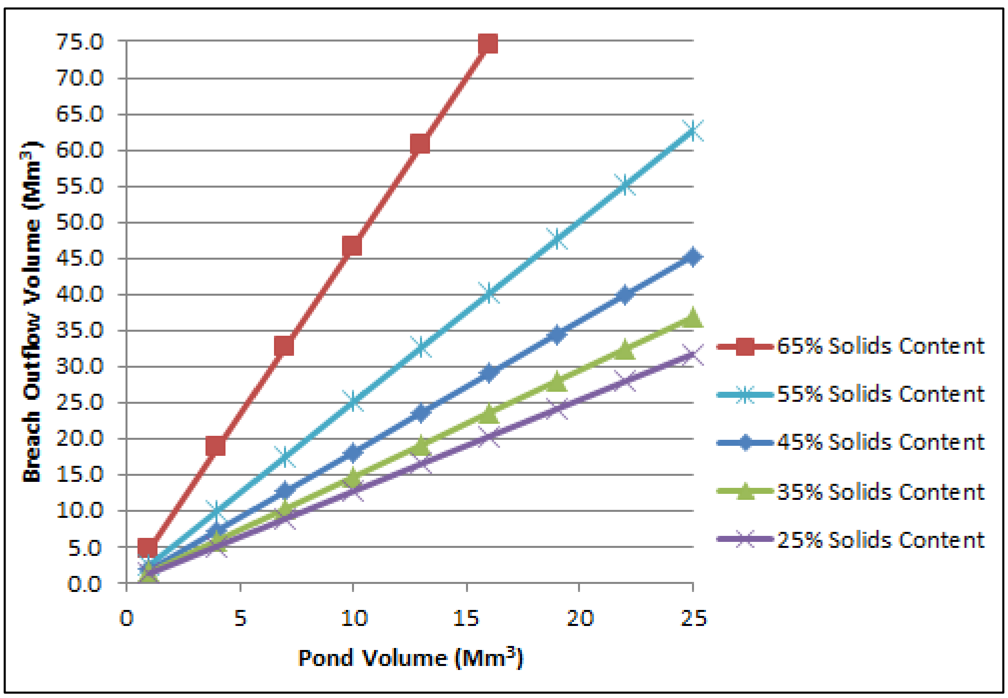

Figure 1: Sensitivity of Breach Outflow Volume to Pond Volume

3.2 Sensitivity to Initial Dry Density

The density of the stored tailings will also have an impact on the mobility of tailings during a dam breach. Tailings mobility decreases as density increases. Increased density is typically achieved through initial settlement and longer-term consolidation. Improvements in density can be accelerated by passive processes such as drainage provisions and consolidation under self-weight or active processes such as dewatering and compaction. Tailings consolidation releases interstitial water and increases the mass of solids per unit volume, thereby increasing the volume of water required to mobilize the tailings. It is recognized that there are other physical processes associated with increasing in situ tailing densities that will affect the mobility of the solids, but these are not considered in this conceptual model.

Figure 2 shows the relationship between the predicted breach outflow volume and the average dry density of the tailings. The comparison was done for a pond volume of 10 Mm^3 consistent with the example project included in this paper. The solids contents of the outflow are again shown between 25% and 65% solids in 10% increments for comparison. The breach outflow volume has a non-linear relationship with the density of the tailings, although below approximately 35% solids, the relationship is relatively linear. Above 45% solids content and below a density of approximately 1.3 t/m^3, the breach outflow volume estimates increase rapidly for the lower density tailings. This is consistent with what is expected in reality considering that a tailings density approaching 1.0 t/m^3 is typically representative of finer tailings and slimes that were deposited below the tailings facility pond. The moisture content for these materials would be 40 to 60% or greater, which would make them more likely to flow. These materials are often isolated from the tailings dam by a higher density coarse tailings beach that typically forms closer to the dam near tailings discharge locations.

A significant jump is again evident for the breach outflows between 55% and 65% solids, and is present even at higher densities. This difference is more pronounced for the density and breach outflow volume relationship than for other tested relationships presented in this paper. This is related to the density and moisture content of the tailings deposit under consideration. The 65% solids content curve begins to deviate considerably from the other curves as the dry density decreases. A similar trend but at a lower density is apparent for the 55% solids content curve as well.

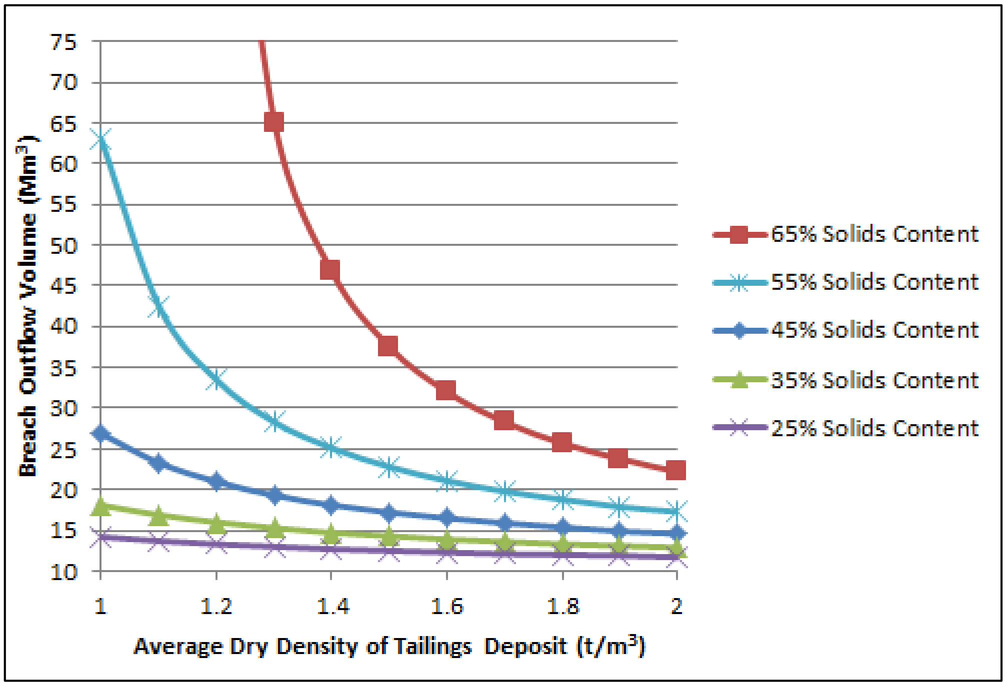

Figure 2: Sensitivity of Breach Outflow Volume to the Average Dry Density of the Tailings

The tailings deposit for this hypothetical project was described as a "soil" with an average dry density of 1.4 t/m^3, a degree of saturation of 100% and a moisture content of 34%. Characteristics of a flowing slurry (water content and solids content) do not technically apply to a soil; however, if these characteristics were applied to the tailings deposit then the theoretical solids content for lower density tailings would be similar to the higher solids contents used for breach outflow estimates (e.g. a soil with density of 1.1 t/m^3 has a solids content of 65%). A summary of tailings dry density and theoretical water and solids content is provided in Table 1.

Table 1: Theoretical Water Content and Solids Content of Settled Tailings

Average Dry Density (t/m^3)	Degree of Saturation (%)	Moisture Content (%w)	Water Content (w.c.)	Solids Content (%s)
1.0	100	61%	39%	61%
1.1	100	54%	35%	65%
1.2	100	46%	32%	68%
1.3	100	40%	29%	71%
1.4	100	34%	26%	74%
1.5	100	30%	23%	77%
1.6	100	25%	20%	80%
1.7	100	22%	18%	82%
1.8	100	19%	16%	84%
1.9	100	16%	13%	87%
2.0	100	13%	11%	89%

1. Water content (w.c.) = %w ÷ (1 + %w)

The reason for the observed deviation on Figure 2 is in the increasing moisture content associated with the decreasing tailings density. Explained in mathematical terms, at any selected mixing solids content, there will be a corresponding moisture content where the denominator in Equation 13 becomes zero and the solution goes to infinity. For example, if the selected solids content for mixing is 65% then a tailings moisture content of 54% would invalidate Equation 13. A moisture content of 54% is consistent with tailings density of 1.1 t/m^3, as shown in Table 1. In other words, a soil with 65% solids content cannot be mixed with more water and remain at 65% solids. This means that if the moisture content of the tailings under consideration is near this limit then the mobilization estimate will asymptotically reach infinity, because such mixture cannot occur. The physical constraints described by Equation 13 should be carefully considered when making "conservative" assumptions. There is a difference between conservative and unrealistic.

3.3 Sensitivity to Degree of Saturation

The degree of saturation of the tailings will have an impact on the mobility of tailings in a breach, but to a lesser extent than pond volume and deposited tailings density. The relationship is non-linear, and varies depending on the solids content.

Figure 3 shows the relationship of predicted breach outflow volume with saturation of the tailings. The comparison was again made for the hypothetical project with a pond volume of 10 Mm^3 and a tailings density of 1.4 t/m^3. The solids contents of the outflow are again shown between 25% and 65% solids in 10% increments. The increase between 55% and 65% solids is substantial. The trend for a breach outflow with 65% solids content is considerably more sensitive to the degree of tailings saturation, whereas for solids contents below 55% the breach outflow is relatively insensitive to the degree of saturation. The bulking ratio between pond volume and outflow volume can also be estimated from Figure 3. This ratio ranges from 3.0 to 4.7 for 65% solids content, 2.1 to 2.5 for 55% solids contents, and around 1.3 to 1.8 for solids contents less than 45%.

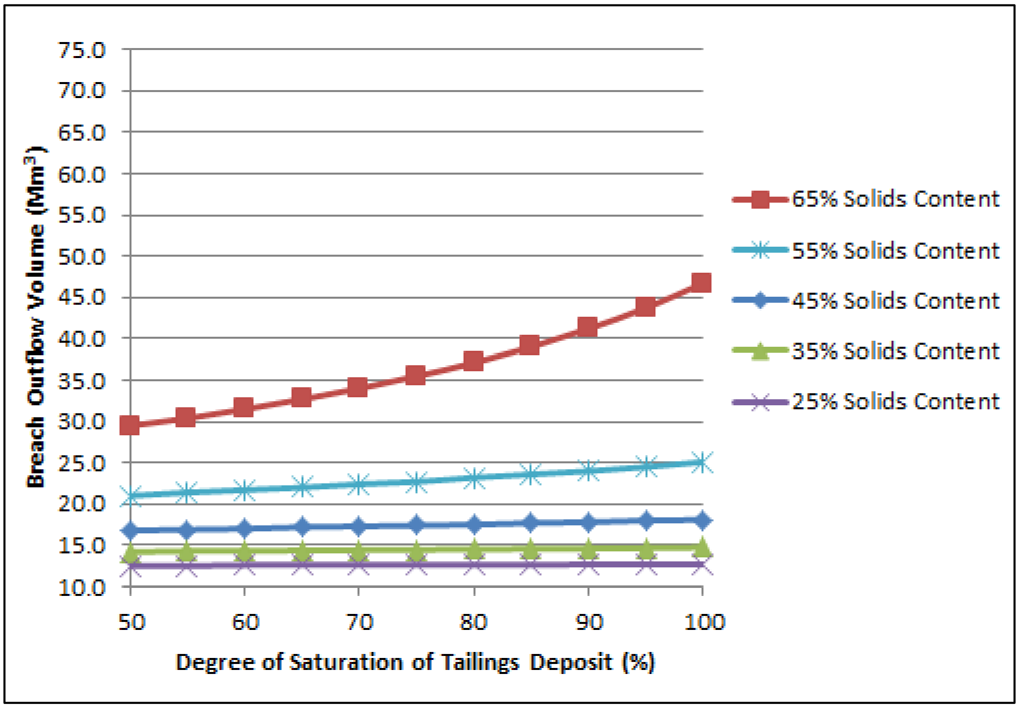

Figure 3: Sensitivity of Breach Outflow Volume to the Degree of Saturation of the Tailings

Degree of saturation does not appear to be a significant driver in estimating the breach outflow volumes compared to the pond volume and tailings density. The reduction in mobilization is less than approximately 10% for breach outflows with less than 45% solids content, and more pronounced for higher solids contents. Partial saturation does reduce tailings mobilization potential and should be included for completeness. Saturation is important when considering the ability of tailings to flow if the breach process is not driven by erosion. Saturation would be more important when considering mobility of liquefied tailings in facilities containing little water or locally in tailings beach zones adjacent to the dam.

4 DISCUSSION AND CONCLUSIONS

This paper proposes a methodology for estimating the volume of water and the tailings released with the initial flood wave during a dam breach of a tailings facility. The breach outflow volume can be calculated as a function of stored water and physical characteristics of the tailings deposit. The presented approach indicates that a larger operating pond would mobilize more tailings than a smaller pond. The following sections include some concluding thoughts and discussion on opportunities for applying the methodology presented in this paper.

4.1 Solids Content in the Breach Outflow

There are several physical attributes of stored tailings that affect the flowability of tailings in the event of a facility breach. Three of these physical attributes are considered in this paper: the volume and location of stored water, the tailings density, and the tailings degree of saturation. All three are influenced by the estimated solids content of the breach outflow, which plays a controlling role in the tailings mobilization estimate. Instantaneous mixing to a given solids content is not a realistic assumption. The solids content in the outflow would vary as the breach process develops; however, it is impractical to vary the solids content in the calculations, which would add a different layer of uncertainty to the estimate. A simpler approach is to choose a representative solids content for the entire initial flood wave. The selected solids content estimate is at the discretion of the practitioner and should be developed on a case by case basis. The practitioner should take into consideration the physical constraints that limit the range of reasonable values.

There is an opportunity to investigate a reasonable upper bound solids content during project development. Test programs for tailings physical and rheological characteristics are common during project development. Simple slumping tests can demonstrate the relationship between solids content and yield stress, or how the tailings behave when confinement is removed. The results of simple tailings testing could be used to provide a reasonable rationale for the selected solids content or range of values.

Developing ranges or envelopes that could be considered “standard” ranges for solids content in initial flood wave outflows for a given type of tailings would help standardizing the process. Limited opportunity exists to develop empirical correlations for past tailings facility failures; however, complete information is often not available for these events. Another option would be to consider the limitations of material erosion and entrainment seen in natural flooding.

4.2 Risk Assessment

The assessment of potential consequences caused by a breach of a tailings facility requires an estimate of the volume of water and the tailings released during the breach, particularly in the initial flood wave. The estimate of tailings mobilization presented in this paper follows a repeatable methodology that considers the physical characteristics of the tailings facility. Including these physical attributes in estimating the mobilized tailings volume provides a quantitative tool in estimating the potential consequences of a breach.

The positive effect of altering the physical conditions in a TSF by reducing the amount of water stored within a facility, increasing the tailings density, and decreasing the degree of tailings saturation was demonstrated in this paper. Each of these changes can be shown to reduce the potential breach outflow volume. A reduction of volume of water lost and tailings mobilized would reduce the potential downstream consequences of a failure of a facility.

Risk assessment considers the “likelihood” and “consequences” of an event occurring to develop an understanding of the risk of that particular event. The engineering design of a tailings facility adopts factors of safety and design event levels that reduce the likelihood of occurrence to the extent practical. Another opportunity to further reduce the risk, if likelihood cannot be lowered, is to reduce the consequences of an event. The methodology for estimating tailings mobilization volumes presented in this paper provides an opportunity to investigate possible reductions in the potential consequences of a dam failure without applying extensive and costly analysis.

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