Tailings Dam Failure: Estimation of Outflow Volume

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Abstract

Failure impact assessment is an important activity when considering the potentially disastrous effects of tailings facility failures on human life, environment and the economy. Tailings run out distance, flow depth/velocity and the time to peak are crucial factors when estimating the population at risk and preparing evacuation plans. Dam breach parameters and tailings characteristics are needed to determine the combined tailings and supernatant water breach hydrograph for a hypothetical dam failure. A flood routing model is then required to estimate the run out distance, flow depth, velocity and flow travel time of the released volume. Unlike water storage dams, in which the entire storage sitting above the level of the breach is released, in a tailings dam failure generally a portion of the tailings is released, except in steep valleys or with very low density tailings then a complete entire release is still possible. This volume can be difficult to estimate prior to abreach event.

A new methodology to estimate the released tailings volume and create a breach hydrograph is presented in this study. The method combines supernatant water and tailings volume outflow in order to create the breach hydrograph for input into a non-Newtonian hydraulic model.

The supernatant water in the pool and the dry density of tailings play important roles in defining the sediment concentration and type of outflow fluid. The introduced technique has been applied to estimate the volume of tailings being released in a hypothetical failure event using a conventional three dimensional modeling tool. It is evident that the tailings breach volume is heavily dependent upon the post failure slope of the tailings. The geometry of the facility such as the embankment height and length, the pool volume as well as the breach location effects on the tailings release volume. This study proposes a method to consider the geometrical model of the storage area alongside the geotechnical characteristics and hydraulic of the tailings and sediment concentration for each facility in order to estimate the release volume from the tailings dam rather than using a simplified release volume equation.

Keywords: tailings storage facility, dam breach, failure impact assessment, failure volume estimation

Introduction

Tailings dam break analysis follow five steps: 1) estimation of the release tailings volume, 2) estimation of the water in the tailings (moisture contents) and the free water in the facility (pond size), 3) calculation of tailings concentration, 4) development of the breach hydrograph, 5) routing the hydrograph downstream of the dam.

Unlike dam break analyses undertaken for Water Dams, the failure outflow from Tailings Dams contains a considerable amount of solids resulting in non-Newtonian fluid flow characteristics. Thus, the solid concentration is required to be calculated in the impoundment g to determine the type of fluid immediately prior to the failure. The selection of flood routing package needs to consider the amount of sediment concentration in the impoundment. Many existing dams comprise tailings that may be saturated material encompassing entrained water as well as supernatant water stored above the tailings in the storage facility, which is generated from both mining operations and rainfall. The tailings storage facilities will usually have an emergency spillway structure which is located above the pond elevation to discharge extreme storm events

The water level in the facility in a sunny day condition is identified to be the normal operation level in the pond. For many existing dams, the produced tailings from the mill convey to the tailings storage facility via pipelines laid over the embankment and discharge to the pond by spigots which are located at specific intervals along the pipeline. Therefore, the shape and beach profile is dependent on the tailings flow rate, spigot spacing and tailings characteristics, as well as operational considerations.

Present guidelines do not prescribe a detailed method to assess tailings dam break analyses and downstream hydraulic modelling of the failure flows. The majority of tailings failure assessments use the water storage dam fundamentals, empirical equations and software packages to generate the flood inundation maps. Water dam failure modelling have been widely investigated and there are numerous equations, numerical methods and software packages available to undertake the failure assessment. In contrast the tailings dam failure study has not an established and globally agreed method. The majority of tailings dam failure studies uses the common flood modelling packages to create the flood inundation maps. In many of these studies the run out material is assumed to be water with no consideration of solids concentration and rheological parameters of the tailings.

Rico et al (2008) identified a number of particular characteristics that make tailings dams more vulnerable to failure than water storage dams, namely: (1) embankments formed by locally derived fills (soil, coarse waste, overburden from mining operations and tailings); (2) multi-stage raising of the dam to cope with the increase in solid material stored and effluent (plus runoff from precipitation) released; (3) the lack of regulations on specific design criteria; (4) dam stability requiring continuous monitoring and control during emplacement, construction and operation of the dam, and (5) the high cost of remediation works following the closure of mining activities (Rico et al. 2007).

In a water dam breach it is assumed that the entire pond will release to the level of breach in the piping failure mode. In a tailings facility incident, the released volume depends on characteristics of tailings, amount of free water in the tailings and supernatant water in the pond as well as the liquefaction process. In most cases only a proportion of tailings will be released and the storage are never emptied, except in steep sided valleys and very low concentration tailings.

Rico et. al (2007) studied on 29 tailings dam which failed during 1965 to 2000 around the world. They found out that for tailings dams the height of embankment and runout distance of outflow has poor correlation. Therefore, they produced a relationship between outflow volume and runout distance which resulted in a better correlation. On this basis, they suggested to use an empirical equation that shows tailings outflow volume as a function of total volume of the storage. In their equation approximately one third of tailings and water is released during a failure.

Paulina et al (2018) studied on Rico' methodology considering 35 tailings dam failures based on larger storages and height rather than the original dataset used by Rico. They suggested a new empirical equation to estimate the breach volume as a function of total storage volume; this equation yields smaller release volume compared to Rico's method.

In both methods the released volume was plotted against the total storage volume and a regression line was developed with a correlation of R2 = 0.86% and 88% for Rico and Paulina, respectively. These methods are statistically based and do not take into account the tailings geotechnical or rheological parameters and the geometrical factors of the dam.

Tailings deposition model

Typically, the tailings slurry discharges to the impoundment from a mill via a pipeline network located on the embankment. The tailings deposition model is dependent on the factors like the discharge volume, the frequency of discharge, degree of tailings saturation and dry density of material.

The development of a deposition model is based on the site collected data, site survey and geometric design of the earthen embankments. Basically, the operation and maintenance of the facility, the number and duration of operating spigots would impact on the beach slope as well as the volume of stored water in the pond. Whilst it is difficult taking into account all the operation and maintenance factors in the tailings deposition model the latest as-constructed survey and bathymetry data would be used to generate a three dimensional model which represents the realistic condition. The bathymetry data inform the volume of water in the pond during a normal operation in a sunny day condition. Where the bathymetry data is not available the normal operating level in the pond can be adopted as an average level; this level should be checked against the historical records of pond level.

In a rainy day situation the water level raises in the pool owning the rainfall and the discharge pump or gravity dewatering system are operational. The dewatering of the pool needs to be done to maintain the beach and keep the water away from the perimeter embankment. However, the dewatering system are considered to be non-operational during a hypothetical dam failure. Thus, the maximum water level in the pool which can occur during a rainy day condition is assumed to be at the emergency spillway structure.

Outflow volume estimation

The post failure slope has substantial effects on the shape, extent, length and the volume of the cone of released tailings from the storage. The post failure residual strength will be estimated using the geotechnical data obtained from site investigation and further stability analysis. On this basis the estimated post failure slope for the tailings facilities can be calculated. Previous historical failures indicate that a dam failure could extend to the full height of the dam.

When the storage facility including the tailings material and supernatant water is modelled, the outflow volume can be estimated by developing a release cone, which starts from toe of the downstream embankment. In order to capture the released tailings volume the breach location is located in the lowest level at the downstream embankment. Figure 1 and Figure 2 show the schematic facility configuration for pre and post failure.

The mechanism of failure is based on the formation of a trapezoidal channel within the embankment as described in Froehlichs study (2008). However the released volume in the impoundment is limited to the failure line and the embankment foundation. The trapezoidal cross section at the embankment is gradually transitioned to a triangle shape inside the impoundment.

The initial breach width can be estimated using the empirical equation of Froehlich and assuming the released volume is equal to a percentage of the total stored volume (say 50%). This base width will be adjusted using the same equation when the more realistic released volume is estimated by the geometric modelling.

The stored tailings within the impoundment may be saturated prior to failure. Whilst the embankment volume

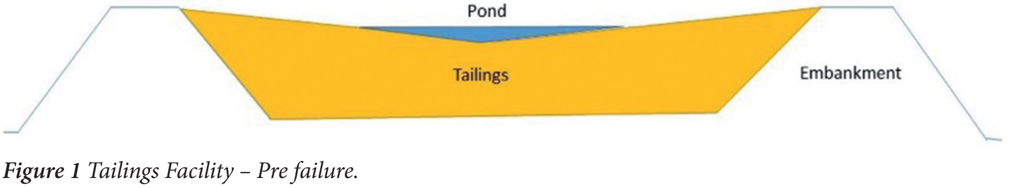

Figure 1 *Tailings Facility – Pre failure.*

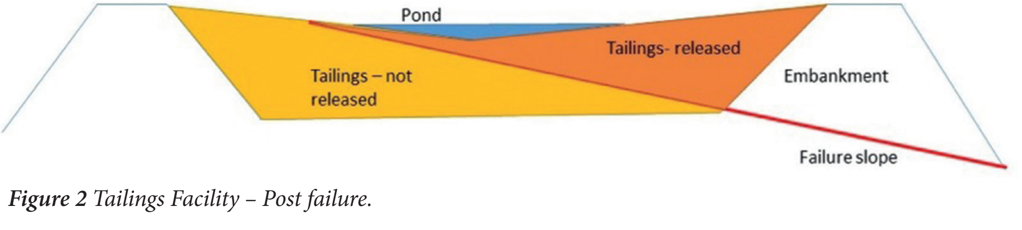

Figure 2 *Tailings Facility – Post failure.*

will be included in the released volume calculation, it has minimal proportion of the total tailings and water volume in the impoundment.

Furthermore, having the geometric model which represents the failure extent and shape in the facility it is possible to determine the encroachment of failure to the pool area. This method can give more realistic volume of released water when the pool is located distant from the failure point.

Tailings Facility – Post failure

Fluid motion is considered to be Newtonian when the shear stress is a linear function of the shear rate or non- Newtonian when viscous behavior is nonlinear and is more complex. The sediment content of the breach outflow is important to classify the flow as water, mud flood, mud flow or landslide. The vast majority of sediment flows fall between 20 to 55 percentage by volume. Very viscous, hyper-concentrated sediment flows are referred to mudflows which are non-homogenous and Non-Newtonian. The mudflow is highly viscous fluid with velocity generally much slower than water on the same slope. Figure 3 shows the flow classification as a function of sediment concentration.

It is required to determine the sediment concentration of outflow and the class of flow prior to selection of the hydraulic modelling package. According to Figure 3 if the volumetric sediment concentration is below 20% the flow could be considered as water. Therefore, the conventional water based flood modelling packages are appropriate to be applied. The water volume inside the water as well as the entrained water are required to be estimated.

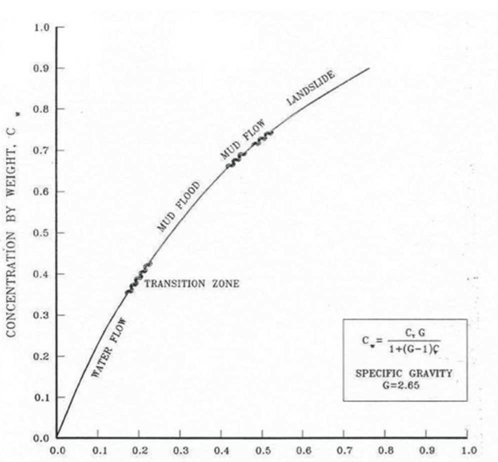

Figure 3 *Flow classification based on sediment concentration (Flo2d-2012).*

Water in tailings

The volume of entrained water can be calculated using the void ratio. Knowing the specific gravity and dry density of tailings the void ratio can be calculated using the below re-arranged equation: $e = \frac{Gs}{Y_d} - 1$

Where,

Gs = specific gravity of tailings solids

γ_d = tailings dry density (t/m3)

Sediment concentration

The volumetric sediment concentration for each failure case needs to be calculated using the supernatant water in the pool above the tailings and the entrained water in the tailings.

The sediment concentration by volume Cv is given by:

$$C_v = \frac{\textit{Volume of sediment (Vs)}}{\textit{Volume of water (Vw) + sediment (Vs)}}$$

The weight of sediment in the pond can be calculated using the total released weight using the dry density of tailings. The weight of solids shall be converted to volume using the specific gravity of solids.

Having the total released volume which includes the solids and entrained water (Vs + Vw) the sediment concentration by volume in the impoundment can be estimated for the "pre dam break" condition.

In the cases that the failure line encroaches the pool the supernatant water volume stored in the pool needs to be added to the total released tailings volume to calculate the sediment concentration of tailings for "post dam break" condition.

The volumetric sediment concentration is an important input parameter to:

- Determine the flow classification and selection of appropriate hydraulic software.
- Develop a breach hydrograph as an input to a "Non-Newtonian" hydraulic software.

Flood modelling

The breach parameters are required to be estimated to develop the outflow hydrograph for a failure incident. The breach hydrograph can be developed using the reservoir flood routing models such as HEC-HMS. The parameters of breach width, side slope, formation time need to be calculated and input to the model. There are number of empirical equations (e.g. Froehlich 2008) to estimate the physical breach parameters such as the average width and time of formation.

Volume conservation should be considered in the breach hydrograph development ensuring the released volume is equal to the total hydrograph volume. The peak discharge should occur at breach formation time estimated from empirical equation. Costa (1988) proposed several empirical equations obtained using dam height and volume of reservoir and the resulting peak flow discharge when it failed.

Numerous packages are available to undertake the flood modelling and route the breach hydrograph to assess the run-out distance of tailings and the impact on the environment. Having the sediment concentration of the outflow above 20% it is suggested to use Non-Newtonian package such as Flo2D. The traditional water base modelling packages can be used to evaluate the inundation areas and flow depth.

Conclusions

A methodology to estimate the released tailings volume and create a breach hydrograph is presented in this study. The method combines supernatant water and tailings volume outflow in order to create the breach hydrograph for input into a non-Newtonian hydraulic model if the volumetric sediment concentration is above 20%.

The post failure slope has substantial effects on the shape, extent, length and the volume of the cone of released tailings from the storage. The estimate of post failure residual strength is required using the geotechnical data obtained from site investigation and further stability analysis.

The geometric model which represents the exiting embankments, pond location, failure extent and shape in the facility gives better understanding about the failure length and the possibility of encroachment of failure to the pool area. This method results in more realistic volume of released water when the pool is located distant from the failure point. The pool water would impact on the total released volume particularly in a sunny day failure.

The volume of sediment in the pond can be calculated using the total released volume using the dry density of tailings and specific gravity of tailings. In order to classify the breach outflow at the failure location, the sediment concentration needs to be estimated using the tailings solid volume and total water volume.

In the cases that the failure line encroaches the pool area it is essential to add the supernatant water volume stored in the pool to the total released tailings volume.

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