Tailings Dam Breach Assessment – A Review

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Abstract

Tailings dam breach modelling studies have received considerable attention recently due to the surge in the number of tailings dam failures and catastrophic consequences such as downstream flooding. Numerical models are crucial tools in risk management for assisting urban planners and emergency responders in planning for the safe evacuation of the vulnerable communities located downstream in the so-called *shadow area* of such dams. Several challenges and uncertainties exist when conducting risk assessments of tailings dam failure. In this paper, currently available modelling approaches for tailings dam breach analysis and downstream flood wave routing are briefly reviewed. This paper aims to help dam engineers and practitioners to keep up with current best practice industry standards and to include state-of-the-art practices in their work.

Keywords: Tailings Dam Breach Analysis, DBA, TDBA, breach hydrograph, tailings, runout

Introduction

Tailings are by-products of mining operations after extracting valuable minerals, and they can contain fine solids (ranging in size from sand to silt), wastewater, and chemicals. Tailings dams are mine waste storage facilities often constructed from waste rock to store the waste solids and water generated during mining operations (Wang et al. 2014). Tailings dam failures can cause serious effects on public safety and the downstream environment. Recently, there has been an increase in the number of tailings dam failures due to several reasons, such as lack of proper dam management, foundation failure, slope instability, and natural hazards. Moreover, tailings dams are constructed in sequential lifts, that is, initially there is a starter dam, and as the reservoir behind it gets filled with tailings, the dam is raised, sometimes using the tailings themselves where the upstream raise method is used. Consequently, the failure rate of tailings dams could be higher than that of other types of dams, and it is extremely challenging for mine operators to ensure the stability of these dams (Roche et al. 2017). To ensure the safety of human lives and the downstream environment, proper risk management (i.e., adopting mitigation measures, emergency plans, exclusion zones, and flood protection structures) is required (Moon et al. 2019).

Tailings flows are generally highly sediment-laden and are non-homogeneous and non-Newtonian flood events. Fluid properties may change substantially as they flow down watershed channels. An increase in sediment concentration affects fluid properties by altering the stress-strain relationship, and it is important to consider rheological properties such as shear stress, shear rate, and yield stress (Pradhan et al. 2018). Therefore, laboratory tests may be required to derive key parameters for better modelling of non-Newtonian fluid behavior. Based on Labanda et al. (2004), thickened tailings can be simulated using the Herschel-Bulkley model. Several granular debris flow modelling studies have been conducted in recent years to understand the dynamics of landslides and debris flows. Debris flow models are widely used for tailings dam failure risk assessment, even though tailings flows are more mobile than rock avalanches, nonvolcanic debris flows, and waste dump failures (Ghahramani et al. 2020).

The objective of this paper is to understand the current state of the art practice in tailings dam breach outflow modelling and how it has evolved over the last few years.

Tailings Dam Breach Modelling

Tailings dam breach modelling is often used in the mining industry. These studies are usually required by regulators to approve the design of an impoundment, because they want to ensure that the risks posed by such facilities are characterized properly and that mine owners have an emergency response plan (ERP) and emergency preparedness plan (EPP) in place to implement in case of an actual dam failure. The rigor with which modelling is performed and evaluated has increased globally in the past several years; it is no longer only a box to check on an application form to fulfil regulatory requirements.

The Canadian Dam Association (CDA) is a global leader in establishing guidelines to better define and frame a tailings dam breach analysis/assessment (TDBA). The CDA recently published a technical bulletin (CDA 2021) that is being used in many countries as a widely accepted guideline. CDA (2021) provides an overview of modelling options for runout analysis as well as for breach modelling, which will be further discussed in this paper.

It is important to understand the physical processes of a tailings dam breach. CDA (2021) identified three general failure modes for tailings dams: 1) collapse of the foundation due to liquefaction triggered by earthquake or other mechanisms (e.g., surface erosion, piping, and internal erosion); 2) water overtopping the dam crest due to insufficient freeboard or spillway capacity, spillway malfunction, crest settlement, or misoperation of the facility; and 3) contaminated seepage failure to the natural environment. Multiple causes can be identified for each failure mode. Gildeh et al. (2020) reviewed 85 historic failures and found that the most common failure mechanisms (60% of all failures) include liquefaction, overtopping, and slope stability (Fig. 1). The failure mode, in conjunction with hydrologic conditions at the time of failure, forms the dam breach scenario. There are two common hydrologic conditions used in dam breach

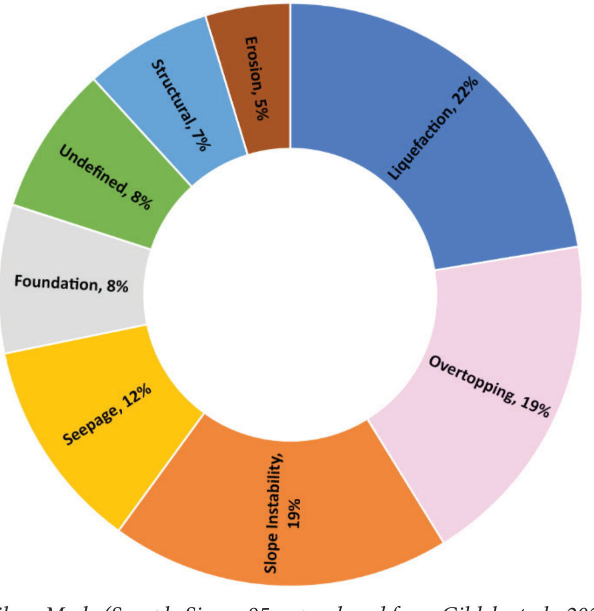

***Figure 1** Historical Failure Mode (Sample Size = 85, reproduced from Gildeh et al., 2020)*

analysis/assessment (DBA): 1) fair-weather, which suggests normal conditions without a storm; and 2) flood-induced, which refers to extreme precipitation, snowmelt, or flooding.

The type of breach outflow varies with the amount of water and tailings released. A schematic of different stages of embankment dam deformation and breach with respect to liquefaction failure is shown in Fig. 2. Post-triggering liquefaction results in deformation of the dam, including settlement of the dam crest (Fig. 2a and 2b). At some point, the dam crest settles below the water level in the tailings basin, and the tailings basin pond water starts moving as a sheet flow over the deformed surface of the interior dam (Fig. 2c). With further deformation of the dam, more water flows over the deformed surface (Fig. 2d), and erosion of the surface may start if the flow-exerted shear stresses exceed the critical shear stress of the surface materials. As the deformation reaches equilibrium, the flow rate over the deformed surface may reach its maximum (Fig. 2e). This flow rate depends on the available volume of water in the tailings basin, water level in the tailings basin when deformation stops, and amount of erosion over the deformed surface. If the initial discharged volume is relatively small compared to the total volume of water in the tailings basin, the maximum breach outflow may occur sometime after deformation ends. The volume of water leaving the tailings basin results in erosion of the fine tailings and erosion of some of the deformed surface materials. When water overtops the total breach width due to deformation, a small amount of eroded surface is added to the outflow, and fine tailings in the basin start eroding. The flowing water over the deformed surface then concentrates at the center area and cuts deeper, sending a greater amount of eroded tailings downstream.

Breach Modelling

Breach modelling identifies the shape of the breach hydrograph and its peak that is routed downstream. The breach prediction methods for earthen dams (i.e., most tailings dams) can be divided into three categories:1) parametric models, 2) semi-physically based models, and 3) physically based models. It is noteworthy that almost all breach models were developed for water-retaining dams and not for tailings dams. Hence, it's crucial to recognize that the prevalent utilization of these breach models relies on substantial simplification. West et al. (2018) have reviewed these three modelling

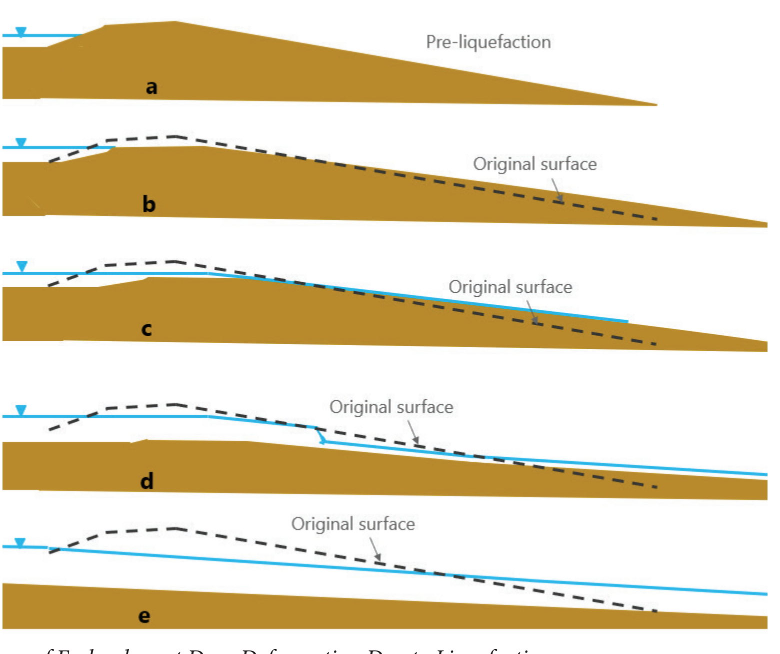

***Figure 2** Stages of Embankment Dam Deformation Due to Liquefaction*

categories extensively, and we do not repeat it here. Instead, a case study comparison of parametric models and semi-physically based models is presented in this section.

A breach outflow hydrograph is necessary to route the breach flood downstream and map the influenced area to be used in the ERP and EPP. As mentioned above, both semi-physically based models and physically based models can generate the breach hydrograph. In this section, two sets of comparisons are made in breach outflow hydrograph generation.

Comparison 1: Two Semi-Physically Based Models vs One Parametric Model

An important factor in selecting the proper application to obtain a breach hydrograph is the immediate downstream topographic condition of the breach location, because it affects the breach hydrograph shape and peak. The immediate downstream of a breach location is the distance from the breach point, ranging from approximately 100 m (for a channel with a steep slope) to 300 m (for a channel with a gentle slope), where the backwater effect may change the breach hydrograph characteristics (Gildeh et al., 2020). To quantify the effect of the downstream conditions on the breach hydrograph, three models (HEC-RAS 2D, FLDWAV, and HEC-HMS) were run with similar breach parameters and downstream topographic conditions (for models that include downstream topographic conditions, i.e., HEC-RAS 2D and FLDWAV). As shown in Fig. 3, the breach hydrographs of the HEC-RAS 2D and FLDWAV, both semi-physically based models, modeled the breach hydrographs almost the same, especially for its peak and shape. However, the HEC-HMS model, which is a parametric model that does not include the downstream condition of the breach location, modeled a lower peak and wider hydrograph than the other two models. The volumes estimated using all three hydrographs were similar in this exercise. Similar volumes but different hydrograph peaks and shapes can affect downstream inundation, particularly the flood arrival times, and thus the consequence of a failure. HEC-HMS is considered to be the easiest in terms of model setup and execution, whereas FLDWAV requires the most time to set up and run the model.

Comparison 2: HEC-RAS 2D Newtonian vs Non-Newtonian

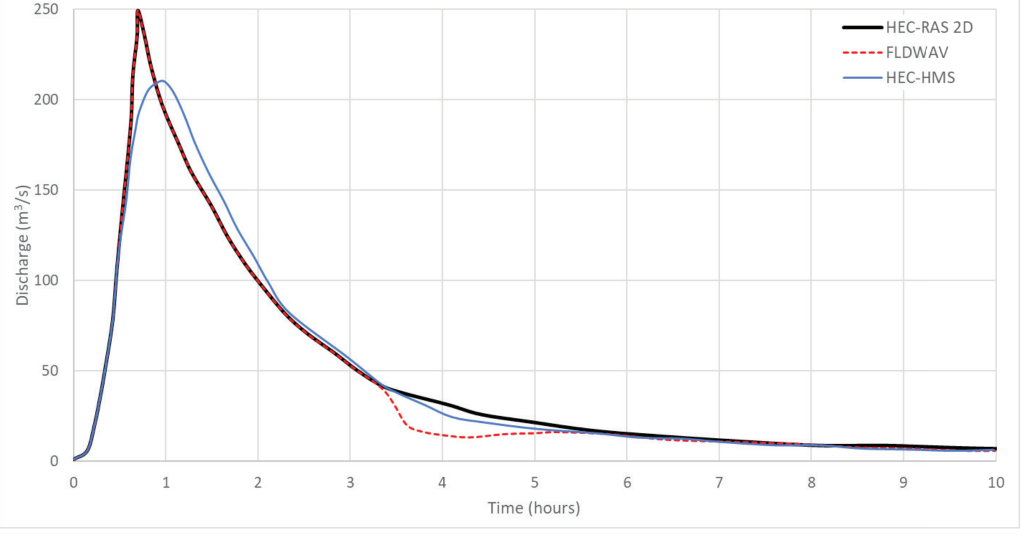

Figure 3 *Comparison of HEC-RAS 2D, FLDWAV and HEC-HMS when generating the breach hydrograph*

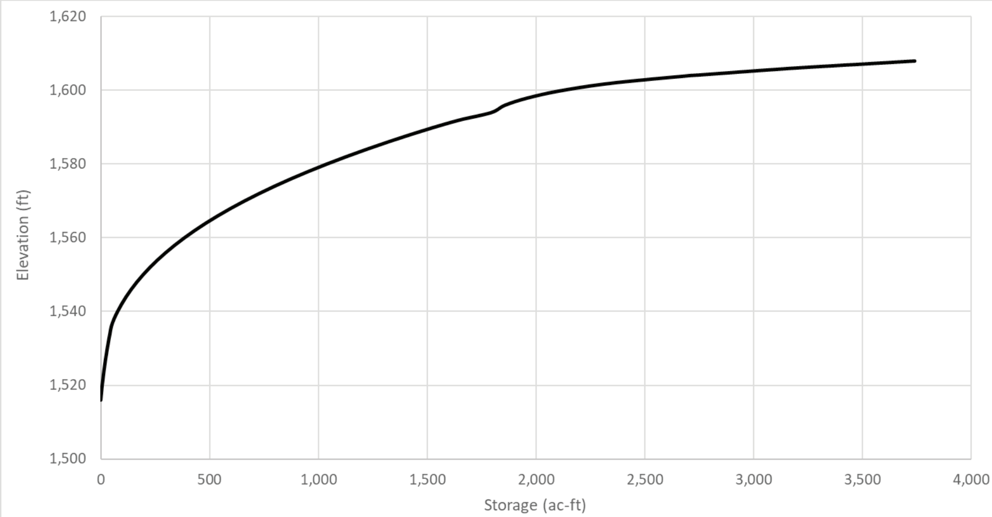

***Figure 4** Stage-Storage Curve for Modelled Breach in HEC-RAS 2D*

Breach

In this second comparison, one of the most popular semi-physically based models (HEC-RAS 2D) was used to compare the difference between its Newtonian and non-Newtonian (recently added to the model) modules. The same stage-storage curve was used in both modules (see Fig. 4), and the breach parameters were estimated based on the same parametric method.

For non-Newtonian fluids, the model requires rheological parameters of the tailings. For this exercise, a typical concentration by volume (C_v) of 29% and yield stress of 4.12 Pa were selected for the released mixture of tailings and water. Two scenarios were tested for viscosity: 1) high viscosity (57.3 Pa-s) and 2) low viscosity (1.22 Pa-s). The results of the three models are shown in Fig. 5 where there seem to be no obvious differences. This suggests that HEC-RAS, a semi-physically based model, is not capable of accounting for actual complex processes of tailings dam breach formation and release. Both models used the same topography and geometry

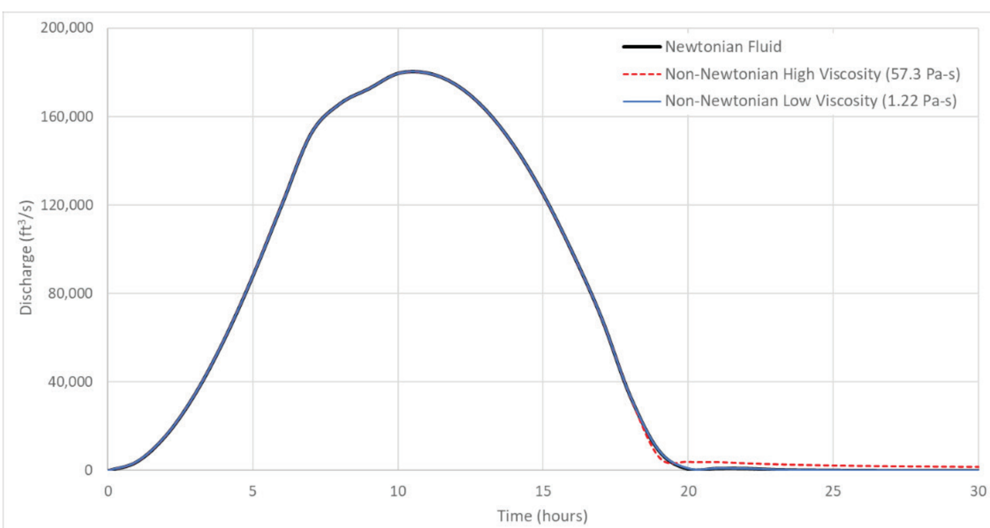

***Figure 5** Comparison of Newtonian and Non-Newtonian Breach Modules in HEC-RAS 2D*

details to ensure the results are comparable, and they are not sensitive to the topographic and geometric conditions in the models.

Downstream Flood Routing

When the breach hydrograph is obtained, the next step often is the runout modelling downstream of the breach. Runout modelling will result in inundation maps to inform risk assessment as well as ERPs and EPPs. In the case of a tailings dam, the released volume will be in the form of a hyper-concentrated or non-Newtonian fluid based on its concentration by weight or volume. Non-Newtonian fluid flow behaves differently than the Newtonian fluid (e.g., water in case of a water retaining dam breach). CDA (2021) summarized the available software packages that are commonly used in the industry to model downstream flood routing for TDBA. For the sake of brevity in this paper, we only point out that the choice of model selected for a particular study or site should be in line with the site characteristics and type of released fluid. It is important to note that field rheological parameters such as viscosity, yield stress, specific gravity, etc. are extremely important in runout modelling and one should pay extra attention to selection of those parameters.

Conclusions

The following conclusions and recommendations can be drawn from this study:

- It is necessary to assess the suitability of the empirical regression relationships for breach hydrographs developed from water retaining dam failures for application to tailings dam breaches. New analyses should be conducted specifically for tailings dam failures. The analysis should be completed based on tailings types and not by combining all data so that each category indicates the same ore type, materials, and rheology.
- Sensitivity analysis with respect to various parameters such as grid, choice of rheological model, fluid properties, sediment properties, and failure mechanisms needs to be conducted. Also, advanced uncertainty analysis methods should be developed to assess the range of uncertainty in the final results linked to the uncertainties in estimating the breach development time and outflow volume.
- More physically-based breach models should be employed for breach modelling, because they better characterize the complex geotechnical behaviour of earthen embankment breaches.

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