Considerations on dam breach analysis of tailing storage facilities

Miguel Huamán A.[1]*, Daniel Pulcha E.[2] and Mishel Meléndez B.[3]

1. *Anddes Asociados SAC, Lima, Perú, Hydraulic engineer, miguel.huaman@anddes.com*
2. *Anddes Asociados SAC, Lima, Perú, Head of the hydrological and hydraulic department, daniel.pulcha@anddes.com*
3. *Anddes Asociados SAC, Lima, Perú, Hydrological engineer, mishel.melendez@anddes.com*

ABSTRACT

The operation of tailings storages facilities (TSF) involves a potential risk for people and infrastructure located in areas downstream, which may include loss of life, inundation, and damage to buildings such as houses, bridges, farm lands and contamination of water sources. .In consequence, it is necessary (or mandatory in some countries) to perform a dam breach analysis of a TSF in order to assess the magnitude of the flood wave and volume of tailing released to define remediation measures. .Furthermore, the results of the dam breach analysis can be used to define the dam classification according to the Canadian Dam Association guidelines. .However, it is important to mention that most guidelines and codes for dam breach analysis are oriented for water dams; nevertheless, there are few technical reports or methodologies available for TSF.

The objective of this paper is to discuss the technical considerations taken into account when a dam breach analysis of a TSF is performed, based on the practical experience to develop simulations in several case studies in Peru. .There are two important points to understand dam breach analysis of a TSF: the generation of hydrographs due to the tailings breach and flow routing for identifying the flood timing, depths and velocities through the natural channel and valleys. .In order to determine which failure mode produces the most critical hydrograph, scenarios such as seismic events, extreme meteorological conditions, poor tailings management, vandalism, among others, were evaluated according to the work area. .Besides, the flow must be modeled as a non-Newtonian fluid using physical, chemical and rheological properties of tailings. .Finally, results of the dam breach analysis for the case studies will be presented.

Keywords: Dam breach, hydrographs, released volume, rheological properties, non Newtonian, tailing flood.

INTRODUCTION

The operation of a tailings storage facility (TSF) always involves a potential risk for the people who live or work near the natural channel located downstream the dam. In addition to physical damage caused to people, a dam breach event may involve inundation and damage to houses, camps, bridges and infrastructure located in the course of the released tailing which would lead to significant human and economic losses. Also, the tailing released as a result of a dam breach would have a significant impact on the environment, contaminating farmland, damaging flora and fauna, and polluting natural sources of fresh water.

To perform a dam breach analysis, it is important to evaluate the probable failure types to which the dam is exposed in order to estimate a hydrograph for tailings release. The typical trigger factors of tailings dam failures, amongst others, are as follows:

- Earthquake
- Piping
- Overtopping
- Improper management of the facility
- Poor construction
- Improper soil foundation
- Poor tailings disposal
- Poor or unsuitable water management
- Vandalism

According to Peruvian standards, every mining structure must be designed to withstand natural events (earthquakes, floods, etc.) of a certain magnitude, and return periods of 150 years for dams in operation and 500 years for inactive dams. However, the structures may fail or collapse in case of events with return periods that exceed the design criteria. Moreover, there are international standards such as the Canadian Dam Association (CDA), which classifies dams according to the consequences caused by an eventual failure from low to extreme, considering the population at risk, loss of human lives, infrastructure, environment and cultural values. The return periods, according to the CDA, can reach up to 10 000 years. Therefore, a dam breach analysis is recommendable in order to assess the risks downstream the dam.

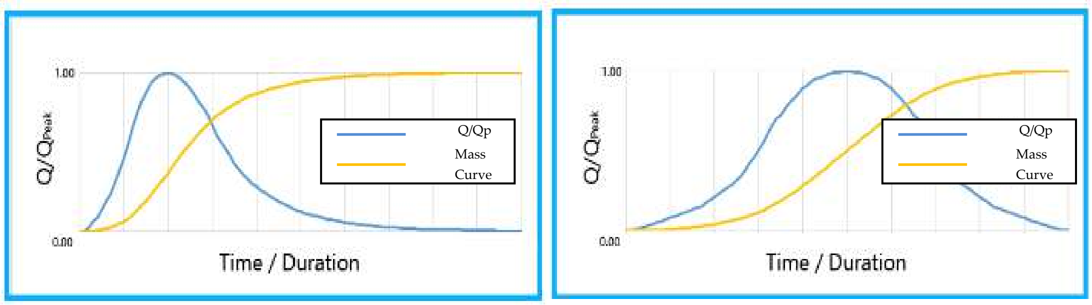
Currently, there are guidelines and/or procedures for dam breach characterization or analysis of water storage dams; nevertheless, there are not technical guidelines available for dam breach analysis of a TSF. A dam breach analysis is based on an estimation of the outflow hydrograph of the released tailing in accordance with the considerations assumed by the modeler, and then, the transit of the estimated hydrograph downstream the dam is generated.

OUTFLOW HYDROGRAPH

The estimated outflow hydrograph for the dam breach analysis of a tailings dam depends on several factors. The most important factors are: failure type or mode, released volume, disposal and management of tailings in the facility, tailing flood model and physical characteristics of the dam. Moreover, the parameters controlling the magnitude of the discharge peak and the shape of the outflow hydrograph depend on the dimensions of the breach, the manner and time of breach development, depth and water volume stored in the tailings storage facility.

Failure type or mode

The failure type may define the shape of the hydrograph; that is, the location and attenuation of the peak flow will be represented in the hydrograph. For example, if the failure is caused by a seismic event or piping, the peak flow may occur in a short period of time after the event. On the other hand, the peak flow may occur in a long period of time if the failure is caused by overflow. Figure 1 shows the hydrographs that may be generated according to the type of failure.



(a) (b)

Figure 1 Typical hydrographs (a) due to seismic event, (b) due to overflow

Released Volume

The volume of water released due to a failure event in a water dam will be established to the lowest level of the breach; however, in case of a tailings dam, the lowest point of the breach means the lowest level of an inclined plane of stabilization of the deposited tailing; besides, the gradient of the plane will vary according to the consolidation and concentration degree of the deposited tailing. According to statistical analyses, several authors agree on concluding that, on average, the released volume of tailing will be less than 40% of the deposited tailing. For example, M. Rico et al. (2007) indicate that the average released volume of tailings is 33% of the stored tailings; also, the authors correlate the released volume and the stored volume, as shown in Figure 2.

Moreover, ICOLD (2001) presents a statistical analysis of the records collected from tailings dam failures. Based on this analysis, it is concluded that, on average, the percentage of released volume of tailing is 37% of the total; also, it is observed that the released volume was above 40% in only 13 (32.5%) records. Table 1 shows a summary of records used for this analysis, and Figure 3 shows the Chronology of the released tailings volume percentage which represents the ratio between released and impoundment volume.

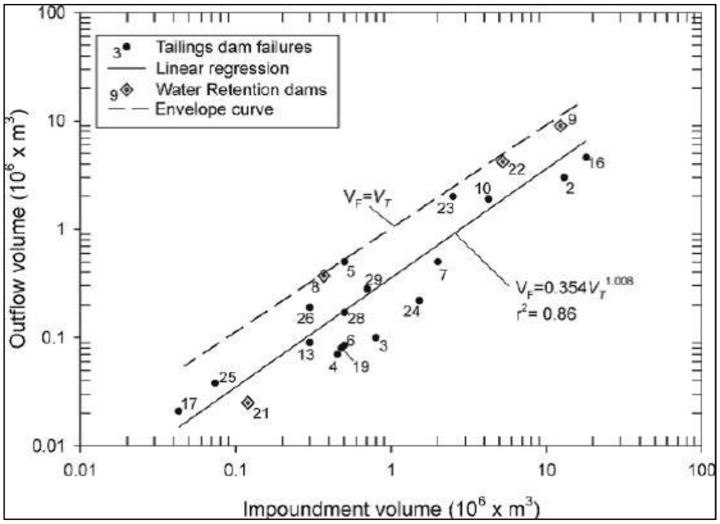


Figure 2 Correlation between released tailings and stored tailings

Table 1 Summary of records for tailings dam breach

Record characteristics	Values
Number of events	40
Start year	1965
End year	2000
Height of dam (m)	4 - 66
% Minimum released volume	1
% Average released volume	37
% Maximum released volume	100
Number of events, released volume above 40%	13
Number of events, released volume below 40%	27

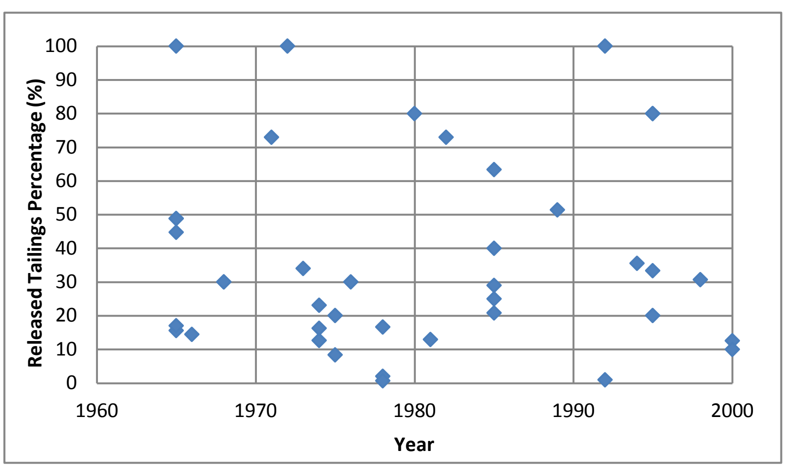


Figure 3 Chronology of the released tailings percentage

Furthermore, ICOLD made a correlation between the released tailings volume (Vr) and the stored volume (Vs), and determined the following equation:

$$Vr = 0.2978 \times (Vs)^{0.9861} \qquad (1)$$

Where Vr represents the released volume and Vs is the stored volume; also, the curve was adjusted with a coefficient of correlation of 89.28%. Figure 4 shows the logarithmic correlation of released and stored volumes, and Figure 5 shows a comparison of the released tailings area and the facility area.

Therefore, according to the statistical analysis, we consider that the first dam breach analysis should consider a released tailings volume of 40%.

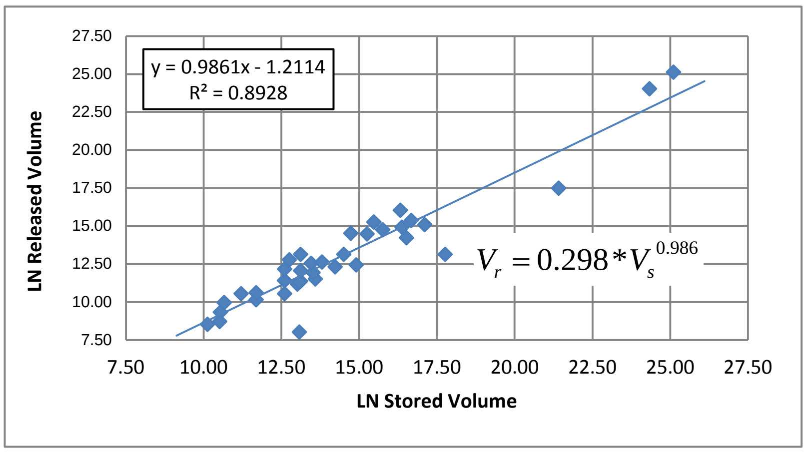


Figure 4 Logarithmic correlation between the released and stored volume

Figure 5 Comparison of areas, released and deposited tailings

Tailings Disposal and Management

Both the type of deposited tailings, according to the percentage of solids, and a water balance study in the facility are necessary to estimate a range of concentrations for the release of tailings in case of a dam breach event. Also, weather conditions in the area of analysis are important to estimate the range of variation of the concentration under a breach event. For example, high concentration ranges are expected when the tailings are deposited as paste or filtered; therefore, the downstream displacement of these tailings would be short in case of a failure; on the other hand, if the type of the deposited tailings is conventional without high thickening, lower concentrations are expected; therefore, largeer displacements of tailings downstream the dam are expected. Nevertheless, these concentrations may increase or decrease according to rainfall and evaporation regimes in the area of analysis; in rainy climate with little evaporation, the tailings concentration would decrease with respect to the initial concentration.

Another very important point is water management in the tailings dam, especially in dams where the supernatant water is extracted through pumps continuously, so the tailings concentration is expected to increase in time. However, the tailings concentration may decrease if there is not a good water management system in the dam; for instance, tailing dams have inadequate or lack perimetral channels. Table 2 and Figure 6 show the flow characteristics according to the tailings type.

Table 2 Flow characteristics per tailings type

Type	Concentration (%)	Displacement	Flow Type
Conventional	25 - 45	High	Turbulent
Thickened	45 - 65	Medium	Turbulent / Laminar
Paste	65 - 75	Low	Laminar
Filtered (Dry Stacking)	75 - 90	Null	--

Figure 6 Tailings Types (Paterson & Cooke)

Tailing Flood Models Several researchers have proposed empirical formulas to estimate the peak discharge caused by a gradual failure of a dam; however, these formulas were prepared for water storage dams; therefore, the available models for peak flow estimation are usually divided into three categories: (i) breach analysis of similar dams, (ii) use of empirical estimation formulas and (iii) models with physical base. Although there are no guidelines or procedures for evaluating a breach in tailings dam, there is research on water dam breach, which is generally used to determine the peak discharge. The following models are amongst the most important:

- Tailing Dam Breach. This tool is included with the FLO 2D model, which reduces the uncertainty in determining the occurrence of failure and discharge volumes in case of a potential failure. Also, it is important in the creation of a hydrograph for the transit of hyperconcentrated sediment flow, based on the calculation of regression equations determined from a historical database of several failures that occurred since the 60's (approximately 70 events). The failures considered for the modeling are hydrological, static and seismic.
- Empirical models. In order to establish an approach to the problem and an order of magnitude of the breaking wave; expressions derived from statistical analyses (empirical estimation formulas) of real breakings are used.
- DAMBRK. It is useful to develop the outflow hydrograph of a dam and the hydraulic movement of the flood downstream the valley. It considers one-dimensional unsteady flow equations of Saint Venant (variable time and distances). The failures are modeled in terms of overflow and piping; besides, a free version of this model was developed for water dams.
- BREACH. It is a widely-used model in water dam breach studies. This model predicts the flood hydrograph as a result of a dam breach, the dimensions of the failure opening, the geometric shape, and the time of formation of an opening in the body of earth dams. Similar to the DAMBRK model, the failures are modeled in terms of overflow and piping.

TAILING FLOOD ANALYSIS

The tailing flow analysis must be simulated with a model that supports non-Newtonian fluids since the discharged tailings will have some degree of concentration of solids, which means that the behavior of the tailings will be very different from a Newtonian fluid. Basically, the parameters used to establish a proper analysis are: digital model of the terrain downstream the dam, tailings rheology, roughness of the channel through which the tailings will transit, and the hydraulic model used for simulation.

Digital model of the ground

The digital model is important for an accurate flow simulation; also, detailed contour lines (every 1 m) are ideal for the modeling as they show details of the channel through which the released tailings will transit. If the topography isn’t detailed, the simulation of tailing flood will be no representative, it means that the profile representing a topography with curves every 25 m shows steep areas and flat areas, which would result in high speeds in steep areas and low speeds or storage (attenuation) in flat areas.

Figure 7 shows the flow behavior in flat areas (tailings flow retention and attenuation), and Figure 8 shows the flow behavior of tailings in a steep channel.

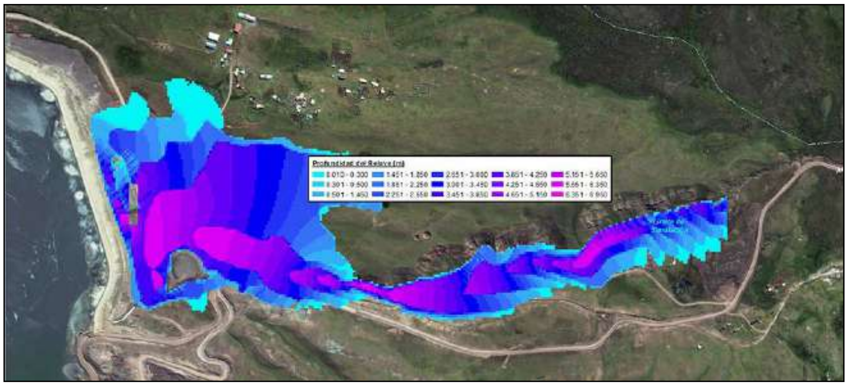


Figure 7 Tailing retention and attenuation in flat areas

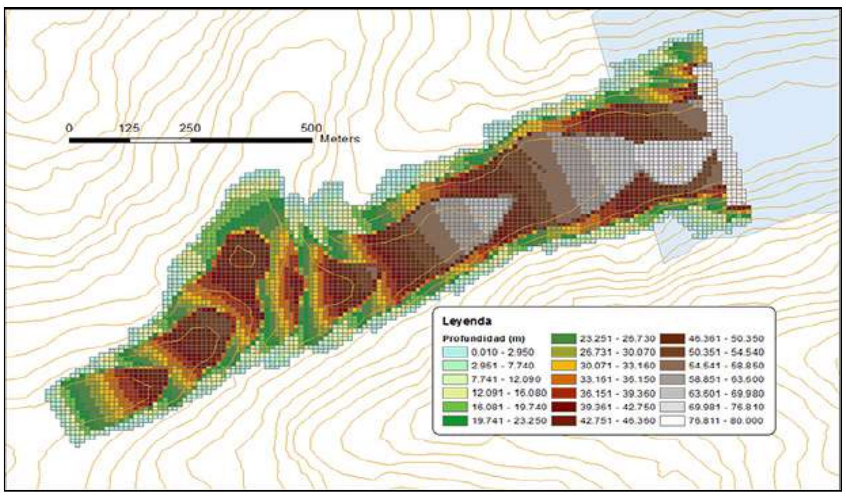


Figure 8 Tailings flow in steep ground.

Rheological characterization

The rheological characterization of the tailings stored in the facility is performed by sampling and laboratory testing of samples obtained at the tailings discharge point in the facility or inside the facility. The rheological parameters of interest are viscosity and yield stress, which are determined using rheometers (viscometers); usually, the variation of the rheological parameter is obtained depending on the concentration of solids. It should also be mentioned that there are other factors that have an influence on the flow behavior such as the concentration of solids, particle size, particle interaction, and chemistry, amongst others.

Figures 9 and 10 show the variation of rheological parameters with respect to the weight concentration of two tailings samples; Figure 10 shows the difference in viscosity of these same samples.

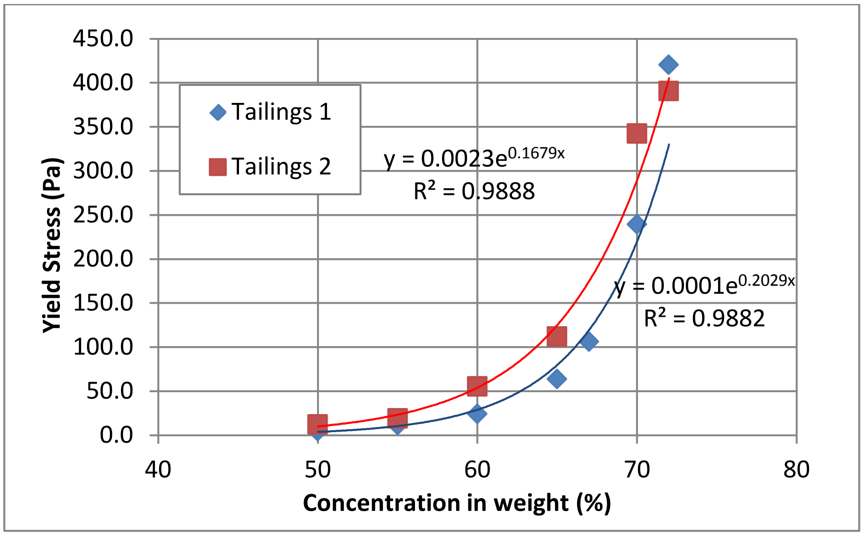


Figure 9 Yield stress variation versus concentration

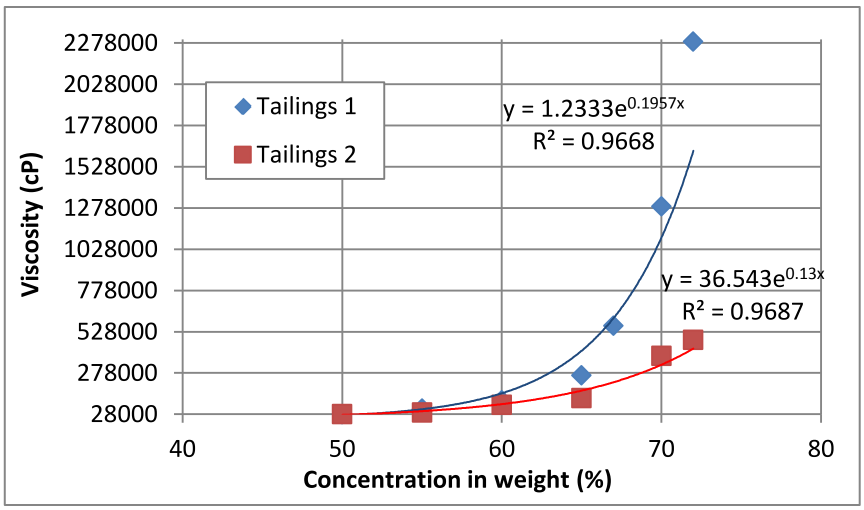


Figure 10 Viscosity variations versus concentration

Hydraulic software

The tailings are considered to have a non-Newtonian fluid behavior; therefore, the computer programs should use hydraulic models for the transit of tailings with the capacity to work with this type of fluids. Below there is a description of the characteristics of some available software capable of simulating the flow of non-Newtonian fluids.

Flo2D

It uses a two-dimensional mathematical model based on finite differences of dynamic transit that can simulate flows in channels, unconfined surfaces and roads; it can also be applied in hyper-concentrated flows, floods and debris. The model also considers a homogeneous fluid with a variable concentration, indicating that there is no difference for sediment sizes. Flo2D uses a simple model of volume conservation and moments, where equations of momentum and continuity are solved by a numerical scheme of finite differences, separating the information in uniform square grids. However, Flo2D cannot simulate shock waves, rapid flow variations or hydraulic jump. In addition, the model considers the following assumptions: the flow is permanent throughout the run, there is a hydrostatic distribution of pressures, and roughness is considered a permanent and uniform resistance of the turbulent flow.

RiverFlow 2D

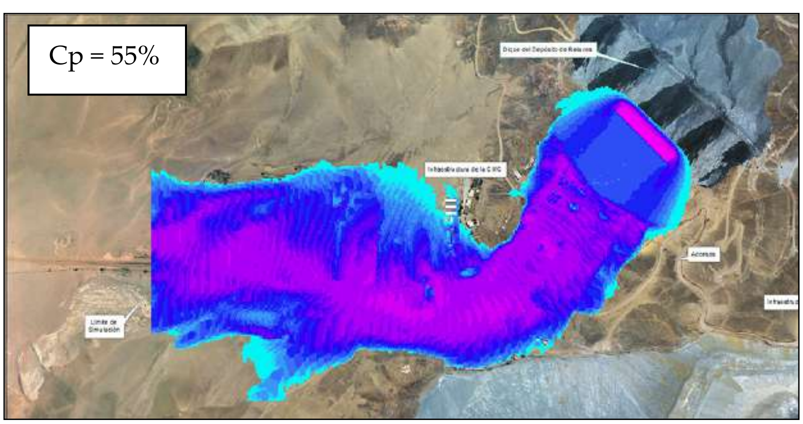
It uses a two-dimensional mathematical model based on finite volumes, which uses shallow water equations based on the integration of the Navier-Stokes equation. Moreover, the model has the capacity to work with non-permanent flows. However, RiverFlow 2D does not solve secondary flows (Eddy-flow) and does not include dispersion terms or turbulence. On the other hand, the model considers the following assumptions: the shear stress at the bed follows the directions of average velocity and depth, and it uses a finite volume solution method with the capacity to include hydraulic structures such as culverts, dams, bridges, amongst others.

DAN-W

It uses a pseudo two-dimensional mathematical model that performs dynamic analyses for landslides, which can be applied in the analysis of flows and/or debris slide, rockslide, large-scale liquefaction failure, and even tailings backfill slides. The model assumes a predefined volume of soil or rock that changes a fluid traveling downstream, following a path with a defined direction and width. Furthermore, the model is implemented with a one-dimensional Lagrangian solution which is capable of using different rheological relations. Nevertheless, DAN-W is a solution for shallow flows, so it is used exclusively in the analysis of rapid landslides. Moreover, the model considers the following assumptions: the geometry is two-dimensional and the sliding mass flow direction is parallel to the profile.

SIMULATION SENSITIVENESS

Based on the tailings sampling and mass balance studies, we can obtain a range of concentrations for released tailings in case of a breach event. Therefore, the breach simulation must consider variations in concentration of the released tailings in the course of time; however, tailings flow simulations with constant concentrations can be carried out throughout the event; to that end, a series of simulations covering the estimated range of concentrations must be carried out. Figure 11 shows simulations with run covering a range of concentration between 55 and 65%.



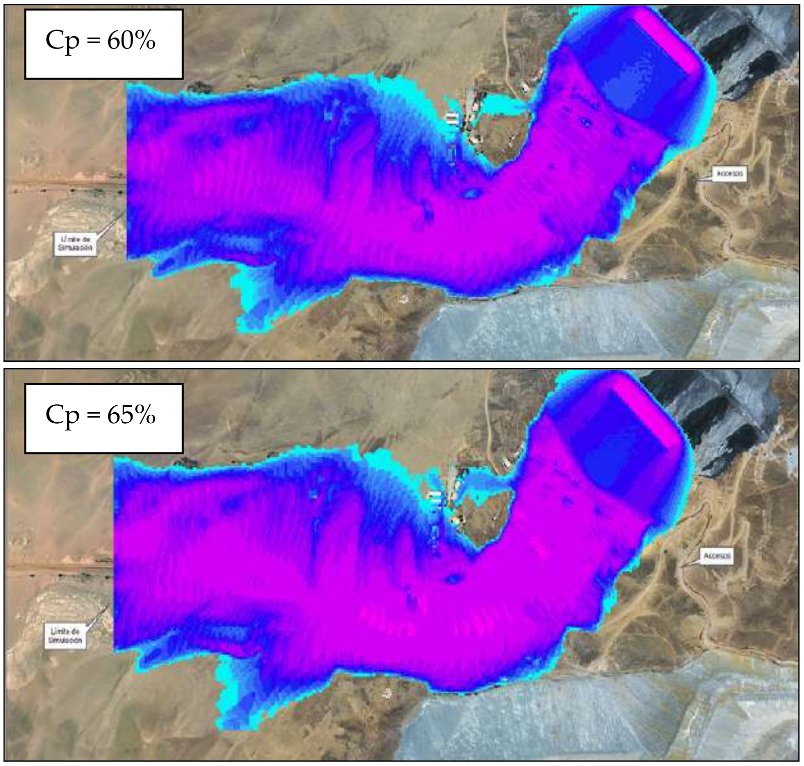
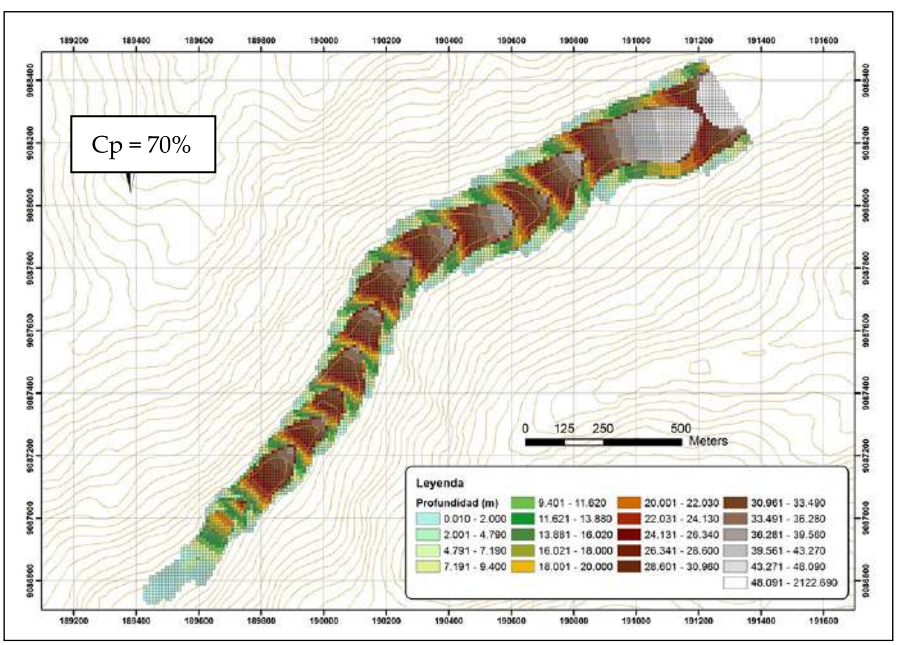


Figure 11 Tailings depth for concentrations between 55 and 65%

Figure 12 shows two simulations for different concentrations of 70 and 78%; as a result, the released tailing is displaced to a distance of 2.5 and 2 km, respectively.



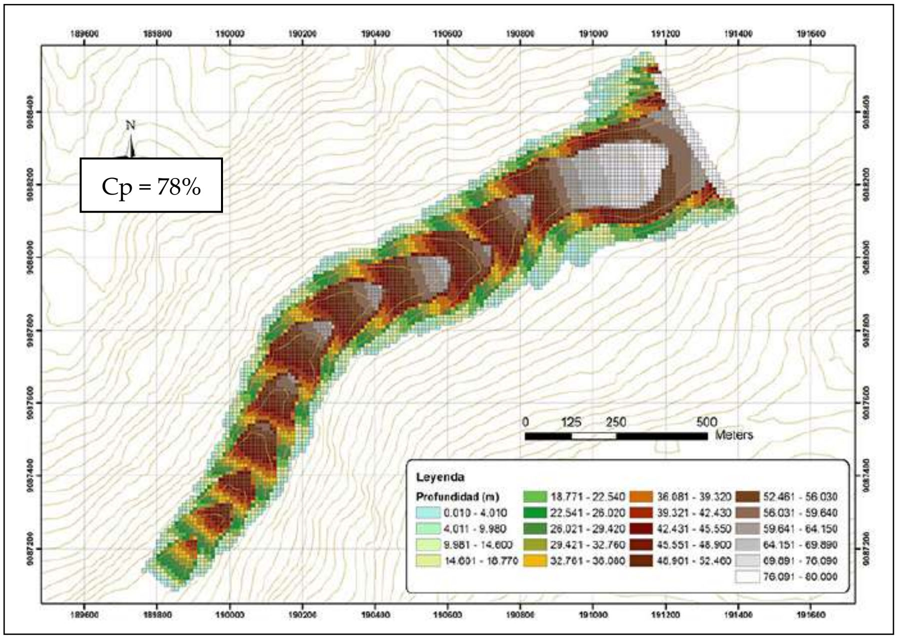


Figure 12 Sensitiveness of displacement with respect to the concentration

CONCLUSIONS

The main factors that condition the outflow hydrograph are: failure mode and type, released volume from the reservoir, tailings disposal and management in the facility, hydrological model, and physical characteristics of the dam. The failure type defines the shape of the hydrograph; as a result, the location and attenuation of the peak flow will be represented.

In case of a dam breach, the whole tailing is not released; on average, less than 40% of the stored volume is released, according to several authors. In addition, the released volume will depend on climatic and operational conditions of the tailings dam.

In general, breach simulations must be performed only in dams whose tailings were disposed as conventional or thickened tailings. Moreover, good management of surface water and supernatant water of the dam reduces the risk of breach due to piping or overflow.

Currently, the only tool that determines the peak flow before a tailings dam breach event is the Tailing Dam Breach; however, some models (BREACH and DAMBRK) and empirical formulas developed for water dam breach can be useful for the approximation of the peak flow.

For dam breach simulation analysis, detailed topographical information of curves every 1 m is required for the best representation of the tailings flow in the area of study.

A rheological characterization of the tailings must be carried out in each project in order to obtain the viscosity and yield stress, since the rheological parameters may change considerably due to the variation of a factor, concentration, particle size, chemistry, amongst others.

It is our recommendation that Flo2D or RiverFlow 2D software be used for tailings flow simulation; these programs are two-dimensional and a suitable representation of the flood areas with a pseudo 3D approach.

The dam breach simulations must be carried out considering a range of solid concentrations to assess the sensitivity of the model.

REFERENCES

Hydronia, LLC (2015) *Two-Dimensional Finite-Volume River Dynamics Model User's Guide,* Pembroke Pines, pp. 31-45.

Pornillos, E.U. (2011) *A technique for measuring the reduction of yield stress of thickened tailings,* 14th International Seminar on Paste and Thickened Tailings.

O. Hungr Geotechnical Research Inc. (2010) *DAN-W Release 10 Dynamic Analysis of Landslides User's Manual,* Vancouver, pp. 2-6.

Azam, S. and Li, Q. (2010) *Tailings Dam Failures: A Review of the Last One Hundred Years,* WASTE GEOTECHNICS, Geotechnical News, Regina, pp. 50-53.

FLO-2D Software, Inc. (2009) *Flo-2D Reference Manual,* Arizona, pp. 14-20.

Rico, M.; Benito, G. and Díez Herrero, A. (2007) *Floods from tailings dam failures,* Journal of Hazardous Materials, pp. 8-14.

ICOLD COMMITTEE ON TAILINGS DAMS AND WASTE LAGOONS (2001) *Tailings Dams – Incident Case Records,* Tailings Dams Risk of Dangerous Occurrences, CIB ICOLD & UNEP PNUE, Paris, pp. 85-97.

Vick, S.G. (1996) *Failure of the Omai Tailings Dam,* GEOSPEC, Geotechnical News, Colorado, pp. 34-40.

U.S. Environmental Protection Agency – EPA (1994) *Embankment Construction, Stability And Failure,* Design and Evaluation of Tailings Dams, Washington, pp. 3-40.

Paterson & Cooke, Chile (2013) *V Curso de Transporte de Relaves Espesados,* Propiedades de Pulpas, pp. 15.