How to develop Dam Break Analysis in order to perform risk classification based of Canadian Dam Association Guidelines

Roberto Jesús Flores Jimenez[1]*, Ausenco[1] Tailings 2019

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ABSTRACT

Estimates of run-out distance for tailings impoundments are mandatory and are required by Authorities in many countries around the world. There are widely accepted differences between water dams and tailings dams regarding their failure modes and discharge processes. Empirical methods based on statistical analysis of past events are available to estimate the discharge volume and the peak discharge and aid engineers to predict potential consequences and assess hazard levels downstream of the dam. On the other hand, simulation tools are available to include rheological parameters and to generate more sophisticated models if necessary.

Despite the above, this kind of analysis still possesses a strong hypothetical approach and presents uncertainties. Questions arise such as: What are the most common uncertainties of such a simulation? Is rheological data so important for tailings modelling, especially when tailings slurry and significant volume of water are considered? What effect can a nearby water bodies have on the run-out distance? What about the accuracy of our prediction models? What about the confidence level of alert times for contingency plans?

The objective of this article is to present the Ausenco view on tailings related flood hazard mapping. This approach includes a comparison between prediction models, real occurrences and available post-event models. Well documented tailings disasters showing Newtonian behaviour are highlighted and analysed for their use from an estimation of consequences viewpoint. Understanding the particularities of these events could help general thinking about prediction of run-out distance and wave transit periods.

Based on the above Ausenco in Peru is applying its engineering judgment following the Canadian Dam Association (CDA) guidelines in order to perform Dam Break Analysis for Dam Classification based on the proposed CDA failure consequences particularly for Peruvian projects.

Key words: flood hazard, run-out distance, tailings

MANY FACTORS, MANY DOUBTS

There are many factors included in a dam break and flood analysis and this number of variables could mean a high-level of uncertainty which can have significant effects on the results. The main uncertainty sources for this kind of study include: i) failure mode and breach development; ii) the discharge volume; iii) hydrologic issues such as the volume of accumulated water on the tailings surface; iv) the rheological parameters of the tailings at the time of failure; v) and topography.

Though failure modes are an uncertainty, this issue has effects on flow characteristics, mainly in the nearest sectors downstream of the dam. The discharge volume could be estimated by the Rico et al equation. The accumulated process water can be handled only as an estimated value while rainwater can be calculated in accordance with local hydrologic and pluviometry method. Uncertainties are generated due to the probabilistic nature and empirical coefficients used, for instance, rheological parameters are generally measured in a laboratory and can differ from the failure moment's values where consolidation, age, moisture content and seismic effects should be considered.

Topography is one of the key factors that determine the quality of flood hazard mapping. In general, high resolution surface data is available. Flood hazard assessment often presents challenges: in determining the vulnerable sector for extensive damage in the areas downstream from the dam. About these potentially affected sectors, some information can be obtained using public-domain digital

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elevation model (DEM) data, typically in a range of resolution with contours every 30 m and access via direct request to authorities. On the other hand, high-resolution topographic data are achievable these days.

Below, it is present some historical cases that were analysed to compare the accuracy of typical prediction models with real registered impacts and to discuss some details with respect to the subject of this document.

PREDICTION MODELS VERSUS REPORTED CASES

There are at least two recent and well documented tailings impoundment failures where registered data allow a comparison between prediction models and real occurrences after failures: the Ajka failure in Hungary, 2010, and the Fundão dam failure in Brazil, 2015. In the case of the Ajka failure the post-event simulation was carried out by Józsa, Krámer & Baranya, 2011, using a Newtonian 3D model calibrated in accordance with the real flooded area. The comparison for this case was made considering both post-event numerical results and satellite image. In the case of Fundão dam failure only the flooded area indicated on satellite images was considered for the comparison. Both prediction simulations presented in this paper were carried out by a numerical 2D tool.

Figure 1 shows the predicted flood extension (yellow area) where the red polygon corresponds to the real inundation area (defined from the corresponding Google Earth satellite image), while Table 1 includes a numerical comparison of some important parameters.

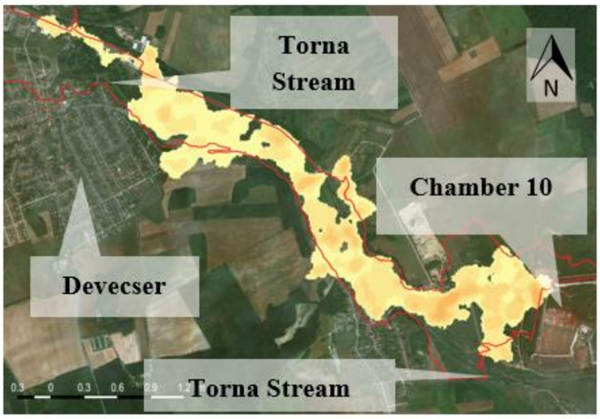

Figure 1 Ajka failure, Hungary: predicted (yellow zone) versus real flooded area (red line area)

According to the compared data, the following observations can be taken from the Ajka failure:

- The prediction model indicates flow arrival time, depths and velocities which show similar values in comparison with real occurrences.
- Predicted discharge volume is approximately 15% lower than the reported value.
- There are increasing differences in flood path and extension as we move away from the dam. For example, the prediction model does not indicate impacts on internal zones of the city of Devecser. This is probably due to that the lower resolution topography excluded fine details like the Torna streambed that had an important role to conduct flood wave (towards the Northern part of Devecser).
- Flood hazard level is very high for people living in Kolontár, especially in the first houses downstream of the dam. In this sector, the predicted 9 minutes of arrival time (Table 1) will generate difficulties for any contingency plan.

The same 2D hydraulic analysis was carried out for the Fundão dam failure, trying to strictly take

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into account the data available before the dam failure. Figure 2 and Table 2 show the prediction results in comparison with post-event registrations. For this second simulation, observations and conclusions are:

- Predicted discharge volume is 37% lower than reported data.
- Predicted peak discharge is probably lower than the (unknown) real value.
- Despite the lower predicted volume, the model predicts fairly well the real flood path.
- Unacceptable differences are observed mainly between predicted and real arrival times due to such topographic elements (depressions and other storage facilities) that have delaying effects on the flow and, therefore, differences between hydraulic parameters are also generated.

Table 1 Comparison between prediction and verification model data – Ajka failure, Hungary

Parameter	Prediction model	Reported data	Notes
Discharge volume	$1.51 \cdot 10^6\ m^3$	$1.75 \cdot 10^6\ m^3$	Using the Rico et al equation for the prediction model. Total discharge volume for the verification model was computed by the Ministry of Defence of Hungary.
Breach development time	15 min	15-20 min	Berm construction material: grey mud. Fast dam break was considered in the range of minutes due to construction material and the reduced dimensions of the structure.
Peak discharge	3,351 m^3/s	No available information	Simplified hydrograph was adjusted considering the breach time and dischargeable volume.
Average flow velocity in Kolontár	2-4 m/s	2-3 m/s	Kolontár is the first populated area downstream the dam.
Average flow depth in Kolontár	1.0-5.0 m	2.0-2.5 m	
Flow arrival time to Kolontár	9 min	6-7 min	Time to one-foot depth was considered in the prediction model as arrival time.

Despite the underestimated discharge volume and the use of low-resolution topography, the affected sectors in both prediction models coincide quite well with the real flood area limits with respect to Kolontár and Bento Rodrigues

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villages. Figures 3 and 4 demonstrate the affected zones for both populated areas respectively.

In both cases Newtonian behaviour was identified (Józsa, Krámer & Baranya, 2010; and Morgenstern et al, 2016) and from this point of view the precision of the outputs is as expected, the predictions results presented above were gained from a judged water simulation model. No rheological data were added to the models. This hypothesis is opposite to the general thinking and it was required in order to reproduce the situation as precise as possible to the real consequences of the cases studied above.

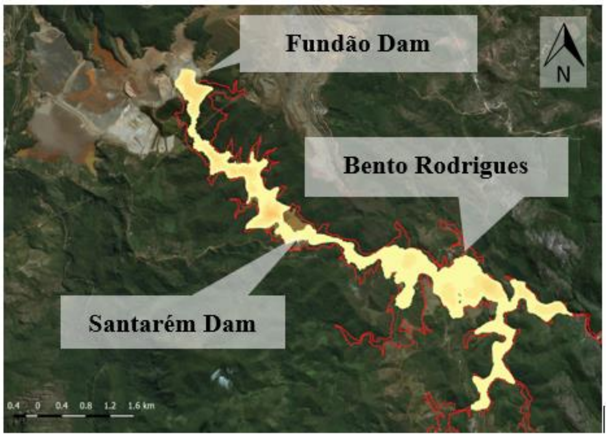

Figure 2 Fundão tailings dam disaster, Brazil: predicted (yellow zone) versus real flood area (red line area)

Table 2 Comparison between prediction model and reported data – Fundão dam failure, Brazil

Parameter	Prediction model	Reported data	Notes
Discharge volume	20.3 $\cdot 10^6\ m^3$	32 $\cdot 10^6\ m^3$	Using the Rico et al equation for the prediction model.
Breach development time	1.8 hrs	"in a matter of hours"	Slow dam break was considered in the range of a few hours due to significant dimensions of the structure.
Peak discharge	3,210 m^3/s	No available information	Simplified hydrograph adjusted according to breach time and dischargeable volume.
Average flow depth in Bento Rodrigues	1-8 m	No available information	Some non-official sources mention even at 10 m depths.
Flow arrival time to Bento Rodrigues	2.1 hrs	9 min	Prediction value is due to the delaying effects of topographic imperfections and Santarém dam retaining capacity.

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Figure 3 Kolontár flood prediction model (left side image) versus after-disaster situation (right side image)

Figure 4 Bento Rodrigues flood prediction model (left side image) versus after-disaster situation (right side image)

DAM FAILURE CONSEQUENCES

Information obtained from flood hazard mapping helps to estimate Dam Failure Consequences. The engineer should be aware that the discharge hydrograph has relevant influence on model outputs used for this issue. This is because discharge volume and overland roughness govern the flood area extension, while peak discharge value and breach development time are responsible for velocities and flow arrival time. The discharge hydrograph is based on three parameters, volume, peak discharge and breach development time, where volume can be estimated with a moderate-good precision, and breach time and peak discharge with a poor-moderate precision. If volume is conserved for the hydrograph and breach time or peak discharge is adjusted, flood area extension can be conservative. On the contrary, the flood wave arrival time will be considered as a more important output. Due to aforementioned uncertainty factors, flood area should be considered as the main output while flood wave arrival time should be handled carefully.

It seems that when relevant amount of water is accumulated on tailings surface, the flood wave would have a fluid Newtonian behaviour. The flood consequences should determine the Dam Classification based on the Dam Safety Guidelines issued in 2007 (2013 Edition) by the Canadian Dam Association.

Terrain hydraulic resistance coefficient seems to have considerable effect on flow velocity and moderate effects on depths (flood extension area). This issue should be relevant in vegetation covered sectors which could distract engineers estimating coefficient values, while nobody could guarantee that overland roughness coefficient areas would still remain at the moment of dam failure and while flood would convey over them. On the other hand, roughness coefficients could vary from one season to another and this kind of scenarios should be estimated with a defined level of certainty.

THE ROLE OF WATER

Table 3 shows some selected historical cases where hydrologic conditions could have an important role in failure modes and the magnitude of damage. Two criteria were defined previously for this selection: high number of loss of human lives and/or severe environmental damage. Every case has its own singularities, but it could be concluded that higher fatalities are associated with proximity to populated areas downstream of the study cases.

The released material may represent; based on reproduced post event model parameters, a Newtonian behaviour due to the presence of water in any form (i.e., accumulated rainwater, process water, saturated material by rainfall or additional effects by snow melt or local springs and streams). Without the presence of water, failures would cause another level of damages. There are several other cases excluded in Table

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3 where causes of the tailings impoundment failure seems to be related to rainfall and water management problems (i.e., Bafokeng, 1974; Merriespruit, 1994; Arcturus, 1978). Finally, Nature can often surpass human imagination.

Table 3 Some of the tailing's disasters (authors' selection criteria)

Year	Name/Place	Hydrologic – hydrogeologic condition (1)	Environmental damage of water bodies
1966	Aberfan (WALES)	RF, STR	-
1966	El Cobre (CHILE)	IW	El Cobre and Melón Branches, Aconcagua River
1966	Zgorigrad (BULGARIA)	RF, IW, STR	Leva Creek
1972	Buffalo Creek (USA)	STR(?), IW	Buffalo Creek, Guyandotte River
1985	Stava (ITALIA)	IW	Stava Gully and Avisio River
1995	Omai (GUYANA)	IW	Essequibo River
1998	Aznalcóllar (SPAIN)	IW	Agrio and Guadiamar Rivers
2000	Baia Mare (ROMANIA)	RF, SM	Sasar, Lapus Streams, Somos, Tisza, Danube Rivers, Black sea
2010	Ajka (HUN)	RF, IW	Torna Creek, Marcal, Rába and Danube Rivers
2014	Mt Polley (CANADA)	IW	Polley Lake, Hazeltine Creek, Quesnel Lake, Cariboo River
2015	Fundão Dam (BRAZIL)	IW	Gualaxo do Norte, Carmo, and Doce Rivers, Atlantic Ocean
2019	Corrego do Feijão (BRAZIL)	Still unknown	Paraopeba River

(1) Caused by: RF – Rainfall, SM – Snow melt, STR – streams and springs, IW – Saturation, seepage and drainage problems.

NATURAL WATER BODIES DOWNSTREAM OF THE STUDY CASE

Seems like once tailings have entered into a natural permanent water body, the concept of "run-out distance" loses its validity. Mixing with water, the pollution could travel hundreds of kilometres. The "run-out distance" concept is proposed to be used for overland flow and for flow in dry gully beds. On the other hand, the above presented red mud case simulation shows clearly the importance of natural streambeds and its role to "conduct" flood waves within a valley. This example enhances, again, the importance of accurate topographic details.

DEFINING DAM BREACH ANALYSIS EVALUATION SCENARIOS BY AUSENCO BASED ON CDA 2007

CDA 2007 section 2.5.2. propose that the dam breach evaluation should address initial hydrologic conditions for the following:

- Sunny day failure – This is a sudden dam failure that occurs during normal operations.

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- Flood -induced failure – This is a dam failure resulting from a natural flood of a magnitude that is greater than what the dam can safely pass.

Then based on Ausenco's experience and engineering judgement the following needs to be defined:

- Normal operations conditions
- Natural flood of a magnitude that is greater than what the dam can safely pass.

Ausenco´s definition of normal operations conditions should be defined during the design stage of the infrastructure; and updated, as needed, during construction, operation, closure and post closure phases.

Ausenco´s definition of natural flood of a magnitude that is greater than what the dam can safely pass; could be obtained from historical records or should be estimated based on historical records maybe at project site; and updated as appropriate quality information becomes available for the remaining project phases and the related performed Dam Break Analysis. Also understanding the meaning of "can safely pass"; Ausenco proposes this means to have implemented a system that allows the discharge of natural floods during any stage of the dam existence.

These are definitions in order to address the guidelines referred above. In addition, Ausenco proposes to consider other scenarios to be considered for specific Perú requirements, on study cases mentioned in this document and case by case to be agree between parties involved.

Therefore, the following has to be defined for a Dam Break Analysis:

- Dam failure scenario to be analyzed during operation and closure
- Activating failure mechanism

The approach followed sometimes was:
To consider that the entire capacity of the impoundment is discharged independently of the failure mechanism, and at any moment during the existence of the dam.

The proposed Ausenco´s approach is as follows:

Once the criteria/principles (see CDA 2007 section 1) have been defined the next step being worked on by Ausenco is to identify the likely real failure scenario that could occur based on the available information and its review by participating experts; as shown by the registers of events that occurred in such a way that the total content of the impoundment was discharged at the time of the dam failure occurrence, based on an exhaustive analysis of the different variables present at the time of dam failure occurrence. Based on the above Ausenco considered necessary to develop its own standards and tools being used at this time; and that has been received and accepted for the services provided and being provided to date; and that above all it facilitates the dialog between the parts that participate in the development of its services.

Ausenco considers CDA Dam Break Analysis criteria and other similar appropriate bench markings for Peru standards, but requires proper site-specific engineering complement by parties involved in the dam break analysis, CDA 2007 recognizes the above-mentioned statement.

AUSENCO´S PROPOSED MAIN DAM BREACH MECHANISM FOR FAILURE

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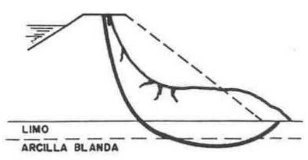
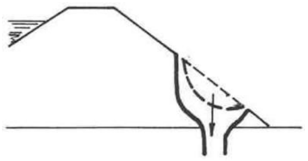
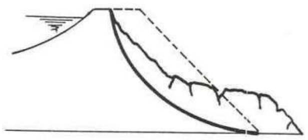
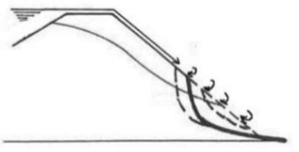
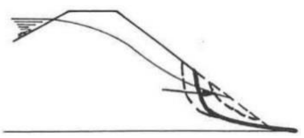
Type	Characteristics	Scheme
Foundation unstable (Structural Failure)	Downstream slope landslide	
	Settlement at the dam toe	
Earthquake	Dam total collapse	
Overtopping	Regressive erosion at the dam downstream slope	
Piping	Internal erosion of the downstream slope	

Dam Break Analysis require definitions of the mechanism of failure in order to estimate the Dam Breach time, related Flow Hydrograph and other parameters to be defined by parties involved in the Dam Break Analysis. There could be other groups of failure mechanism and proposes these be defined case by case.

CONCLUSIONS

- CDA 2007 (edition 2013) guidelines provides a good starting point for Dam Break Analysis for Peru in Ausenco´s opinion.
- Qualified professionals responsible for dam safety evaluations and analysis; and with appropriate experienced should be guiding the Dam Break Analysis
- Reality many times surpasses human imagination; therefore, it is necessary to implement mechanisms that make it possible to register relevant data related to new cases of dam failures to expand our understanding of failure events, making it possible to prevent and be prepared for similar events.
- Deterministic approach or risk assessment approach in order to define Dam Break Analysis scenarios to be modelled? this is something to be defined by the involved parties and guided by experienced professional.
- Always be attentive to publications from organizations such as the International Committee of Large Dams and associated organizations such as the "Comite Peruano de Grandes de Presas" and others.
- In case of Peru a particular parameter of importance should consider Peru´s topography, which could represent, in Ausenco´s opinion, a key parameter in order to fairly estimate flooded inundation areas & levels and flood arrival times.
- We have to keep in mind that Peru is located in a seismic area; that could be included in Dam Breach modelling provided the seismic events can be modelled in such a manner that reflect a dam breach condition and the resulting discharge hydrograph.
- For designing and environmental impact assessment purposes Dam Break Analysis should be developed considering water Newtonian fluid characteristics; meanwhile proper fluid characteristics should be defined.
- The following aspect should also be considered for design purpose, environmental impact assessments and other Project interests and its stakeholders, the dam break/breach analysis should consider to be developed taking in consideration the Newtonian fluid characteristics of water; as a base case

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criteria until the proper characteristics of the fluid to be modelled has been defined.
- Peru should develop its own Dam Break Analysis guidelines.

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