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International Symposium on

"Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries"



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Foreword

From the Chairperson of the Local Organising Committee of ICOLD 2016 and Chairperson of the South African National Committee on Large Dams (SANCOLD)

We are extremely happy that this ICOLD Symposium was staged in South Africa as part of the 84th ICOLD Annual Meeting held in Johannesburg in May 2016.

Sunny South Africa is known:

- for its friendly “rainbow” nation as demonstrated during the highly successful 2010 Soccer World Cup event;
- for its beautiful scenery with the Big Five animals in our National and Private Game Parks, the Drakensberg Mountains with its Lesotho Highlands dams and Cape Town with its world heritage site Table Mountain;
- to have 5 030 registered dams of which more than 1 114 are large dams;
- for contributing significantly since 1965 to ICOLD and Africa regarding development of the art and science of dam engineering.

Our SANCOLD Local Organising Committee worked very hard to ensure that this event was well organised, had a high technical content and could provide a forum to experience Africa.

This Symposium reflects much of local, regional and international experience with dams with an emphasis on the developing Africa. The keen interest we received from authors reflects that the subject matter is apt and we hope that these Proceedings together with the delivered Symposium Presentations will form a valuable resource for the future of dams throughout the world.

Danie Badenhorst
Chairperson of the Local Organising Committee of ICOLD 2016
Chairperson of SANCOLD

Preface

Not only do many countries in Africa and other developing countries still require major water resources and dam engineering development for both water and energy supply but these countries also experience problems with proper long term operation and maintenance of their existing infrastructure. These problems in many cases lead to unsafe and unsustainable conditions that negatively impacts on the surrounding communities as well as the environment.

To try and mitigate this and share the some of the collective wisdom and knowledge available in the larger ICOLD family it was decided have organise an International Symposium titled "Appropriate technology to ensure proper Development, Operation and Maintenance of Dams in Developing Countries" to address some of these issues, in conjunction with the 84st Annual Meeting of the International Commission on Large Dams (ICOLD). The ICOLD Meeting host, the South African National Committee on Large Dams (SANCOLD), organized the Symposium.

These Proceedings contain papers on 9 different themes. Before the Symposium call for papers, 8 different themes were identified as appropriate. A number of relevant abstracts that satisfied the main theme but that did not necessarily satisfied any of the 8 chosen themes were received and subsequently categorised under a theme called "Other". The 9 themes for the Symposium therefore are:

1) Social and environmental impacts and mitigation measures;
2) Advances in the rehabilitation of dams and appurtenant works to extend their service life including the following:
    a) Improving spillway capacity and flood hydrology determination;
    b) Structural improvements to mitigate the effects of Alkali aggregate reaction, internal erosion potential, foundation failure;
3) Innovative river basin management including the optimisation of the operation of dams;
4) Reservoir sedimentation and management;
5) The state of the art of the tailings dams for their complete lifespan;
6) Strategies for proper surveillance of dams;
7) Sustainable hydropower development in developing countries; and
8) Other

We have received a total number of 333 papers for the Symposium. After the review process 245 papers from 42 different countries were chosen for publication in the proceedings. Of these 245 papers, 96 papers from 34 different countries were chosen for oral presentation in 4 parallel sessions and another 68 papers from 26 different countries were chosen for poster presentation.

All papers submitted for the Symposium were subjected to a full process of peer review and the proceedings contain only those papers that were accepted following this process. The review of the papers was undertaken by the members of the review panel acting independently on one or more assigned papers. This invaluable assistance, which has greatly enhanced the quality of the Proceedings, is gratefully acknowledged.

Finally, the editor wishes to thank the authors for their efforts at producing and delivering quality papers of appropriate quality and relevance. We trust that the Proceedings will be a valued reference for those working in the various fields covered and that it will form a suitable basis for discussion and future development and research.

Louis C. Hattingh
Editor

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KEY STEPS FOR CONDUCTING TAILINGS DAM BREACH STUDIES

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ABSTRACT

Engineering practitioners currently use a combination of guidance documents, published papers, and professional experience to support tailings dam breach and inundation studies. There is considerable knowledge and information available in this relatively new field of practice, but standardised and comprehensive guidelines specific to tailings dams are not available. Practitioners face several key challenges: (a) the more established and mature guidance is typically focused on water storage dams; (b) the available literature may only address specific aspects of dam breach assessment and inundation modelling; (c) the available literature sometimes relies on historical data that may not be consistent with the proposed application; and (d) the results are highly sensitive to the selected modelling inputs. This paper reflects on the currently available literature on tailings dam breach and inundation studies, compares how the major components for these studies are approached, and discusses how the resulting conclusions may vary. The key aspects of tailings dam breach and inundation assessment that are considered include: initial conditions and hydrology; boundary conditions; breach parameters; tailings mobility and discharged volume; and flood routing and inundation mapping.

1. INTRODUCTION

Martin, Fontaine and Cathcart (2015) prepared the paper, "*Practical Tools for Conducting Tailings Dam Breach Studies*" for the Canadian Dam Association Conference. This paper builds onto that and will provide the South African context.

Tailings dam breach studies are becoming generally expected and often required for operating and planned Tailings Storage Facilities (TSFs). The guidelines that are typically followed by practitioners around the world for tailings dam breach analyses were originally developed for water retaining dams, and as such, are not fully applicable to tailings dams. Generally, international guidelines don't prescribe procedures for conducting tailings dam breach analyses.

Tailings dam breach studies are being requested for various purposes listed below. The suitability of these studies for such purposes is not reflected on, or discussed in this paper.

- To determine the dam hazard classification based on potential incremental consequences of failure to socio-economic and environmental values;
- To prepare inundation maps in support of emergency preparedness and response planning;
- As part of the environmental studies for a proposed new project or expansion of an existing project;
- As part of alternatives assessments to evaluate various TSF locations or alternative tailings storage technologies.

Dam breach studies include characterisation of a hypothetical dam breach, flood wave routing, inundation mapping, and evaluation of impacts to socio-economic and environmental values. Standardised procedures and guidelines for conducting tailings dam breach studies do not exist at this time in South Africa. Mining and dam safety practitioners across the world are making efforts to standardise the procedure and are struggling with the practicalities of conducting meaningful assessments when every step of the process is inherently uncertain.

A range of methods may be applied in each step of the analysis depending on the extent of information available and the level of accuracy needed. A wide range of options is left open to practitioners in terms of how to conduct the assessment. The most appropriate approach and the accuracy of the results that can be achieved will be driven by the availability, resolution and accuracy of the input data. Increased complexity does not always result in increased accuracy, and as such, complexity should not be an objective, but rather a tool to be used carefully. Considering all this, a preliminary high level assessment may very well provide a sufficient level of detail to meet the stated purposes of a dam breach study.

A frequently cited reference specific to tailings dam breaches is by Rico et al. (2007) that presents empirical relationships for outflow volume, runout distance and peak discharge based on past tailings dam failures. Even though there are over 200 known cases of tailings dam failures worldwide, the documentation of these cases 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.

This paper is intended as a starting point for ongoing discussion about what approaches and methods are best suited to specific aspects of tailings dam breach and inundation studies. Key steps in conducting these analyses are identified and some practical tools are proposed with the objective of providing practitioners with information that will allow them to use the available literature and avoid potential difficulties that have been identified through our experience.

2. MODES OF DAM FAILURE

A dam is defined as any existing or proposed structure which is capable of containing, storing or impounding water, whether that water contains any substance or not (NWA, 1998). It should be noted, however, that modelling a breach of a dam that retains both water and tailings is considerably different from modelling a breach of a facility with very little or no water stored. These different processes are described in more detail in this section.

SANCOLD mentions two modes of failure (SANCOLD, 1990):

- *Overtopping* failure
- *Piping failure*

No specific guidelines are given for the hydrologic conditions to assess. The following conditions are considered applicable in this case:

- *Sunny day failure* – “a sudden dam failure that occurs during normal operations”, which may be “caused by internal erosion, piping, earthquakes, mis-operation leading to overtopping, or another event”.
- *Flood induced or rainy day failure* – “a dam failure resulting from a natural flood of a magnitude that is greater than what the dam can safely pass”.

These initial hydrologic conditions apply to both the impoundment levels and to the flow conditions at the facility and in the downstream drainage network that will be impacted by the passage of the breach flood wave.

One of the main differences 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, which has a relatively low solids content. 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. Furthermore, for TSFs that have a supernatant pond, a tailings dam breach typically results in two discharge mechanisms: (a) an *initial flood wave*, and (b) 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.

An *initial flood wave* would occur immediately following the failure of a TSF dam. The free water within the TSF supernatant pond would start to discharge and mobilise both tailings from the impoundment and construction materials from the TSF dam. The flood wave would propagate downstream causing significant erosion and inundating the downstream receiving environment (Figure 1a). The extents of inundation are largely driven by the size of the impoundment, the rate of breach development, the peak discharge and the downstream topography, with consequences potentially extending downstream for tens or hundreds of kilometres. The flood wave would carry the tailings solids and dam construction materials, as well as the material eroded along the way, resulting in very high solids concentrations. Some of the coarser material carried with the flood wave could deposit along the way, while the fine sized tailings would be carried in suspension until the flow velocities are low enough for this material to settle (e.g. in a lake or ocean).

This discharge mechanism is the main focus of most dam breach analyses and inundation studies because it poses the greatest risk to life safety and has the greatest potential to cause physical damage to the downstream environment. The initial flood wave is typically modelled as water, or a Newtonian fluid, which is a simplifying assumption that results in conservatively high flow velocities and discharge rates. Heavily sediment laden water is a non-Newtonian fluid, but modelling this type of fluid requires knowledge of the rheology (viscosity and yield stress), which is dynamic and impractical to predict. Furthermore, a non-Newtonian fluid option is not available for most of the flood routing software. It should be noted, however, that research conducted for a hypothetical breach using water and a non-Newtonian fluid has shown that the differences in peak discharge at various points downstream are within 5%, while the differences in depth are on the order of 10% (Bernedo et al. 2011). Considering that the shear stress imposed by the passage of the flood is orders of magnitude larger than the yield stress of the tailings slurry, this result is perhaps not so surprising. The errors associated with assuming that the released fluid flows like water is well within the modelling accuracy, considering the uncertainty inherent in all the assumptions and simplifications required by the modelling process, and it suggests that there may be little to be gained by using a non-Newtonian model.

The *flow of liquefied tailings*, or the second discharge mechanism, would occur following the initial flood wave, as some portion of the tailings mass would be expected to undergo static liquefaction resulting from the loss of confinement and the local steepening of slopes created by the initial discharge. Tailings that are not mobilised in the initial flood wave may slump through the breach in a paste-like fashion until the tailings mass stabilizes downstream. Similarly, for facilities with little or no free water stored, the flow of liquefied tailings would be the only consequence of a loss of confinement.

A liquefied tailings flow cannot be modelled as water. The viscosity and the yield stress of liquefied tailings play a significant role in the flow, which would behave like Bingham plastic fluid (Jeyapalan et al. 1983; Seddon 2010; Kulesza 2011). Some historic cases indicate that the cone of depression of the tailings mass remaining in the TSF forms at angles of 3.5˚ to 6˚, while the liquefied saturated tailings stabilize downstream at slopes of 1˚ to 4˚ (Lucia et al. 1981, Blight and Fourie 2003), with the deposition of the slumped tailings largely depending on the downstream topography and stream/valley slopes. The inundation extent from the flow of liquefied tailings would be considerably less than from the initial flood wave, but the slump would deposit far more solids in the first few hundred meters or several kilometres downstream of the breach location (Figure 1b).

Figure 1. (a) Erosion caused by the initial flood wave following the Mount Polley dam failure (MPMC, 2015); and (b) Cone of depresion of slumped liquefied tailings caused by the Merriespruit dam failure (www.tailingsinfo.com, 2015)

3. STANDARDIZED SAFETY CLASSIFICATION

SANS 10286, 1998, as part of their Safety Classification, prescribes the determination of the Zone of Influence of the facility. For active facilities the boundary if the zone of influence should be determined as follows:

a) upstream of any point on the perimeter, the lesser of a distance of 5h from the toe (where h is the height of deposit at the point under consideration); and the distance to the point where the ground level exceeds h/2 above the elevation of the toe at the point on the perimeter;

b) on sides parallel to the ground slope – a distance of 10h from the toe; and

c) downstream of the lowest point on the perimeter, a distance of 100h.

In practice, we have found that this method provides inadequate results and are often too small when compared to the potential impact of the initial flood wave. It sometimes gives a fair indication of what the secondary slump impact may be.

4. KEY STEPS IN A TAILINGS DAM BREACH STUDY

Nine key steps have been identified by the authors for conducting detailed tailings dam breach studies that include dam breach and flood routing modelling and inundation mapping. These steps are summarised below, noting that some of the steps may not be required depending on the purpose of the study and that most of the steps are applicable for water retaining dams too.

4.1 Define Study Objectives

Determine the purpose of the study including what the results will be used for. Simple methods of approximation may be more appropriate for early levels of study (e.g. scoping studies, preliminary engineering). The choice of tools to be used for the analysis will depend on the extent of information available and the level of accuracy needed.

4.2 Conduct Data and Information Gathering

Collect and review the available information and identify data gaps related to: (a) the TSF and the design and staging of the dams and other relevant facilities; (b) topographic and bathymetric data and type of terrain downstream of the TSF dams; (c) hydrologic information for the facility and the downstream drainage network; and (d) identification of downstream points of interest.

4.3 Identify TSF Dam Breach Scenarios with Credible Failure Modes

Review each dam configuration and identify those that have credible failure modes (i.e. overtopping or collapse) for all stages of project development including construction, operations, and closure. Consider starter dams, ultimate dams, and stages in between. Determine the number of TSF dam breach scenarios based on the number of dams with credible modes of failure, the number of stages, and the relevant sunny day and flood induced failure modes.

4.4 Determine Hydrologic Parameters

Determine the starting elevations for the supernatant pond, as well as the mean annual and flood flows for the site and the main downstream tributaries. The flows can be estimated from available site and regional data, or using rainfall-runoff modelling (tools like HEC-HMS or HydroCAD). The results of hydrologic modelling carry many uncertainties and largely depend on the experience of the modeller, the choice of the modelling tools used, and the assumptions made.

4.5 Determine Breach Characteristics

Determine (a) the volume of free water in the pond; (b) the volume of mobilized tailings; (c) the peak discharge; (d) the dam breach parameters (width, shape/side slopes, breach formation time); (e) the outflow flood hydrograph; and (f) the sensitivity range for various breach parameters. These characteristics are estimated based on available empirical relationships, or through modelling using breaching software (e.g. BREACH, DAMBRK). If empirical relationships are used, the outflow hydrographs can be developed in simple modelling tools (e.g. HEC-HMS or HydroCAD) by matching the predicted peak discharge while keeping within the predicted physical dimensions and breach formation times. The outflow hydrographs are then used as inputs for flood wave routing.

4.6 Select and Set-up Hydrodynamic Model

Model setup typically consists of: (a) importing all relevant geometry (e.g. dams, spillways, cross-sections or elevation data, and relevant infrastructure downstream); (b) setting up the hydrologic conditions; (c) determining boundary conditions; and (d) model calibration and validation. Hydrodynamic modelling is then conducted to establish flood extents, water depths and velocities, flood arrival times, and maximum discharges at various locations downstream. Modelling is conducted for credible failure scenarios, with and without a dam breach, to establish a basis for quantifying incremental impacts.

4.7 Determine the Effects of Tailings Slumping

Tailings slumping occurs due to a non-Newtonian flow of thick liquefied tailings. A Newtonian type flood wave would occur initially where water is stored in the TSF, followed by slumping of non-Newtonian liquefied tailings. If little or no free water is stored in the TSF, only tailings slumping may occur. The slump may form thick deposits of tailings solids gradually thinning out with distance from the breach. A simple approach to estimate the extent of tailings slumping is to assume a residual slope for the cone of depression within the TSF and a downstream slope for the settled tailings (Lucia et al. 1981, Blight and Fourie 2003). This approach considers balancing the outflow and settled tailings volumes using volumetric tools (e.g. Muck3D). Other methods used with increased complexity are based on landslide models (e.g. Fell and Hunter 2003) and Bingham plastic fluid models (e.g. Jeyapalan et al. 1982).

4.8 Prepare Inundation Maps

Inundation maps should be prepared for selected scenarios to achieve the study objectives and can be overlaid on topographic maps, orthophotos, or Google Earth/Bing map images. Inundation maps should show the maximum extent of flooding downstream of the breach and should include information on flood peak arrival time, depth of flow, and velocities, where relevant. Water surface extents without and with a dam breach should be shown such that the extent of the incremental impact can be evaluated. The resolution and accuracy depends on the available input information and flooded area at risk.

4.9 Determine Study Findings

The study findings should be consistent with the objectives of the study, including: (a) determine the dam hazard classification based on potential incremental consequences; (b) prepare inundation maps in support of emergency preparedness and response planning; (c) as part of the environmental studies for a proposed new project or expansion of an existing project; (d) as part of alternatives assessments to evaluate various TSF locations or alternative tailings storage technologies; (e) other purpose deemed suitable by the practitioner.

5. CHALLENGES AND PRACTICAL CONSIDERATIONS IN CONDUCTING TAILINGS DAM BREACH STUDIES

Tailings dam breach practitioners are faced with numerous uncertainties when making assumptions and simplifications necessary to conduct these analyses. Some of the specific challenges encountered by the authors in the process are briefly discussed in this section.

5.1 Topographic and Bathymetric Data

Some of the limitations of dam breach modelling, downstream flood wave routing, and inundation mapping, stem from the quality of topographic and bathymetric data available for the downstream drainage network. Bathymetric data often do not exist even for major river channels, while detailed topographic information (e.g. 1 m contour data) is typically available only for areas close to the dam. Obtaining such data can be very expensive and time consuming, and often not required depending on the expected consequences and level of accuracy needed for the study.

Modelling is often done using publically available topographic data of poor quality and with large contour spacings. Such contour spacing does not enable detailed delineation of river channels and associated floodplains and restricts the accuracy of inundation maps. Lack of bathymetric data or numerous surveyed cross-sections means the flow within the natural stream channels cannot be modelled accurately. Coarse topographic and bathymetric information is unfavourable for hydrodynamic modelling and flood wave routing and creates challenges for the practitioners who need to manually manipulate the information and select the channel and valley hydraulic characteristics based on these limited data sets.

5.2 Determining Credible Failure Modes

Depending on the purpose of the study, the credible failure mode evaluation may need to include the assessment of all dams at various stages during construction, operation, and closure. For example, flood extents at some stage during operations may not be representative of the worst case scenario due to a smaller outflow volume, but may be equally important to consider if the construction camp or other mine facilities are located downstream of the dam.

5.3 Determining Initial Hydrologic Conditions

5.3.1 Water Levels in the Impoundment

The water levels in the impoundment are taken as:

- The normal operating pond level for a sunny day scenario, and
- FSL of the dam.

The duration of the design flood/storm event considered can have a significant impact on the magnitude of flow a TSF has to deal with. This matter is still open to debate.

5.3.2 Initial Hydrologic Conditions for the Downstream Drainage Network

A sunny day failure scenario is modelled to be coincident with mean annual flow conditions in the downstream channels. A flood induced failure becomes more challenging as it is uncertain which area of the downstream network would be flowing at its peak at the time of failure of the facticity under consideration.

Additional uncertainty is embedded in estimating an event as large as 1000-years, as confidence in the predicted estimate decreases as the extrapolation is made further beyond the number of years with reliable record. In general, statistical analysis of annual exceedance probabilities for a single station should not extend beyond 2 times the number of years of record (ICOLD). This means that in order to estimate a 1000-year peak flow with reasonable confidence using frequency analysis, the historical flood record would need to 250 to 500 years long.

5.4 Determining Breach Characteristics

The quantitative assessment of the potential consequences of a flood from a TSF dam breach requires estimating the volume of water and tailings released in the breach, the peak outflow discharge, the physical characteristics of the breach (height, width, and side slopes), and an estimate of the time of breach formation. These characteristics are used to develop a dam breach outflow hydrograph, which is subsequently routed through the downstream drainage network to simulate the inundation limits.

6. CONCLUSIONS

Tailings dam breach modelling is becoming an accepted part of the planning process for operating and proposed TSFs, with various objectives ranging from dam hazard classification to alternatives assessment. In order to conduct a dam breach analysis, a failure mode must be selected, the size of the embankment breach must be approximated, the volumes of released tailings and water must be estimated, and the resulting runout pattern of the released material must be modelled. The considerable uncertainty involved in each step of the analysis, combined with the lack of any standardized or mandated approach for completing such an analysis, results in substantial uncertainty in the modelled results. It is important that all dam breach modelling results be viewed in the context of this framework and its limitations, and that clients, regulators and the public be educated in this regard.

Modern tailings storage facilities are designed to contain mine tailings and associated water, often for all conceivable conditions; therefore, it is sometimes difficult to foresee a credible failure mode for properly engineered structures. Furthermore, physical constraints need to be considered and applied where appropriate throughout the process, as was discussed in the section on breach outflow volume. Simply applying an empirical relationship can result in unrealistic or impossible results. Modelling unrealistically large breaches without due consideration of the physical constraints may produce unrealistically large consequences. Such unrealistic results provide no value to stakeholders and provide little insight into the actual risk and potential impacts posed by the facility.

Even though the mining and dam safety communities are making efforts to standardise the procedures for tailings dam breach studies, conducting meaningful assessments is challenging when there is such a high level of uncertainty throughout the assessment process. Practitioners must rely on good professional judgement and experience when carrying out and presenting their work. Streamlining and standardising the process of conducting tailings dam breach studies would not necessarily remove the uncertainties and improve on the results significantly, but would help the engineering practitioners conduct these studies in a similar fashion and make the results more comparable. This paper discussed some of the fundamental parameters that need to be considered and presented the key steps that the authors have found useful in their practice. It is the authors' hope that discussions around the dam breach assessment process continue and are perhaps incorporated into future guidance documents.

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