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INUNDATION MODELLING OF NON-NEWTONIAN TAILINGS DAM BREACH OUTFLOWS (*)

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CANADA

SUMMARY

The Mount Polley, Fundão, Feijão and other tailings dam failures have had catastrophic environmental and social impacts. Tailings dam owners, operators, regulators, and stakeholders rely on dam breach studies to evaluate potential consequences of a failure and make informed decisions and ultimately safeguard the public. However, scientific understanding of the breach processes and physical phenomenon of tailings outflows is still developing. Uncertainties in model inputs combined with lack of standardized methodologies for completing the various analyses required for these complex studies present considerable challenges to professionals. Experience and judgement must be relied on to construct tailings dam breach models and assess the results.

Tailings dam breaches typically result in hyperconcentrated flows due to the mobilization of stored tailings solids. After determining the hypothetical outflow volume and the breach hydrograph, the breach outflow is routed downstream using hydrodynamic or geomechanical modelling tools to estimate the inundation. Site-specific tailings rheology is required to characterize these flows, which is rarely

* *Modélisation des écoulements non newtoniens dans les brèches des barrages de stériles*

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available. This paper describes recent experiences with modelling the flood wave propagation of non-Newtonian tailings dam breach outflows using hydrodynamic modelling tools. Challenges encountered and lessons learned from various case studies are discussed, including availability and quality of input data and selection of appropriate models for the given conditions. All these factors have profound impacts on the results.

RÉSUMÉ

Les ruptures du Mont Polley, de Fundão, de Feijão et d’autres barrages de stériles ont eu des impacts environnementaux et sociaux catastrophiques. Les propriétaires, opérateurs, régulateurs et parties prenantes sont dépendants des études des brèches de barrages pour prendre des décisions et sauvegarder le pub-lic. Cependant, la compréhension scientifique des processus et du phénomène physique des écoulements de résidus se développe encore. Les incertitudes dans chaque entrée de modèle combiné avec le manque de méthodologies normalisées pour accomplir les diverses analyses requises pour ces études complexes présen-tent des défis considérables pour les professionnels. L’expérience et le jugement doit être fondée pour construire des modèles de brèches de barrages de stériles et évaluer les résultats.

Les brèches de barrages de stériles entraînent généralement des écoulements hyper-concentrés en raison de la mobilisation des résidus solides stockés. Après avoir déterminé le volume d’écoulement hypothétique et l’hydrographe de la brèche, l’écoulement de la brèche est acheminé vers l’aval à l’aide d’outils de mod-élisation hydrodynamique ou géomécanique pour estimer l’inondation. La rhéologie des résidus propres au site est nécessaire pour caractériser ces écoulements, ce qui est rarement disponible. Ce rapport décrit les expériences récentes de modéli-sation de la propagation des ondes de crue des débits de rupture de barrages de stériles à l’aide d’outils de modélisation hydrodynamique non-Newtoniens. Les défis rencontrés et les leçons apprises pour une sélection diverse d’études de cas sont discutés, y compris la disponibilité et la qualité des données d’entrée et la sélec-tion de modèles appropriés pour les conditions données. Tous ces facteurs ont des impacts profonds sur les résultats.

1. INTRODUCTION

Dam breach inundation studies are required to evaluate the potential impacts and hazards associated with a tailings facility at all stages of design, whether the facility is proposed, operating, or closed. The results from these studies can inform the dam consequence classification, emergency preparedness and response planning, and can also be used in environmental impact assessments, alterna-tive assessments, or for other purposes that are critical for the design and safety management of tailings facilities.

Dam breach studies are an important requirement and an integral part of the Global Industry Standard on Tailings Management (GISTM) released on August 4, 2020, which provides a framework for safe tailings facility management. The goal of the GISTM is to work towards achieving zero harm to people and environment with zero tolerance for human fatality [1]. Furthermore, mining companies and governments around the world are also introducing requirements and regulations for tailings dam breach studies (e.g. Resolution 13 issued on August 18, 2019, or Resolution 32 issued on May 11, 2020, both by the Agência Nacional de Mineração (ANM) in Brazil, [2, 3]).

Recent work to standardize approaches for tailings dam breach studies has been completed by the Canadian Dam Association (CDA) in a Technical Bulletin on Tailing Dam Breach Analyses [4] (CDA TDBA Bulletin for short), which were previously summarized in Martin et al. [5]. The science and understanding of the physical processes driving tailings dam breach events and the hyperconcentrated flows released in breach outflows is still evolving. As such, many uncertainties in the required inputs and in appropriate modelling methodologies still exist.

Research efforts are increasing to cater to the mining industry's need to better predict tailings dam breach outflows. The Canadian Tailings Dam Breach Research Project (CanBreach) is one example of a joint research and technology development effort between several Canadian Universities (University of Waterloo, Queen's University, and the University of British Columbia), the mining industry, and the professional community. To advance the understanding and modelling capabilities of breaching and runout processes, CanBreach is combining forensic analysis and field observations of past failures with laboratory-scale experimentation and numerical modelling.

In addition to various research efforts, numerical tools for modelling the breach outflow hydrograph (e.g., BREACH, DL Breach, FLDWAV, FLO-2D, HEC-RAS, HEC-HMS, or WinDAM), and hydrodynamic tools for modelling the downstream propagation of non-Newtonian tailings breach outflows (e.g., FLO-2D, FLOW-3D, and RiverFlow2D, or tools in development at the time this paper was prepared like HEC-RAS Version 5.1, TELEMAC 2D, and TUFLOW) are constantly evolving. These modelling tools are becoming increasingly complex as they aim to incorporate additional processes, such as the mixing and dilution with incoming flows from downstream tributaries, or the erosional and depositional processes caused by the passage of a breach flood wave.

There are two high level steps in a dam breach study related to modelling: (1) determining the critical failure modes, the outflow volumes and the breach outflow hydrographs; and (2) developing a hydrodynamic model to route the flood wave and predict how the breach outflow impacts the downstream environment. While the former step is briefly addressed, the latter step is the focus of this paper. Specific challenges involve the availability and quality of input data, followed by the selection of an appropriate hydrodynamic model while considering the limitations of each model. Inputs to the model are discussed in general, and specific applications and difficulties are demonstrated using case studies. It is acknowledged, however, that some of the findings in this paper may be outdated by the time of final publication considering the fast pace of research and development of the numerical tools.

2. DAM BREACH STUDY PROCESS

2.1. General

The physical processes of a dam breach event may vary substantially depending on the presence of a supernatant pond and on susceptibility of the dam fill and/or the tailings to liquefy and flow [4, 5]. The breaching process may be erosional, driven by overtopping or piping with the discharge of the supernatant pond carrying eroded tailings and dam fill materials. Due to the loss of containment, the tailings mass may undergo flow liquefaction resulting in additional discharge of liquefied tailings, or it may undergo progressive slumping of unsupported non-liquefiable tailings until the tailings slopes reach equilibrium. The runout from such a failure may range from water floods to mud floods to mudflows, as characterized by O'Brien [6] and discussed further in the CDA TDBA Bulletin [4].

The breaching process may also be nearly instantaneous if triggered by a different failure mechanism such as mass liquefaction of the dam fill and/or tailings mass, similar to what occurred at the Feijão dam near Brumadinho, Brazil, in January 2019. In this scenario, the outflow would comprise liquefied dam fill and tailings materials, as well as any water contained within an impacted supernatant pond, if present. The outflow of liquefied tailings and water would also cause additional erosion of tailings and dam fill materials as it leaves the facility. The runout from such failures may range from mudflows, to flow slides or tailings flows, or it may be a mixture of water floods, mud floods and mudflows for facilities with a pond that discharges in a breach [4].

2.2. Breach hydrograph

For a hypothetical dam breach, the professional must determine a reasonable and critical failure mode, the breach outflow volume, the breach characteristics, and the resulting breach outflow hydrograph. The breach outflow volume for water retaining dams is typically considered to be the entire stored volume above the breach invert at the time of a hypothetical failure. The breach volume for tailings dams, however, most often includes the supernatant pond and a volume of stored tailings that are released as a result of erosion or static liquefaction. It is expected that the tailings would continue to mobilize until a stable residual slope is formed in the facility.

Breach parameters (size, shape, and time to fail) and peak outflows can be estimated using several existing empirical equations and guidelines that were summarized by Wahl [7, 8], West et al. [9], and Brunner [10]. These include the works of: MacDonald and Langridge-Monopolis (1984), Costa (1985), Bureau of Reclamation (1988), Von Thun and Gillette (1990), FERC (2015), Froehlich (1995, 2008, 2016), Walder and O'Connor (1997), Xu and Zhang (2009), Pierce et al. (2010), and others. The limitations regarding the applicability of empirical equations to tailings dams include the following:

- The equations were developed for water retaining dams;
- Most equations were developed with limited data sets for failures of relatively small dams (with dam breach studies for larger dams must rely on extrapolated results);
- The various equations often generate a wide range of possible breach parameters and peak outflows, as was illustrated in Martin and Akkerman [11];
- Most equations would not be applicable for liquefaction type failures of upstream constructed tailings dams.

In consideration of these limitations, sensitivity analysis using the possible ranges of breach parameters are required in order to evaluate the impact on peak outflows and downstream consequences. Monte Carlo analysis can be used to provide a meaningful stochastic analysis of peak breach outflows for various combinations of breach parameters, as described by Goodell [12]. Assuming that a breach occurs, the final breach outflow hydrograph can be developed for the combination of parameters that resulted in a selected peak discharge (e.g., the 95^{th} percentile peak discharge, or the peak discharge that has a probability of exceedance of 5% if a dam breach occurred).

Physically-based numerical breach models attempt to model the erosional processes using a combination of sediment transport, soil mechanics, and hydraulics principles. Models based on typical water retaining dam configurations currently exist, however, the applicability of these physically-based models for tailings dam breaches is still uncertain. These models are not well suited for upstream constructed tailings dams that are relying on the strength of potentially liquefiable tailings. Similarly, the impact a tailings beach commonly adjacent to the dam would have on a breach development is not well understood.

2.3. Hydrodynamic modelling and flood wave routing

Determining the breach outflow hydrograph, while complex and highly uncertain, is only part of the process. Hydrodynamic models are commonly used to predict the potential downstream impacts following a breach event. Generally speaking, hydrodynamic models compute the depth and velocity of a flood wave incorporating the equations for conservation of continuity, energy, and momentum. All numerical models are simplifications of real-world phenomena that calculate results discretely, both temporally and spatially, in addition to including parameterizations to describe physical processes not included in the basic conservation equations. The temporal and spatial discretization may result in discretization errors, arising from the fact a fixed and finite number of elements is used to represent a continuous variable (fluid flow). The discretization error may be reduced with finer resolution (or mesh size) in the hydrodynamic model, at the expense of greater computational requirements.

The discretization and various parameterizations are treated slightly differently in various software packages. Knowledge of these differences and their limitations is important when selecting and constructing a model to best estimate the downstream inundation. One common simplification used in dam breach modelling is using two-dimensional (2D) instead of 3D models, in which the vertical velocity variations are removed and depth-average calculations (i.e. shallow water approximation) are used instead. This assumes that the variation in the vertical velocity component is negligible compared to the horizontal velocity components. The computational requirements are considerably reduced when using a 2D instead of a 3D model. Similarly, the velocity variation across the channel may also be averaged, resulting in 1D models that are correspondingly faster than 2D models. Further details on selecting steady vs. unsteady, or 1D vs. 2D. vs. 3D models are discussed in USACE [13].

Dam breach events are typically highly turbulent and unsteady, and the vertical velocity component may not be negligible compared to the horizontal velocity components, especially immediately downstream of a breach. The required downstream extent of a dam breach model, however, almost always limits the study to depth-averaged or 2D models rather than 3D models due to computational requirements. With highly dynamic and complex flow directions typically associated with dam breach and overland flooding, 2D is preferable to 1D modelling. A 1D model may suffice if the flow is expected to be relatively unidirectional without much overland flooding in canyon-like terrains, or when the model domain is very large ($>$100 km) such that the computation requirements prohibit a 2D model. Hybrid 1D/2D models can be applied to utilize the advantages of both approaches, however, these may result in model stability issues at the 1D/2D interface, which occasionally negate the possible advantages.

Given the flood wave dynamics and their large area of impact, 2D models often strike a reasonable balance between improved complexity and computational requirements. Advancements in processing power and cloud computing may change this in the coming decade allowing full 3D models to eventually become standard. 2D models will remain in use for tailings dam breach inundation modelling in the near future, and as such are the focus of this paper.

Another common simplification in tailings dam breach models is an assumption of a fixed-bed model, where erosion and tailings deposition due to the passage of a flood wave are neglected. This simplification is often needed due to lack of available data to support erosion modelling over large downstream extents, or due to hydrodynamic models not being capable to perform both sediment transport and non-Newtonian flow calculations concurrently. Some of the current software developments are starting to overcome this deficiency but are yet to be sufficiently proved in practice.

3. HYDRODYNAMIC INPUT DATA

3.1. General

Inputs for the hydrodynamic model include the breach outflow hydrograph, the representation of the downstream terrain, the natural flows occurring in the downstream watercourses at the time of the breach, and the rheology or non-Newtonian flow properties of hyperconcentrated flows that are typical for tailings dam breaches.

The quality of the results of any computer model are highly dependent on the quality and representativeness of the input data. Regardless of the skill and knowledge of the modeller or the sophistication of the model, low quality inputs will result in poor quality and potentially inaccurate outputs, and therefore, an extremely important element for all dam breach studies is careful consideration of the data used to build these models.

3.2. Terrain data and surface roughness

The terrain downstream of the facility is integral to determining the inundation and impact of a hypothetical dam breach. Gridded elevation data sets, commonly referred to as Digital Elevation Models (DEMs), are used to represent the terrain in the hydrodynamic models. These data can come from various technologies, such are drone measurements (tens of hectares), aircraft surveys (few km^2 to few tens of km^2), or satellite measurements for larger areas (few tens of km^2 to few hundreds of km^2).

There are two main measures of the quality of a DEM: (1) the horizontal resolution, or the size of each gridded elevation cell; and (2) the vertical accuracy, represented by the vertical distance between the modelled and the true elevation due to systematic and random errors. Fine horizontal resolution with higher accuracy is required to adequately describe the topography. Publicly available satellite data typically range from 30 m to 90 m horizontal resolution for various locations around the world. Site-specific DEMs from drone or aircraft data can reach resolutions of 0.5 m but may be costly to procure for large model extents.

The scale and scope of a dam breach study, the complexity of the downstream area, and the potential impact of a hypothetical dam breach should be taken into account when assessing the quality of a DEM. It is frequently up to the professional to determine if a publicly available coarser resolution data would be acceptable compared to a more expensive higher resolution data developed specifically for the dam breach study. This decision is often subjective and comes with professional judgement and experience, but in general, it is governed by the type of terrain and potential risk to the downstream population. Flat terrain or heavily populated areas would typically require higher resolution topographic data in order to define the potential inundation with higher accuracy.

Further complication with terrain data is that most of the measurement methods do not include sub-aqueous terrain data (bathymetry) for the water bodies (e.g., rivers, lakes, etc.). A separate hydrographic survey is required to provide this information. For larger river systems, the bathymetry can have a profound effect on the possible flood wave attenuation. If no bathymetry data is available, the professional must either use the terrain "as is" and assume/accept the attenuation is negligible, estimate the shape and depth of the river channel and "burn" in channels to the terrain data prior to modelling, or recommend that bathymetry data be collected.

An example of the impact the terrain can have on the inundation results is shown on Figure 1. A tailings dam breach study was updated six years after the initial study was completed, following material changes at the mine site. The publicly available topographic data improved in resolution and accuracy in the meantime. The newer terrain has a clearly defined channel while the older terrain does not, as shown in the cross section on Figure 1. Although the updated analysis indicated a larger breach volume and higher peak flow, the inundation area in the downstream watercourse was smaller due to a better topographic definition indicating a confinement in the terrain.

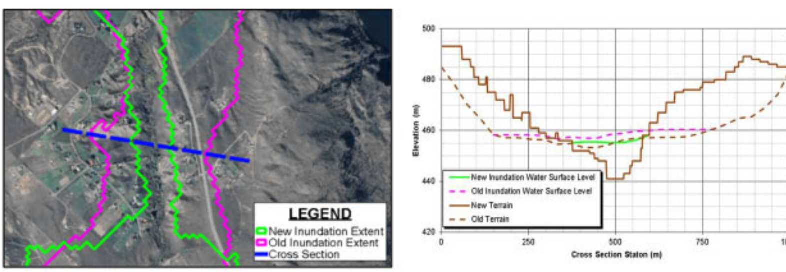

Fig. 1
Example of the impact of topographic resolution on the inundation extent.
Exemple de l'impact de la résolution topographique sur l'étendue de l'inondation.

Lastly, surface roughness that defines the resistance to flow must be assigned to the terrain. Most 2D models describe the surface roughness with a Manning's n value, however some may define it using roughness height. Regardless of the definition, various sources exist and can be referred to when selecting these values. Publicly available digital land use maps are becoming more prominent, allowing for easier classification and spatial variation of the roughness parameter within the hydrodynamic model domain. Professional experience should be used to adjust the parameter in some areas based on satellite imagery. Sensitivity of the inundation extent and flood wave arrival time to the selected surface roughness should be evaluated.

3.3. Hydrology and natural flows

While the severity of the inundation is directly related to the breach volume and peak outflow, the background or natural flows in the downstream watercourses can also have a large impact on the inundation and attenuation of the breach flood wave. Two hydrologic conditions are typically considered for dam breach studies: (1) flood induced or rainy day, where the failure is coincidental with extreme flood conditions (e.g. the Inflow Design Flood or IDF); and (2) fair weather or sunny day, where the failure occurs due to any trigger under normal operating conditions.

The downstream watercourses in flood induced scenarios should be modelled at flood levels expected to occur concurrently with the assumed flood (e.g. IDF) at the facility. The larger the downstream drainage, the more difficult determining the downstream flood magnitude becomes. A heavy storm centered at the facility would decrease in intensity over large areas. Catchments that are farther downstream, which contribute to the watercourses along the main flood wave path would not concurrently experience the same level of storm intensity. Furthermore, different catchments would have different response times, and while one catchment could be contributing its peak flow, the others could either be receding or intensifying. This means that while the facility is experiencing the IDF, the downstream catchments could be experiencing anywhere from bankfull flows (often represented by a 2-year flood) to a flood equivalent to the IDF. The local climate, catchment characteristics, and distance to the breached facility should guide the selection of the return period flood event for each contributing catchment. Selecting high return period flow values results in larger overall inundation and faster flood wave arrival time, but potentially lower incremental inundation. Conversely, low return period flow values would result in the opposite.

There is substantially less subjectivity in selecting flow conditions for a fair weather scenario. Mean Annual Discharge (MAD) is typically used for downstream watercourses, which is often easier to estimate and requires less professional judgement and subjectivity. If the MAD is small compared to the breach flow (approximately two times or more lower, as noted in FEMA [14]), it can be neglected in the hydrodynamic model as the flow would not materially increase the inundation, nor would the watercourse storage materially change the attenuation of the breach flood wave. The MAD should be included in the model for larger rivers where the impact of the flow and storage is not negligible.

3.4. Rheology

Input data specific to tailings dam breaches consider the rheology of the hyper-concentrated flows, often represented by the yield stress and the dynamic viscosity at different volumetric solids concentrations. With increasing solids concentration in the flood wave, the flow regime transitions from Newtonian flows (such as water) to non-Newtonian flows (mud floods to mudflows to debris flows and landslides), as classified by O'Brien [6] and applied to tailings flows in CDA TDBA Bulletin [4]. The flow properties of non-Newtonian fluids are an active area of research, which includes uncertainties associated with measuring and implementing these properties into the flood wave routing of tailings dam breaches.

There are typically three main parameters that define the flow characteristics in a hydrodynamic model: the solids concentration, the yield stress, and the viscosity. The viscosity is a measure of the fluids flowability (e.g., fluids like honey with high viscosity are less flowable), while the yield stress is a measure of the stress required to mobilize the tailings mass at low confining pressures. There is limited published data on viscosity and yield stress. Figure 2 represents the compilation of available data from various sources.

These data include mudflow samples in Colorado (Glenwood, Aspen and Natural Soil) presented in O'Brien and Julien [15], various samples (Bentonite, Coussot, Kaolinite, St. Helens and Quick Clays) presented in Julien [16], NA Tailings samples from a copper / gold mine (yield stress only) presented in Adams et al. [17], tailings slurry samples from a gold mine (Project X data, confidential), and samples from the deposited tailings runout of the Fundão failure in Brazil in 2015 presented in Días [18] (yield stress only) and Machado [19]. Generally, more yield stress than viscosity data are available in various literature.

Tailings from hard rock mines (e.g., copper, nickel) behave differently at similar solids concentrations than tailings from soft rock mines (e.g., coal), or tailings with high clay content. For example, NA Tailings with higher clay content (>25%) and Quick Clays shown on Figure 2, have a higher yield stress at lower solids concentrations than NA Tailings with a lower clay content (<25%), or Project X samples that also had a very low clay content. Similarly, the Aspen samples had a higher clay content and a higher yield stress than the Glenwood samples, as discussed in [15]. The iron tailings samples from the Fundão failure had a very high specific gravity of about 4, which likely contributed to high flowability with low yield stress and low viscosity at high solids contents.

Extrapolation is often required for tailings samples for volumetric solids concentrations above 45% - 55%, as these are difficult to measure (see example trend for Project X in Fig. 2). Site-specific rheology data that would be representative of the spatial variation and variation through the depth of the tailings deposit are difficult to procure and are rarely available. Furthermore, rheological trends may vary

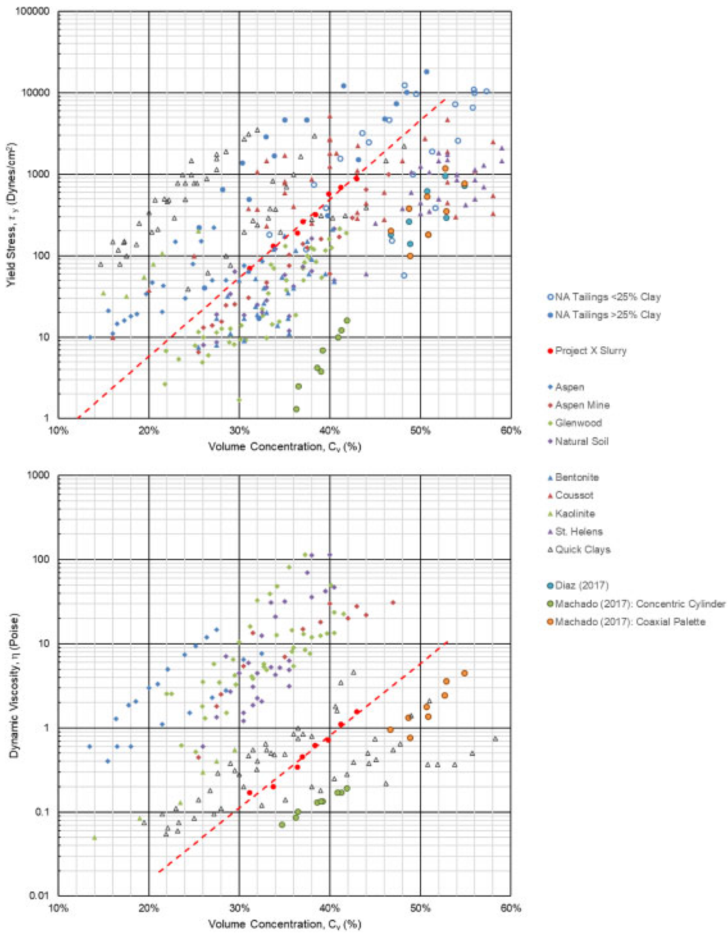

Fig. 2
Yield Stress and Viscosity Variation with Volumetric Solids Concentration.
Variation de la limite d'élasticité apparente et viscosité avec concentration volumétrique de solides.

temporary and spatially as the mine life progresses and the stored tailings settle and densify within the facility.

Although viscosity and yield stress are commonly used in conventional fluid mechanics to characterize the shear properties of a fluid, these can be inadequate to describe some granular flows with low moisture content in which particle-to-particle contacts become dominant and control the flow [4]. Additional rheological constitutive relations from the field of continuum mechanics need to be considered to characterize tailings flows for these cases; however, such tailings flows are beyond the scope of this paper.

4. CASE STUDY 1

4.1. PROJECT BACKGROUND AND AVAILABLE DATA

The tailings facility in Case Study 1 is part of an active gold mine in South America. The facility has a ring dyke configuration on a divide between two watersheds. The downstream area is rural with 20 to 30 permanent residences within the first 20 km of the facility on one side, and mine facilities, stockpiles and open pits on the other side of the facility. Multiple breach locations were considered for this facility, but only the breach runout towards the populated rural farmlands is discussed in Case Study 1. The study area followed the downstream watercourses for 110 km and the total contributing watershed area was approximately 8,500 km^2. The downstream watercourses are at a steady slope of 0.5%.

High resolution aerial surveys were available for the mine site. A satellite DEM based on Shuttle Radar Topography Mission Version 3.0 (SRTM) was obtained for the downstream watercourses and rural areas from the United States Geologic Survey (USGS) website. The DEM has a horizontal resolution of 30 m and a reported accuracy of around 5 m, or better for flat terrains similar to the area downstream of the facility.

The nearest hydrologic station on the breach flood wave path is 70 km downstream of the project with a relatively short flow record of 20 years. To confirm appropriate flood flow values for the downstream watercourses, a regional hydrologic analysis was conducted. Flood frequency analysis was completed on 30 hydrology stations within 400 km of the project location with periods of record from 30 to 50 years. The IDF for the facility is a 10,000-year event, which was also adopted for the immediate downstream watershed. Catchments further downstream were assigned a 1,000-year event to reflect the intense monsoons experienced in the region.

Site-specific rheology information was not available, and as such, the rheology was based on data found in literature (O'Brien and Julien [15], and Adams et al. [17]). Based on comparison of site-specific tailings characteristics to those from the literature, a strong and weak rheology (representative of low and high flowability, respectively) was assessed as part of the sensitivity analysis to evaluate the impact of different rheologic parameters on breach runout progression and inundation. The strong and weak rheologic parameters that were used in this study were approximately one order of magnitude higher and lower than the baseline rheology (viscosity and yield stress).

4.2. SELECTED HYDRODYNAMIC MODEL

The selected model in this study was FLOW-3D, developed by Flow Science, Inc. [20]. The Shallow Water Module in FLOW-3D was used in conjunction with the non-Newtonian fluid properties. FLOW-3D models non-Newtonian flows using a laminar flow approximation and either the Bingham or the Herschel-Bulkley generalized equation. The laminar flow approximation does not consider turbulent stresses that could be significant for dam breach flows, flows on steep slopes, flows with low solid concentrations (20% to 40% by volume), and flows on rough surfaces. Furthermore, at the time of the study and writing of this paper, FLOW-3D did not have the capacity to simulate the dilution of the tailings laden breach flood wave with incoming flows from downstream tributaries, and as such, the non-Newtonian fluid properties (yield stress and viscosity) had to be set at a constant value that corresponded to the solids concentration specific to a given model domain. The downstream model extent was subdivided into smaller domains to capture the dilution due to incoming larger tributaries.

4.3. MODEL RESULTS AND LESSONS LEARNED

During normal operations, the supernatant pond in this facility is more than a kilometer away from the dam, and as such, it would not discharge during a fair weather breach. The runout would constitute tailings solids and interstitial water only. It would have a volumetric solids concentration of approximately 50% and would behave like a mudflow, as discussed in [4], [5], and [6]. In consideration of the low roughness associated with the grassy farmlands and shallow slopes downstream of the facility, the turbulent stresses generated by the breach outflows were estimated to be less dominant than the viscous forces governed by the rheological properties. As such, the laminar approach in FLOW-3D was considered valid for modelling the mudflow runout.

The total volumetric solids concentration was estimated to be between 20% and 30% for the flood induced scenario. This scenario was modelled as a Newtonian flow, as the breach flood wave would be diluted to below 20% solids concentration upon reaching a larger watercourse located a short distance downstream of the facility. The rheologic parameters would have a much smaller effect in this case than the turbulence associated with the breach outflows.

Lack of site-specific rheology data proved to introduce a large variation in the fair weather results, increasing the uncertainty of the study. The impact of the rheology was evaluated as part of the sensitivity analysis, with the results shown on Figure 3. The mudflow was predicted to travel more than twice as far when using the weaker rheologic parameters (blue outline) compared to the stronger rheologic parameters (red outline). This result demonstrates how sensitive the results could be to these inputs, and highlights the need for the careful choices a professional

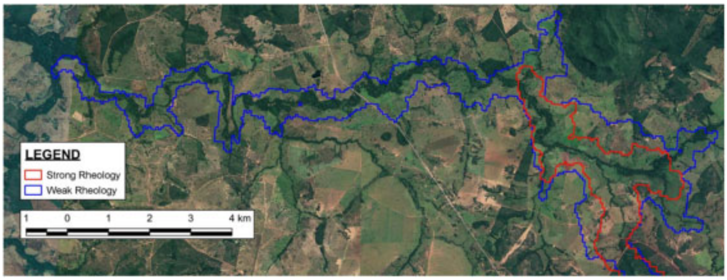

Fig. 3
Inundation extent under different assumed rheology trends.
Étendue de l'inondation avec différentes tendances rhéologiques supposées.

must make when selecting inputs in the absence of site-specific data. The results of the assessment prompted the dam owner to collect rheology data to reduce uncertainties in future studies.

5. CASE STUDY 2

5.1. PROJECT BACKGROUND AND AVAILABLE DATA

The tailings facility in Case Study 2 is an inactive, reclaimed tailings impoundment located in a mountainous area in coastal North America. Reclamation work included reshaping and capping the facility to prevent ponding of water, constructing spillways and diversion channels around the facility that pass the IDF, and constructing stabilization buttresses along the embankments. The slope immediately downstream of the facility is 50%. The average slope for the downstream watercourse is 10%, reducing to 2% on an alluvial fan approximately 3.5 km downstream where a major river is intercepted. The total contributing watershed area is about 20 km^2. The area of impact includes narrow canyons surrounded with dense mixed forests, and a few farmlands with a small permanent population located adjacent to the major river at the downstream end of the model. A DEM with a horizontal resolution of 1 m and a vertical accuracy of around 15 cm was available for the dam breach study.

The IDF for the facility is the Probable Maximum Flood (PMF). Based on the small total watershed area in this study, the downstream watercourse was also assigned a PMF flow for the flood induced scenario. The MAD in the watercourse was considered negligible and was not included in the fair weather scenario. The flow in the major river was modelled at bankfull conditions in both scenarios to assess the impact of potential backwatering on the breach flood wave propagation through the populated area. Due to the geographic setting for the project and the large watershed size for the major river, a large flood in the river coincidental with a

PMF at the facility is not likely to occur, which governed the selection of bankfull flows for the flood induced scenario. Near-bankfull flows in the major river that last over several weeks do occur regularly during the freshet period in the spring, which may be coincidental with normal hydrologic conditions at the project site. This governed the selection of bankfull flows for the fair weather scenario.

Considering that ponding is not possible in the tailings facility, the breach outflows in this study would have a very high volumetric solids concentration of about 54% in both the flood induced and the fair weather scenarios, resembling a dense mudflow. Site-specific rheology information was not available, and as such, the rheology was based on data found in literature (O'Brien and Julien [15], and Adams et al. [17]). Similar to Case Study 1, a reasonable range in rheological values was assessed as part of the sensitivity analysis.

5.2. SELECTED HYDRODYNAMIC MODEL

The FLO-2D hydrodynamic model, developed by FLO-2D Software Inc. [21], was selected for this study. FLO-2D uses a quadratic rheological model developed by O'Brien and Julien [15] that describes the continuum of flow regimes from turbulent to viscous flows as the solids concentration increases.

FLO-2D has limited options for modelling the initial/pre-breach conditions. The model starts entirely dry in every simulation and the background flows must be routed through the model domain for a period sufficiently long for these flows to reach a steady state prior to starting the routing of the breach flood wave. The domain wetting period is required for all scenarios in which the failure is coincidental with a flood event. This can significantly increase the computational requirements, which is not feasible for projects with large model domains such is the domain in Case Study 1. Case Study 2 had a relatively short model domain, and therefore, the additional computation time was acceptable. In comparison, the hydrodynamic models used in Case Studies 1 and 3 have the capability to set initial flow conditions for the downstream drainage based on prior model results, and are therefore not limited similarly to FLO-2D in this regard.

5.3. MODEL RESULTS AND LESSONS LEARNED

FLOW-3D was initially used in this case study; however, the conditions for this project proved to be an example where the laminar flow approximation for non-Newtonian flows in FLOW-3D was inappropriate. The flood induced conditions encountered in this project include turbulent stresses developed due to steep slopes, high roughness associated with flows through the densely forested narrow canyons, and solids concentrations diluted with the background PMF flows, which would not be accounted for in FLOW-3D.

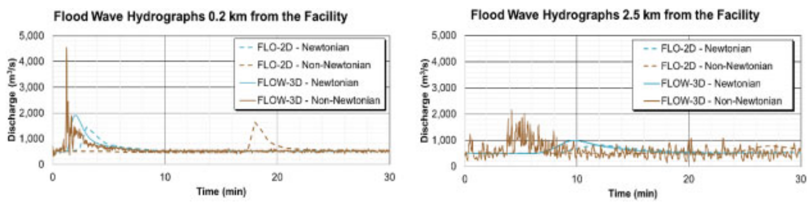

Fig. 4
Comparison between FLO-2D and FLOW-3D for Case Study 2.
Comparaison entre FLO-2D et FLOW-3D pour l'étude de cas 2.

The non-Newtonian flood wave propagation in FLOW-3D was unstable and faster than when the outflows were modelled as Newtonian fluids, which was not considered realistic for this project. This led to selecting the FLO-2D platform for routing the breach flood wave and modelling the inundation. A comparison between FLO-2D and FLOW-3D is shown on Figure 4, which includes Newtonian and non-Newtonian simulations in both models.

Sensitivity analysis on the rheologic parameters in FLO-2D indicated a similar trend as in Case Study 1, where the flood wave travelled farther and faster when using the weaker rheologic parameters (lower yield stress and viscosity) compared to the flood wave with stronger rheologic parameters (higher yield stress and viscosity). The resulting inundation was sensitive to both the selection of the hydrodynamic model and to the rheology input data.

6. CASE STUDY 3

6.1. PROJECT BACKGROUND AND AVAILABLE DATA

The facility in Case Study 3 is the same as in Case Study 1. The project background and available data are detailed in Section 4.1. This case study focuses on a breach scenario on the opposite side of the facility to Case Study 1, which would outflow towards the mine facilities. The supernatant pond is located against a water retaining dam on this side of the facility, and there is no tailings deposition adjacent to this dam. The breach flood wave would contain eroded tailings that would get mobilized from deeper within the facility as the pond discharges.

The breach flood wave was found to be contained by the open pit approximately 500 m downstream of the dam. The terrain between the dam and the open pit is higher than the toe of the dam. The adjacent stockpiles and the elevated terrain would interact with the breach outflows creating backwatering and impacting the breach development. The breach outflow hydrographs and the peak discharges were consequently modelled in conjunction with the downstream flood routing to capture the flow dynamics caused by the higher topography that would limit the outflow volume. The modelling approach was therefore different than for Case Study 1.

6.2. SELECTED HYDRODYNAMIC MODEL

The selected model was HEC-RAS Version 5.0.7 (2D), developed by the US Army Corps of Engineers [22]. This hydrodynamic model was selected for its dam breach tools and capability to account for backwatering as it calculates the outflow from the supernatant pond. HEC-RAS is currently limited to Newtonian flows, and rheology cannot be included in the model. The breach outflow contained the supernatant pond with eroded tailings and the volumetric solids concentration was estimated to be between 20% and 30% using the methodology of Fontaine and Martin [23]. Even though this flow would be non-Newtonian based on the solids concentration, Newtonian flow was modelled in this case. It was anticipated that the backwatering caused by the elevated terrain would have a greater impact on the results compared to the effects of the rheology.

6.3. MODEL RESULTS AND LESSONS LEARNED

The modelling results demonstrated the considerable impact of the downstream terrain on the breach development and outflow, which in turn affected the downstream inundation. The backwatering from the downstream terrain limited the progression of the breach outflows within minutes, as shown on Figure 5.

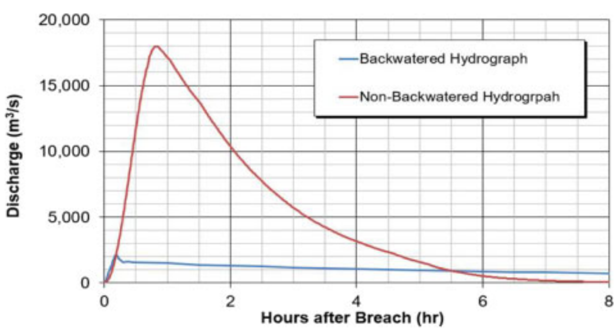

Fig. 5
Breach hydrographs with and without backwatering effects.
Hydrogrammes de brèches avec effets de remous d'eau et sans effets de remous d'eau.

With the downstream elevated terrain essentially acting as a weir, the outflow extended over several days. The outflow volume in this case was roughly two thirds of the volume that would potentially discharge if backwatering was not present. The model selection in combination with the physiographic setting proved to be very important in estimating the outflow hydrograph and the downstream impacts of this hypothetical breach.

7. CONCLUSIONS

Tailings dam breach inundation estimates must be credible in order to be useful, yet they must also be prudently conservative to guard against potential loss of life and severe environmental, cultural, and economic consequences. These estimates are based on multiple sources of data in combination with subjective model parameter evaluations and assumptions, which all have different levels of impact on the model results and final inundation extents.

1The results from the case studies underscore the importance of high quality input data requirements, as well as the professional experience and knowledge required to select appropriate hydrodynamic models with consideration of the various simplifications inherent in these models. The case studies discussed in this paper were recently completed, yet some of the approaches taken are already becoming outdated due to the ongoing rapid advancement in both the development of modelling tools and the quality of model inputs. Non-Newtonian flow modelling tools are evolving at a rapid pace as research efforts and computational power increase.

One of the major difficulties unique to tailings dam breach studies is the availability of rheology data and the implementation of the non-Newtonian flow characteristics within hydrodynamic models. Rheology data for stored tailings are rarely available; however, dam owners are starting to collect these data to improve the input requirements for dam breach studies.

The British statistician George Box wrote that “all models are wrong, but some are useful,” and this statement is very applicable to tailings dam breach studies and the associated hydrodynamic models. Dam breach assessments are never simple and will always carry uncertainties, but they can provide useful information when combined with good professional judgement and experience. The quality of tailings dam breach studies will continue to improve with advances in data collection technologies, improvements in the scientific understanding of breaching processes and non-Newtonian flows, and progresses in the engineering state of practice.

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