Overview and lessons learned from performing tailings dam breach modelling with TELEMAC-2D

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Abstract – **Following the dramatic recent tailings dam failures that occurred during the last decade, significant advances have been performed in the fields of tailings dam breach assessments and runout modelling. Numerous research projects and guidelines (e.g., Canadian Dam Association guidelines on Tailings Dam Breach Analysis, International Council on Mining and Minerals' Global Industry Standard on Tailings Management) paved the way for an updated framework to tackle the challenges related with the safety and the identification of potential consequences in case of a failure event.**

In parallel, similar advances have been made amongst several hydrodynamic modelling packages in order to model runout of high-concentrated flows that are governed by non-Newtonian rheological behaviour. This article aims at giving an overview of the lessons learned from performing runout modelling using the non-Newtonian rheological models recently implemented in the two-dimensional depth-averaged TELEMAC-2D code.

The article is based on tailings dam breach assessments performed for the Tailings Storage Facility (TSF) of Garpenberg in Sweden, a mine owned by Boliden. More precisely, focus is put on detailing modelling procedures and relevant features of TELEMAC-2D that can be used in order to model different steps such as *i)* breach opening and outflow hydrograph estimation, *ii)* flood wave modelling, *iii)* transition between non-Newtonian and Newtonian behaviors depending on mixing between tailings and downstream water bodies, and *iv)* hazard assessment and mapping. Finally, the article summarizes the current advantages and shortcomings of the non-Newtonian rheological models implemented in TELEMAC-2D and presents a list of possible improvements.

Keywords: tailings, dam breach analysis, runout modelling, non-Newtonian, TELEMAC-2D.

I. INTRODUCTION

Significant advances have been observed in the field of tailings dam breach assessments and runout modelling in the last few years, both within research projects and guidelines but also the availability of hydrodynamic modelling software modelling flows that are governed by non-Newtonian rheological behavior. This article is based on a case study where a Tailings Dam Breach Analysis (TDBA) was performed for the Tailings Storage Facility (TSF) at Garpenberg in Sweden, a mine owned by Boliden. An overview of the lessons learned from the case study, relevant features available in the TELEMAC-2D that can be used, details in the modelling procedures that are of importance for runout modelling for a TDBA, as well as advantages, shortcomings, limitations, and possible improvements are presented from an engineering perspective.

II. CASE STUDY

A. *Garpenberg Mine*

A case study was conducted for Boliden's TSF at Garpenberg in Hedemora, Dalarna County, Sweden (see Figure 1). Garpenberg is a complex ore mine carrying mainly zinc, copper, and lead. While mining in the area has historic evidence that dates back to 300 BC, the recent mining operations as well as the construction of the TSF started in the 1960's. The embankment dams have been raised using the upstream method (in which each subsequent dam raising stage is created by building an embankment founded partly on underlying tailings, towards the reservoir), but the design has been revised and will transition to a centerline raise over the original dam crest during the coming three years. The dams are mainly founded on till but there is some evidence that peat remains in parts of the low-lying areas. An aerial view of the TSF is depicted in Figure 1. There are seven dam sections around the TSF (A, C, D, E, E2, I and I2).

The goal of the tailings dam breach and runout analysis was to understand the potential consequences of a breach at six different dams surrounding the TSF as a part of the permit application. The six different breach locations around the TSF considered are illustrated in Figure 2 (section I2 is not included as consequences from failure have already been studied in an earlier project).

The area surrounding the TSF consists of several large lakes with small rivers connecting these lakes, and houses located along the rivers and lakes. This area is not densely populated, but there are local industries that lie in a proximity of the TSF, and thus the risks due to a dam breach are not negligible.

B. *Framework*

The tailings dam breach and runout analysis were conducted in accordance with the Swedish dam safety guidelines (GruvRIDAS and Svenska Kraftnät, the National Grid regulator), the Canadian dam safety guidelines (provided by CDA) as well as the Global Industry Standard for Tailings Management (GISTM). These latter guidelines define a framework to determine the failure classification of the tailings facility by assessing the downstream conditions and selecting the classification corresponding to the highest consequence classification for each category. The consequence classes are determined by the incremental losses for five categories of consequences: 1) Potential population at risk, 2) Potential loss of life, 3) Environment, 4) Health, social and cultural, and 5) Infrastructure and economics [1] [2] [3].

Figure 1. Garpenberg mine. Top: Location of the mine in Sweden. Bottom: Aerial view of the TSF. Source: Lantmäteriet ©.

C. *Dam breach parameters used*

1) Failure mode

The dam breach location has been chosen at the largest dam height or at the location expected to lead to the largest consequences in terms of outflow volume. The credible failure mode considered for the six dam sections corresponds to a stability and/or foundation failure, which then leads to the development of a breach, followed by the liquefaction of the tailings in the TSF. This failure mode corresponds to the highest expected consequences triggered by a geotechnically plausible scenario. The breaching process considered is illustrated in Figure 3.

The breach geometry has been defined based on analysis of historical events and guidelines, and a breach ratio (width-height ratio) of 5 has been used in the case study. This ratio corresponds to a conservative but reasonable hypothesis based on the analysis of historical failures of both tailings dams [4] and rockfill embankment dams [5] in order to take into account the large rockfill volume on the downstream face.

2) Outflow volumes and hydrological scenario

Outflow volumes can be characterized by an estimated erosion cone developing in the TSF. Based on the authors' experience, this method is well suited for TSF with liquefiable tailings and a limited supernatant pond as is the case for Garpenberg. Comparisons with other estimation methods were made and confirmed that the outflow volume based on an estimated erosion cone provided the most conservative assumption. The erosion cone slope can be considered to be lying in a range from 2 to 5 degrees, resulting in a large difference in potential

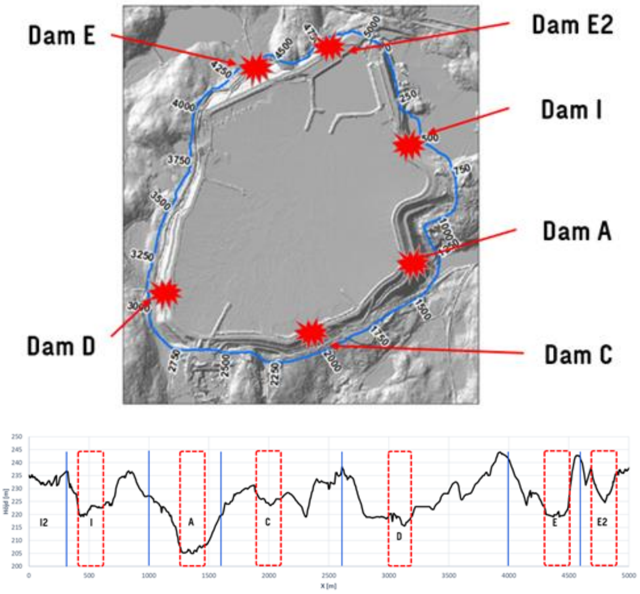

Figure 2. Garpenberg case study. Top: Location of six breach locations considered. Bottom: Location of six breach locations with respect to downstream terrain levels. The blue vertical lines materialize the limit between each of the dam sections.

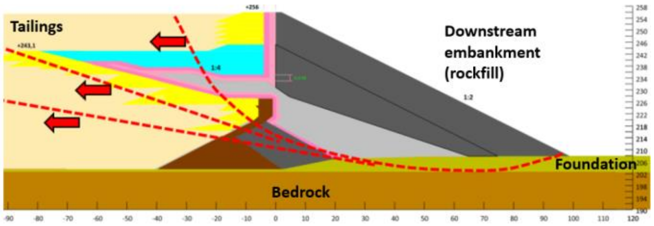

Figure 3. Garpenberg case study. Illustration of credible failure mode considered in the TDBA.

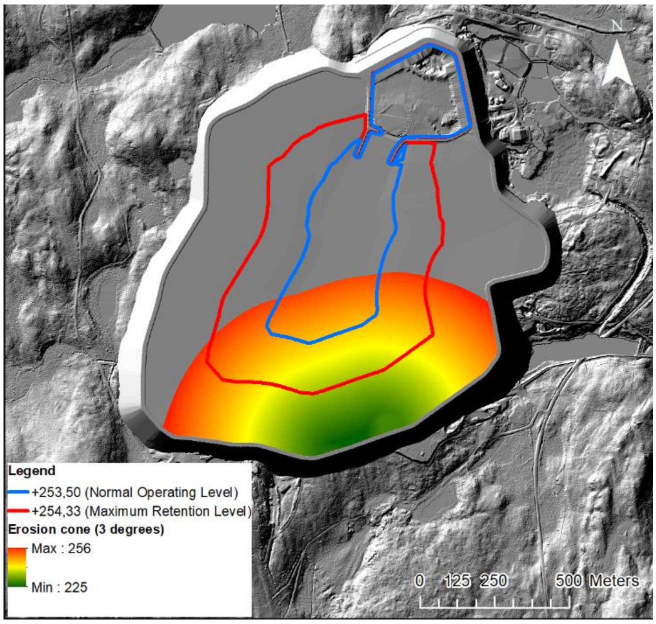

Figure 4. Garpenberg case study. Erosion cone for dam C (slope of 3 degrees, outflow volume of 5.3 Mm^3). Blue and red lines illustrate the supernatant pond extents for the normal operating level and maximum retention level (design flood), respectively.

outflow volumes. In this case study, a range of 3 to 5 degrees were considered based on the analysis of the tailings residual shear strengths at all dam locations and at different depths.

This resulted in outflow volumes ranging from 1.3 Mm^3 to 19.6 Mm^3 depending on the dam section, breach height, breach width and slope angle. The erosion cone for Dam C with a 3 degree slope is illustrated in Figure 4.

To define the hydrological scenarios, the outflow volumes are compared with the volume of water in the TSF for both a normal flow condition (i.e., Sunny day scenario) and a high flow condition (i.e., Flood-induced scenario). The additional volume of water during a high flow condition is small compared to the amount of outflow volume due to liquefaction (max. approx. 9%), and the incremental consequences are expected to be similar for the two hydrological scenarios. Thus, the runout analysis has only been conducted for normal flow conditions.

3) Rheological properties

The non-Newtonian properties of liquefied tailings have been modelled using the Bingham rheological model. This model is well suited for homogeneous suspensions of fine particles, particularly mudflows, and is commonly accepted for modelling flowing tailings [6]. The equation of the Bingham model reads:

$$\begin{cases} \dot{\gamma} \ = 0 & if \ \ \tau_0 \ \le \ \tau_y \\ \tau_0 \ = \ \tau_y + \ \mu\dot{\gamma} & if \ \ \tau_0 \ > \ \tau_y \end{cases} \tag{1}$$

with τ_0 the non-Newtonian shear stress [Pa], τ_y the fluid yield stress [Pa], μ the fluid dynamic viscosity [Pa·s] and $\dot{\gamma}$ the shear rate [s^{-1}] that is function of the flow characteristics. For more details about the implementation in TELEMAC-2D, readers may refer to [7]. In addition to the yield stress and dynamic viscosity, the fluid bulk density ρ [kg/m^3] is another parameter defining the fluid rheology.

For the Garpenberg case, the Bingham model was used in combination with the “pseudo-biphasic model” in order to take mixing effects with downstream water bodies into account (see more information about this model in Section III). When using the “pseudo-biphasic model”, the yield stress, dynamic viscosity, and the fluid bulk density are expressed according to the volumetric sediment concentration C_V [-]:

$$\tau_y = \ a10^{bC_V} \tag{2}$$

$$\mu = \ c10^{dC_V} \tag{3}$$

$$\rho = \rho_W + (\rho_S - \rho_W)C_V \tag{4}$$

with ρ_W the water density [kg/m^3], ρ_S the sediment specific density [kg/m^3], a, b, c and d coefficients [-] related to the rheology of the material.

Based on available geotechnical investigations, the tailings stored within the TSF can be assumed to have an in-situ bulk density of ρ = 2040 kg/m^3 and a corresponding volumetric sediment concentration of C_V = 0.52. The specific density is ρ_S = 3000 kg/m^3. Based on available rheological tests and experience from analysis of other historical events, two values for both the yield stress (50-750 Pa) and the dynamic viscosity (0.5-50 Pa·s) have been chosen to perform a sensitivity analysis. A summary of the rheological parameters is given in Table I.

Table I . Garpenberg case. Rheological parameters used in the TDBA.

Parameter	Value
τ_y	50-750 Pa
μ	0.5-50 Pa·s
ρ	2040 kg/m^3
C_V	0.52
ρ_S	3000 kg/m^3
a	0.00345915-0.05188732
c	0.00003459-0.00345915
b and d	8.0*

* A value of 8.0 is considered as a good approximation to model the exponential relationship between τ_y , μ and C_V [8].

4) Sensitivity analysis

A sensitivity analysis has been performed in order to assess the influence of the following dam breach parameters on the runout and consequences:

- Outflow volume (slope of erosion cone 3 and 5 degrees).
- Breaching duration (0.5 hour and 1 or 2 hours depending on breach height).
- Rheological properties:
    - Low scenario (τ_y = 50 Pa, μ = 0.5 Pa·s).
    - High scenario (τ_y = 750 Pa, μ = 50 Pa·s).

III. PERFORMING TAILINGS RUNOUT ANALYSIS WITH TELEMAC-2D: OVERVIEW AND LESSONS LEARNED

This section presents an overview of the modelling features available in TELEMAC-2D to perform a TDBA and describes the lessons learned from the case study. The section is articulated around the classical workflow used in TDBA, from the release of outflow volume, flood wave modelling in downstream areas to hazard mapping and assessment. Results are presented for the dam section E2 only as it is not possible to cover all the dam sections considered in this article. Dam breach assumptions (failure mode, erosion cone slope, breach ratio, breaching duration and rheological properties) are similar for all dam sections.

A. Breach opening and outflow hydrograph estimation

The most important steps in a TDBA is the estimation of the total outflow volume for the failure mode and the breach development time. These two parameters can then be used to estimate the outflow hydrograph. For a dam failure involving liquefied tailings, the estimation of these parameters is a difficult task and is often associated with very large uncertainties. The outflow volume is commonly only a fraction of the total stored volume, and the outflow process is not driven by a pure rheological process but is the result of complex geotechnical processes. This topic is growing with some methods and tools starting to become available to increase the level of detail for breach modelling [9] [10]. However, these methods are still difficult to implement in common engineering practice.

The current methodology commonly used in TDBA to estimate outflow volume and breaching time is based on available documentation from historical events and/or from empirical approaches often used in dam breach modelling. To assess the range of uncertainty in the final results linked to the uncertainties in estimating the outflow volume and breaching time, a sensitivity analysis can be performed by modelling several combinations of plausible parameter values.

For the Garpenberg case, outflow volumes have been estimated by assuming that the failure leads to the formation on an erosion cone within the TSF defined by the breach width and by a slope linked to the residual shear strength of the tailings (see Figure 4). The outflow process can then be modelled directly within TELEMAC-2D by incorporating the erosion cone into the mesh, assigning an initial tailings level within the cone as an initial condition and using a breach structure with time-dependent opening that controls the outflow process according to the predefined breach development time. The breach opening was modelled using the “widening” option, which allows the reproduction of the expected opening phenomena reasonably well (for non-instantaneous failures). The outflow is then governed mainly by the rate of opening of the breach and by the resistive forces (tailings’ non-Newtonian rheology and bottom friction). An illustration of the outflow through the breach is presented in Figure 5.

Although this method is a simplification of a very complex process and has some limitations (see Section IV), it can be used to generate outflow hydrographs in a rather simple and systematic way, which is well suited for performing sensitivity analyses. An example of a generated outflow hydrograph is presented on Figure 6. This hydrograph from dam section E2 corresponds to a total outflow volume of 3.0 Mm^3 of tailings and water released (3-degree erosion cone slope), breach maximal height and final width of 27 and 135 m (breach ratio of 5), respectively, low rheological properties and for a breach development time of 0.5 hour.

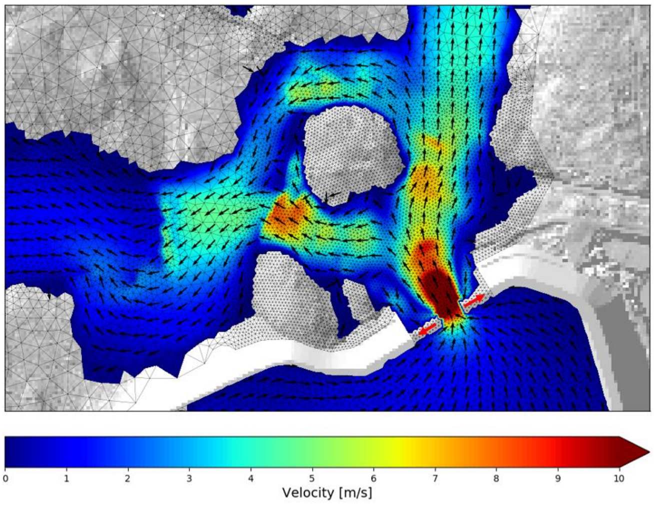

Figure 5. Outflow from dam section E2. Velocity field 20 minutes after breaching start. The breach widening modelled is depicted with the two red arrows.

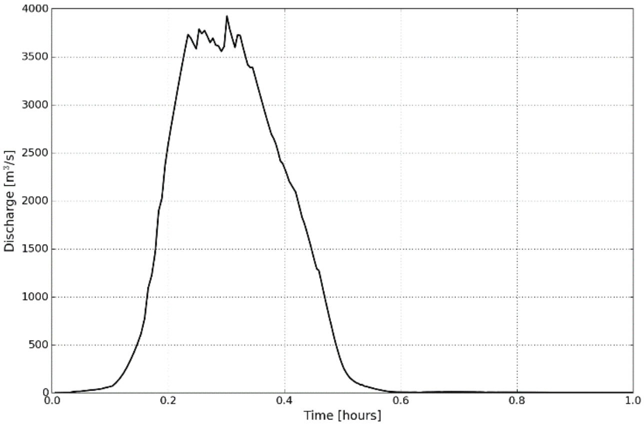

Figure 6. Outflow hydrograph from dam section E2.

The spikes that can be observed around the peak are linked to the breach widening process during the simulation. With the "widening" breach option available in TELEMAC-2D, the nodes located on each side of the opening breach are instantaneously lowered from crest to bottom during one time step, hence triggering a rapid discontinuity of the breach geometry which generates a corresponding increase in the outflow discharge. The outflow discharge then diminishes or stabilizes until the next nodes are lowered, and so on. Similar observations have been made for other dam sections and dam breach scenarios. This "artefact", that can be seen as a defect, is not problematic in the sense that outflow volume remains entirely correct and might even be closer to a real breaching process than a steady breach opening. It is however possible to limit or smooth this effect by lowering the mesh size in the breach region, but at the cost of smaller time-steps due to the satisfaction of the Courant number criterion used in the Finite Volume (FV) kernel. The spikes of the outflow hydrograph disappear however quickly due to flow attenuation of the flood wave.

B. *Flood wave modelling*

Flood wave modelling is a rather standard step, even with non-Newtonian rheological models. However, an interesting point to mention is the possibility to model cascade failures of downstream dams, embankments or levees using the dam breach module of TELEMAC-2D. As hydrodynamic modelling performed as part of a TDBA usually implies a large number of scenarios due to the need to perform sensitivity analyses, the possibility of modelling cascade failures directly within the simulation is a great advantage and avoids model simplifications (for example, aggregating outflow volumes from the TSF and the clarification pond located near downstream into a unique hypothetical failure event) as well as saving time (less interpretation).

C. *Mixing between tailings and downstream water bodies*

In most cases, the tailings released from the tailings dam failure that reach the downstream river system and/or lakes will contribute to dilute the sediment concentration by a certain amount. The rheological properties of non-Newtonian fluids are extremely sensitive to the actual sediment concentration. A small dilution ratio can lead to a significant reduction of the yield stress and dynamic viscosity. It is common that the volumetric sediment concentration C_V for tailings within TSFs lie in the range 0.5 to 0.6. The limit between Newtonian and non-Newtonian behavior can be considered to lie around 0.2-0.3 [1] [6] which means that the non-Newtonian behavior of the released tailings can be expected to be negligible once the flood wave is diluted by a factor of approximately 2.

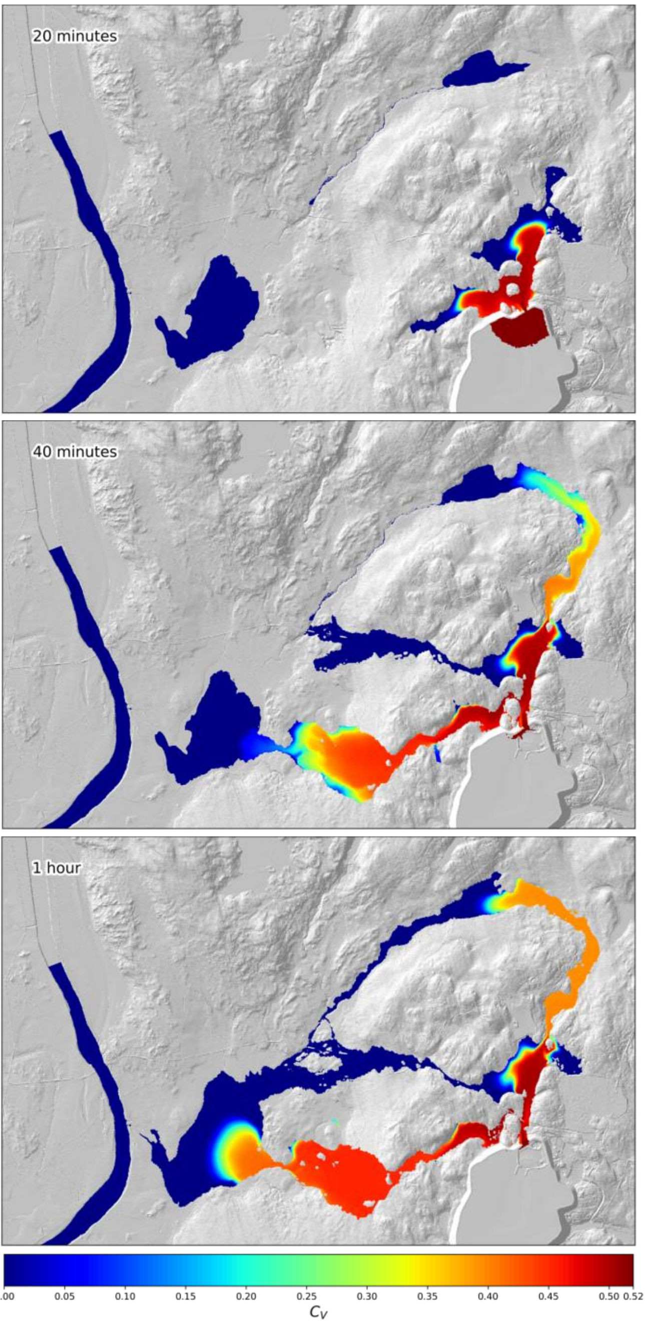

Figure 7. Evolution of volumetric sediment concentration C_V downstream of dam section E2 at different times after breaching start.

The "pseudo-biphasic model" available in TELEMAC-2D can be used to model the mixing between Newtonian and non-Newtonian fluids. The principle of the model is described in [7]. A passive tracer is used to represent the volumetric sediment concentration C_V and can be assigned either as an initial condition (to distinguish between tailings within the TSF and rivers or lakes, the latter corresponding to C_V = 0) or boundary conditions (commonly to model a river inflow with C_V = 0 or an outflow hydrograph with $C_V \neq 0$). The fluid rheological properties (bulk density, yield stress and dynamic viscosity) are then computed as a function of C_V using (2) to (4).

Figure 7 presents the evolution of the volumetric sediment concentration C_V downstream of dam section E2 at different times. It can be observed that the local C_V values are varying significantly between the different flow paths depending on dilution in downstream lakes and rivers. For example, the western flow path is characterized by high C_V values and hence high rheological properties whereas those parameters in the northern flow paths are highly influenced by the dilution effects (lower C_V values and hence lower rheological properties).

This model can also be used to take into account the release of both tailings and water during the breaching process. An example from the Garpenberg case study is the release of the water volume corresponding to the supernatant pond using sources located at the edge of the erosion cone with a prescribed tracer value of C_V = 0. This is of course a simplification which implies several assumptions (discretization of the supernatant pond by using point sources with assumed outflow hydrograph) but can be acceptable if the water volume is only a minor part of the total outflow volume.

D. Hazard assessment and mapping

The hazard assessments are conducted based on the results from the model and available guidelines for human safety due to floods. The criterion for human safety is often based on the product of flow depth (D) and velocity (V), called the DV product [m^2/s].

Much of the DV criteria available in the different guidelines are mostly provided for water hazards and not for mudflow. For mudflow, the density of the fluid is greater than that of clear water, and therefore a lower threshold of the DV product is assumed to be more adequate for use in the assessment of hazards for loss of life or population at risk [11]. In the case where there is mixing of water and sand, due to a lake or a river downstream of the dam, the C_V value is used to define which threshold DV values are used in which area, i.e., large DV threshold values directly downstream of the dam with little to no mixing of the outflow material, and lower DV threshold values further downstream of the dam after mixing where the outflow material has a similar rheological characteristics as water.

A detailed analysis of the flood wave can give information on flood characteristics over time, especially the type of fluid and its density during the flooding process. Examples are provided in Figure 8 and Figure 9, for two locations along the flow paths affected by a failure at dam section E2 (northern and western flow paths, respectively). The figures show the maximum DV values observed at locations where buildings are affected as well as time series showing evolutions of flow depth, DV, C_V and fluid density. It can be seen that,for the northern location (Figure 8), flooding is initiated by the water from the lakes located downstream of dam section E2, which has negligible sediment concentration. It is only after approximatively one hour that the tailings, mixed with water, reach this location, but the flood peak has already passed. Hence, the flood hazard can be assessed with standard guidelines. For the western location (Figure 9), the tailings concentration in the flood wave is quickly increasing shortly after flooding start as there is only a small lake located downstream of dam section E2 along this flow path. The fluid density reaches approximatively 1900 kg/m^3 10 minutes after flood peak. Hence, fluid density can affect the flood hazard assessment for this location.

IV. CURRENT LIMITATIONS AND POSSIBLE IMPROVEMENTS

A. Outflow hydrograph

As described in Section III, TELEMAC-2D can be used to model the outflow of liquefied tailings from a breach. As earlier mentioned, it should be clear that this can only lead to a very simplified outflow process as the breaching and subsequent material release usually combines geotechnical, rheological and hydraulic processes. For critical cases, it is advised to perform a detailed breach analysis involving state-of-art methods and experts. The Material Point Method (MPM) can be cited as a promising modelling technique to tackle such problems as detailed in [9] and in the Report of the Expert Panel from the Brumadinho failure in Brazil that occurred in 2019 [12]. Another example of dam breach model for tailings dams is the EMBREA-MUD model developed by HR Wallingford [10] [13].

Modelling outflow of liquefied tailings using non-Newtonian rheological models such as the Bingham model should be done with care. In such a simulation, the fluid is characterized by its constant nominal rheological properties (unless if using the “pseudo-biphasic model” to account for mixing with water) corresponding to a liquefied, flowable material, even during the breaching process. This is of course a conservative simplification since the whole outflow volume does not liquefy instantaneously nor have identical properties across the whole mobilized volume. When modelling a very rapid breaching process such as the Brumadinho failure (breaching time was in a range of seconds) [12], modelling the instantaneous release of tailings with constant rheological properties is very likely to overestimate the outflow process and peak discharge. This has been observed in simulations of the Brumadinho failure when comparing results from TELEMAC-2D and MIKE21 with the estimated outflow hydrograph using the EMBREA-MUD breach model. It has also been observed that simulations in which the triggering time for liquefaction was defined depending on time and position within the reservoir gave results in good agreement with the EMBREA-MUD outflow hydrograph [7].

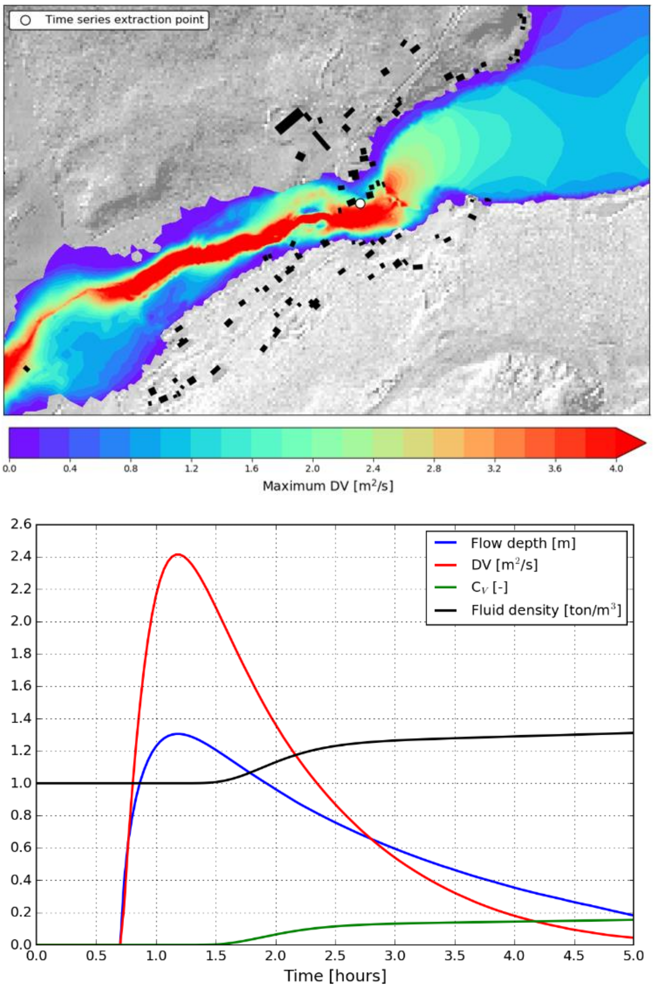

Figure 8. Dam section E2, hazard assessment in northern flow path. Top: maximum DV values. Bottom: time series at location marked in top image.

The simplification mentioned above is not limited to instantaneous failures. Estimation of outflow hydrographs for breaching times in the range of 0.5 h or more can become tricky as the tailings flowability characterized by the nominal rheological properties can lead to a faster release than the pre-defined breaching time. This behavior could be observed in the Garpenberg case study. In such a case, using a fictive breaching time longer than the theoretical one can be a way to ensure that the outflow process duration is compatible with the dam breach assumptions to be considered.

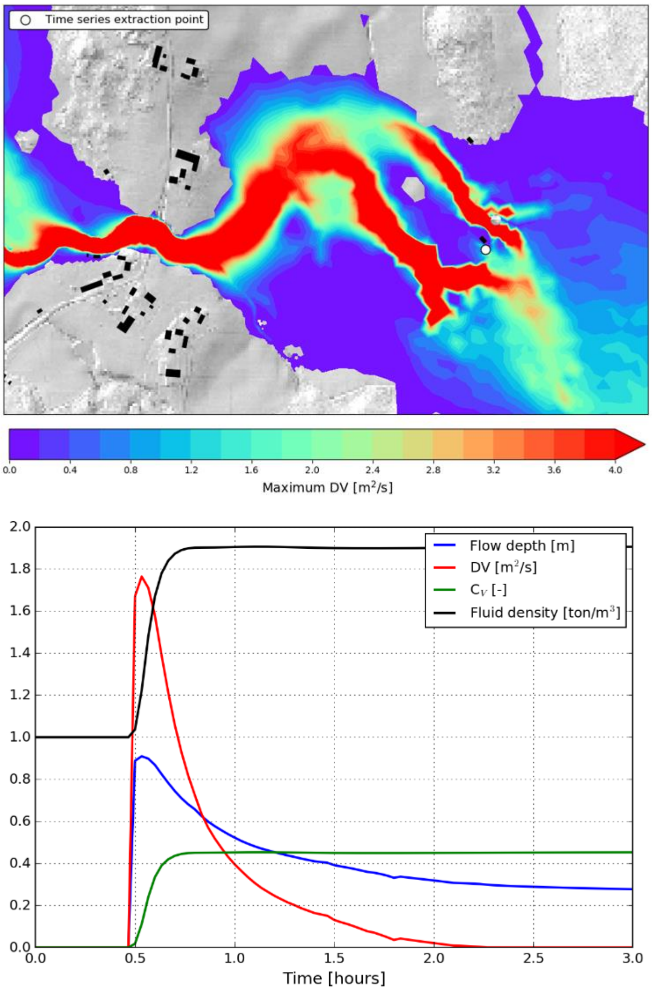

Figure 9. Dam section E2, hazard assessment in western flow path. Top: maximum DV values. Bottom: time series at location marked in top image.

B. Numerical diffusion

As it has been observed in the validation cases used to test the non-Newtonian models implemented in TELEMAC-2D [7], one limitation lies in numerical diffusion leading to the spreading of the wave front. This numerical diffusion is linked to the semi-implicit treatment of the non-Newtonian source terms which, on the other hand, ensures the numerical stability of the solution even in regions with strong gradients (e.g., wave front). The numerical diffusion can lead to a loss of accuracy especially in regions where the non-Newtonian stresses are dominant. The numerical diffusion considers mainly the flow depth whereas velocity components do not depict the same trend. Application cases show that this effect can become important when using large cell sizes and/or high values for the rheological parameters (yield stress and dynamic viscosity). It is therefore important that the user verifies the model behaviour beforehand and assesses whether this effect is expected to influence the results in a significant manner or not.

When important, this numerical diffusion is characterized by a wave front that does not stop and similarly, a slow drawdown in regions where deposition is expected. The effect can be considered as conservative with respect to the maximum flood extents due to the risk of overestimating the front wave propagation. On the other hand, tailings deposition can become hard to predict. Hazard assessment, which is commonly based on the so-called DV product (see Section III), is not affected since the velocity components are treated in a correct manner (i.e., very small velocities once the pseudo equilibrium state is reached). The user should therefore assess the model performance, especially for coarse meshes and with strong non-Newtonian behavior without dilution with downstream water bodies. As this limitation can be important in some cases, it would therefore be beneficial to address this by improving the algorithm's performance.

C. Mixing between tailings and downstream water bodies

When using the "pseudo-biphasic model" available in TELEMAC-2D, the mixing between the different fluid mixtures defined by different values of C_V is governed by the advection and diffusion of the passive tracer representing C_V. The main limitation of this method is that diffusion at the interface between two fluids, and therefore mixing, is overestimated. The "pseudo-bipahsic model" should therefore be seen as a simplified way to account for mixing effects. As mixing and hence dilution are overestimated, the use of this model leads to conservative results since the extra dilution causes a reduction of the rheological properties. However, from an engineering and TDBA perspective, the advantage provided by this model (to model dilution and the subsequent reduction of the rheological parameters) outweighs its disadvantages.

D. Not accounting for sediment transport processes

The non-Newtonian rheological models implemented in TELEMAC-2D treat the fluid mixture as a continuous medium, unlike sediment transport models in which some sediment processes occurring in classical river or coastal flows are considered (erosion, deposition, settling velocity etc.). Consequently, non-Newtonian rheological models used in 2D hydrodynamic models are not aimed at being used in combination with sediment transport models. It is therefore difficult to account for morphological changes linked to erosion processes when performing a tailings runout analysis with non-Newtonian rheological models. Whereas it is generally accepted to overlook erosion processes during a dam break analysis, a clear limitation of the non-Newtonian rheological models used in depth-averaged hydrodynamic models is the impossibility to account for deposition in lakes. When a flood wave of liquefied tailings reaches a lake, the main part of the sediments will deposit at the bottom whereas the outflow from the lake will consist primarily of water that has a lower density. With TELEMAC-2D and with the "pseudo-biphasic model", the stratification process is going to be simplified by assuming a depth-averaged mixing and no deposition, which generally tends to overestimate the tailings outflow. However, the impact on flood wave characteristics should remain limited if the volumetric sediment concentration C_V of the tailings outflow is below 0.3 (e.g., Newtonian behavior).

V. CONCLUSIONS

This article gives an overview on how TELEMAC-2D can be used, in combination with non-Newtonian rheological models, to perform a runout analysis as part of a TDBA. TELEMAC-2D offers several interesting modelling capabilities (dam breach module, "pseudo-biphasic" non-Newtonian model) making it possible to model complex phenomena associated with failures in TSFs and the subsequent release of liquefied tailings. On the other hand, several limitations that can be of importance are presented and detailed. Specifically, the reduction of the numerical diffusion observed in certain cases would be a welcome improvement to the code.

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