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EMBREA-MUD A TOOL FOR THE SIMULATION OF TAILINGS DAMS BREACHING

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ABSTRACT

Failure of a tailings dam can have disastrous consequences. However, to date, it cannot be accurately simulated. Therefore, the EMBREA-MUD model was developed to fill this gap within the DAMSAT project which is funded by the UK Space Agency. The model is a two component breach modelling tool that simultaneously takes into account outflows of both water and mud (i.e. tailings). The model can also represent erosion of dam material by both water and tailings, erosion of tailings by water as well as dynamic forces between water and tailings layer.

There are however some challenges related to simulation of tailings dam breaching and in par-ticular the breach initiation which can be due to overtopping, piping or other mechanisms, such as foundation failure or sliding. As dams are designed to be stable, these initial failures are un-foreseen and therefore cannot be accurately quantified based on available data. In this paper, these mechanisms were investigated to check whether they could be reproduced assuming an in-itial notch in the dam crest. The case of Mount Polley was used, where the dam failed initially due to foundation failure. The results showed that the "initial notch" approach indeed produced similar peak outflows and time intervals.

1. INTRODUCTION

Failure of a tailings dam can have disastrous consequences. However, to date, it cannot be accurately simulated. Therefore, the EMBREA-MUD model was developed to fill this gap with-in the DAMSAT project which is funded by the UK Space Agency. The model is a two compo-nent breach modelling tool that simultaneously takes into account outflows of both water and mud (i.e. tailings). The model can also represent erosion of dam material by both water and tail-ings, erosion of tailings by water as well as dynamic forces between water and tailings layer. The paper aims at describing the details of the EMBREA-MUD model and its application to a number of test cases including the well-known case of Mount Polley.

2. WHAT IS A BREACH?

In breach modelling context, a breach is hole (or an opening) that is formed within a dam or embankment body. This hole or opening can progressively grow and allows the passage of tail-ings dam reservoir water and/or tailings in an uncontrolled manner. The drainage of the water and/or tailings can thus produce a wave that can cause catastrophic damages loss of life. A re-cent example of a tailings dam failure is the Feijão Dam (Figure 1), 2019, in Brazil, in which more than 250 people were killed as a result of the collapse and the mudflow destroyed some parts of the Córrego do Feijão district, including a nearby inn and several rural properties, as well as sections of railway bridge and about 100 m of railway track. Agricultural areas in the valley below the dam were also damaged by the failure (Robertson et al, 2019).

Figure 1 : Failure of the Feijão Dam (Robertson et al, 2019)

2.1 Breach failure mechanisms in tailings dams

There are four primary failure modes of tailings dams: slope failure, foundation failure, inter-nal erosion and surface erosion (James et al, 2017). These are further described by Liu (2018) as follows:

- Surface erosion (or overtopping): when heavy rain occurs, overtopping may occur, and the overtopping water can erode the embankment within a very short time, result-ing in the breach of the dam and subsequent tailings outflow and dam collapse.
- Slope failure (or instability): due to heavy rain (or snow) events or poor decant pond control, the tailings dam may become saturated, causing a rise in the phreatic surface. This may lead to slope instability of the dam and ultimately a breach. Slope failures can also result from rates of rise that are too high or failure to correctly characterise geotechnical properties.
- Internal erosion (Seepage and piping) – due to an excessively high phreatic surface, seepage and piping can occur, develop and erode the embankment which leads to lo-cal and general dam failures.
- Foundation failure: where the foundation is not sufficiently strong, sudden or exces-sive loading causes the weak foundation to deform, which may lead to an overall failure.

In addition to the above failure modes, Liu (2018) also defined a failure due to Earthquake. This type of failure is due to the development of excess pore water pressure in the tailings dur-ing an earthquake, ultimately leading to liquefaction and collapse of the tailings dam.

2.2 Liquefaction in tailings dams

Soil liquefaction refers to a condition when soil undergoes continued deformation at a low constant residual stress or with no residual resistance, due to build up and maintenance of high pore-water pressures which reduce the effective confining pressure to very low values (Puri and Kostecki, 2013). Liquefaction usually occurs in a saturated, loose, cohesionless soil (such as tailings) where unlimited deformation (flow) can occur (James et al, 2017). Liquefaction of the tailings could be induced seismically by an earthquake loading that causes the breach or statical-ly by the loss of confinement resulting from breach of the dam by another mechanism (Small et al, 2017). The potential for liquefaction of tailings is a function of several factors, but most im-portantly their density and stress state. Thus, the potential for liquefaction varies during the life cycle of the impoundment and generally decreases with time due to consolidation and ageing (James et al, 2017).

2.3 Tailings dam breach flow classification

James et al (2017) identified two factors that have been shown to have important influence on the flows from tailings dam breaches. These are:

- The potential for liquefaction of the tailings near the breach; and,
- The presence of free water (a pond) on the surface near the breach

The two factors were used to propose the following four tailings dam breach flow classes (James et al, 2017):

- Class 1A is for breaches where there is a pond nearby and the retained tailings have sig-nificant liquefaction potential. In this case it is expected that the flow from the breach will consist of water, possibly with eroded tailings, and liquefied tailings.
- Class 1B applies to breaches where there is a pond near the breach and the tailings are not susceptible to liquefaction. The flow under these conditions is expected to consist of wa-ter with eroded tailings.
- Class 2A refers to breaches where there is no pond near the breach and the tailings have significant liquefaction potential. In this event, the flow is expected to be similar to a de-bris or mud flow, depending on the residual shear strength of the liquefied tailings.
- Class 2B is for breaches where there is no pond and the tailings are not susceptible to liq-uefaction. In this case the movement of the tailings is controlled by their shear strength and the driving forces (the slope of the terrain) and would consist of a slope failure.

It has also to be noted that the topography and conditions downstream of a tailings dam can have a significant effect on the quantity of tailings that are released and the runout distance (Small et al, 2017). For example the existence of a river can increase the runout distance signifi-cantly. Therefore, the topography has also to be considered when modelling the failure of tail-ings dams.

3. MODEL DESCRIPTION

The model presented in this paper is an extension of the EMBREA model. EMBREA is the primary embankment breaching program developed at HR Wallingford (Mohamed, 2002, Has-san et al, 2002 and Morris, 2011), UK. It can model overtopping failures for homogeneous, composite and layered embankments, and internal erosion failures for homogeneous and layered embankments. Embankments can be defined as cohesive or non-cohesive when considering ero-sion in the model. It also has the ability to model the failure of surface protection layers, such as grass cover, leading to dam breach. EMBREA is a one-dimensional and a one-fluid (water) model. In the next section, the development of EMBREA-MUD, its extension to two-fluid modelling (water and mud) is presented.

3.1 Model components and interactions between them

EMBREA-MUD incorporates the following layers:

- Fluid 2: Water, with a Newtonian behaviour, and including eroded tailings and dam ma-terial in suspension
- Fluid 1: Mud with a visco-plastic non-Newtonian behaviour: liquefied tailings including eroded dam material
- Solid (layer 0): Dam material (can only be eroded)

Each fluid layer is described by its depth (*h*) and flow velocity (*u*) while dynamic forcing be-tween layers is described through shear stress (τ) (See Figure 2).

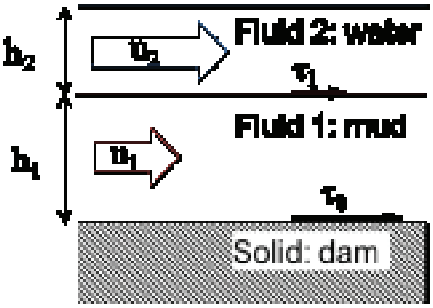

Figure 2 : Layers considered in EMBREA-MUD

The interactions between the layers are:

1. Shear stress τ1 between water and mud (or dam material if no mud is present):

• a dynamic force acting on water, as well as mud if present

• eroding force for mud (or dam material if no mud is present)

2. Shear stress τ0 between mud and dam:

• a dynamic force acting on mud

• an eroding force for dam material

The two fluid layers differ in density and rheological properties, therefore shear stresses τ_1 and τ_0 are calculated differently. Shear stress τ_1 which is related to water is computed from Manning equation,

$$\tau_1 = \frac{\gamma_2 \, |n^2 (u_2 - u_1)|^2}{R_2^{1/3}} \tag{1}$$

where γ_2 is the specific weight of fluid 2 (water), *n* is the Manning coefficient, R_2 is the hydrau-lic radius of water layer and u_1 and u_2 are flow velocities of mud and water, respectively.

Shear stress τ0 is related to mud and is computed according to the Herschel-Bulkley model (Chen et al. 2007):

$$\tau_0 = \tau_y + K\left[\frac{1+\frac{1}{m}}{1-\frac{mR'}{(2m+1)R_1}}\frac{|u_1|}{R'}\right]^m \tag{2}$$

where $R' = R_1 (1- \tau_y / \tau_0)$ and R_1 is the hydraulic radius of the mud layer. *K* is the viscosity coef-ficient and *m* is the flow index, a measure of the degree to which the fluid is shear-thinning (m<1) or shear-thickening (m>1). A special case of this model is the Bingham model where m=1.

Dynamic equations for flow depth h_2 and velocity u_2 of water layer are solved by the quasi-steady approach as in EMBREA (Mohamed et al. 2002). For mud layer , fully unsteady flow equations are solved according to LHLL numerical scheme (Chen et al. 2007) to calculate mud depth (h_1) and velocity (u_1).

3.2 Spatial discretisation

EMBREA is a one dimensional (1-D) model for the dam area, where computational points are represented by dam cross sections, and a single point model for the water storage behind the dam. While the assumption of one water level being representative for the whole storage is ten-able for water, it no longer holds for mud, which is a visco-plastic material. Hence, in EM-BREA-MUD the tailings storage facility is also discretised as a set of computational points.

Two further assumptions were taken into account in developing EMBREA-MUD. Firstly, the tailings storage facility is represented as a rectangle with a representative width, W, and length, L. Many TSFs can be well approximated as having a rectangular shape. Secondly, as EMBREA is a 1-D model, some approximations with respect to flow pattern were made. The flow expan-sion from the breach opening in the dam to the total width of the TSF is not instantaneous, ra-ther it is assumed that the flow towards the breach opening is concentric. Hence, the pond is split into three regions for the purpose of the domain setup as shown in Figure 3.

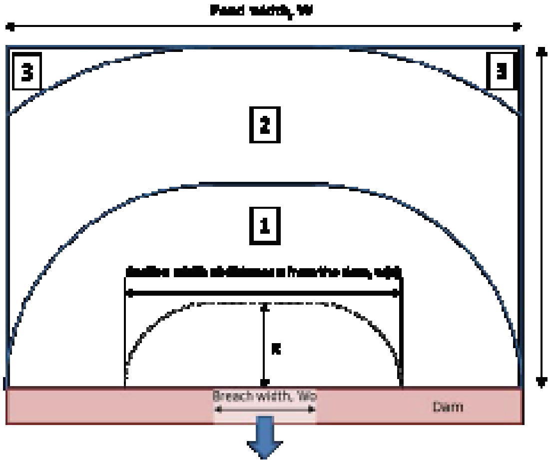

Figure 3 : Plan view showing the three regions considered in EMBREA-MUD to represent the tailings storage domain

In Region 1 the flow is expanding from the breach opening width (Wo) to the full width of the pond (W). The length of this region is $L_1 = (W\text{-}Wo)/2$ and the width w varies with the distance x from the dam according to the length of the projection of the arc perpendicular to the breach flow direction (equation 3a) In Region 2, the width is constant and equal to the reservoir width (equation 3b) and in Region 3 (the furthermost corners) the width linearly drops to zero.

$$w(x) = Wo + 2x \ldots x \leq \mathrm{L1} \tag{3a}$$

$$w(x) = W \ldots L_1 < \mathrm{x} \leq \mathrm{L} \tag{3b}$$

$$w(x) = W\,\{1\text{-}(x\text{-}L)/L3\} \ldots L < x \leq L + L_3 \tag{3c}$$

where $L_3 = (W - Wo)2 \,/\, 2W$.

3.3 Erosion and breach growth

Erosion rates Ei are determined using the erodibility coefficient $\mathrm{K}_{\mathrm{D,i}}$ and the critical shear stress $\tau_{\mathrm{c,i}}$. Index i corresponds to the i–th fluid or layer, i.e. i =1 for mud layer and i = 0 for dam. When the shear stress is less than the critical value there is no erosion ($E_{\mathrm{i}} = 0$), and when the shear stress exceeds the critical value, the erosion rate Ei is computed from the following equation (Hanson and Hunt, 2007):

$$E_{\mathrm{i}} = K_{\mathrm{D,i}}\,(\tau_{\mathrm{i}} - \tau_{\mathrm{c,i}}) \tag{4}$$

where $\tau_{\mathrm{c,i}}$ is the critical shear stress of material in layer i.

In computational points where there is water but no mud is present, the shear stress for dam ero-sion is $\tau_0 = \tau_1$.

The erosion rate obtained with equation 4 is a nominal erosion rate for any given cross section, while its local value along the wetted perimeter varies. This variation, as well as modifications of the cross section at the dam section, are done using one of the options in EMBREA (Mo-hamed et al. 2002), where variation of shear stress along banks is proportional to depth and sidewall collapse is assumed instant with any scour at the toe, as shown in Figure 4.

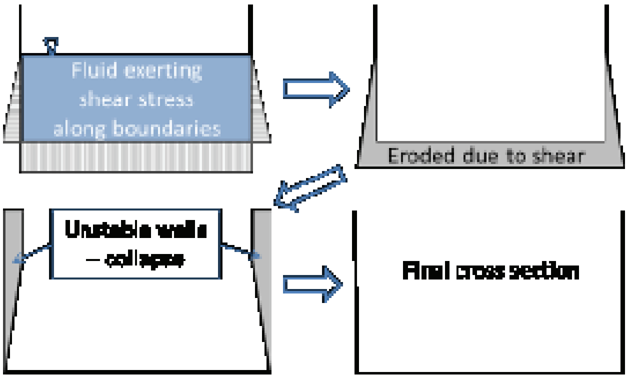

Figure 4 : Cross sections showing breach growth due to shear stress along the breach opening boundary (top) and due to sidewall collapse (bottom)

In EMBREA all the materials eroded from the bed and banks are assumed to enter the water column in suspension. In EMBREA-MUD the eroded material is treated as follows:

- Material eroded from banks from below the top of the mud layer is added to mud layer and assumed to behave as mud once it is eroded,
- Material eroded from banks from above the top of the mud layer is added to the water layer and removed from the system in suspension.
- Material eroded from the bed is added to the mud layer if there is mud in the present cross section, otherwise it is added to the water layer

4. RESULTS AND DISCUSSION

The model was validated against laboratory experiments and then compared against observa-tions made during failure of Mount Polley tailings dam failure.

4.1 Validation of EMBREA-MUD using the results from laboratory experiments

Several tailings dam-break type experiments were found in literature, although they only considered a viscous layer. This was however sufficient for the model validation purpose given that validation aimed at testing the numerical behavior of the newly added mud layer. The water layer and dam erosion have already been tested during the original developments of the EMBREA model (Mohamed et al. 2002; Morris et al. 2005) which did not include a mud layer.

Jeyapalan et al. (1983) conducted a series of dam break experiments with a viscous fluid. In the laboratory tests in a 0.305 m wide flume, the dam failure was simulated by a quick removal of a barrier representing a dam. The tank behind the barrier was filled with a viscous fluid. In the tests, oil was used as a viscous Bingham fluid with the following properties:

- Density $\rho 1 = 900$ kg/m^3
- Viscosity $K = 3.9$ Ns/m^2
- Yield stress $\tau y \sim 0$ (0.01 N/m^2 was used in the model)

The validation of the EMBREA-MUD model was done against the longitudinal profile obtained for Test 2 in Jeyapalan et al. (1983). In this test, the length of the tank behind the barrier was 0.61 m and the initial depth of oil in the tank was 0.152 m. A comparison of the observed and predicted profiles is shown in Figure 5. The comparison between the predicted and observed profile shows a satisfactory matching indicating that the newly added mud component is capable of simulating tailings dam break scenarios.

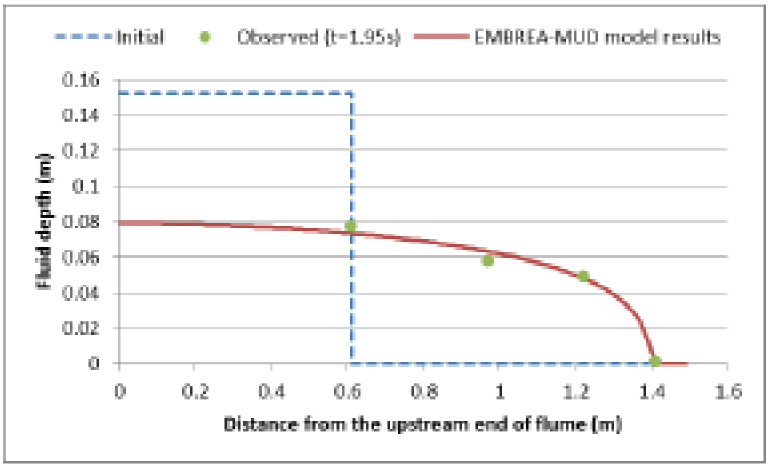

Figure 5 : Comparison of simulated and observed fluid depths in a laboratory experiment per-formed by Jeyapalan et al. (1983)

4.2 Simulation of the Mount Polley tailings dam failure

Mount Polley Mine is a copper-gold mine in British Columbia, Canada. The mine started opera-tion in 1997 and operated until the a tailings dam failure occurred around midnight from the 3 to 4 of August 2014. The failure occurred in the perimeter embankment section of the dam that en-closed the tailings storage facility from the north side (Figure 6).

Over a time span of 16 hours, between 21 and 25 million m^3 of water and tailings were released into the surrounding environment and watercourses (BCMEM 2015). At the time of failure, the dam was being raised to the final crest level elevation of 970 m. The initial failure occurred be-cause of foundation instability that caused the embankment crest level which was 969.1 m at the time of failure, to drop by at least 3.3 m and fell below the last recorded water level measured the previous afternoon, which was 968.83 m (IEEEIRP 2015). The hypothesized (BCMEM 2015) cross section at the location of breach after this failure is shown in Figure 7.

It should be noted here that as the volume of outflowing water was significant, two channels were scoured by water as shown in Figure 6. There was a smaller and shorter channel to the right (looking in the direction of outflow) and a bigger and longer one stretching across most of the length of the pond and turning towards to the further corner (about 2 km long). Mud dynamics was mainly limited to these two channels. For modelling purposes the width of the channel(s) was approximated as the median value of the crest length after the collapse (360 m) and two estimates based on an empirical relation for flushing channels. The width of channels created during a drawdown flushing of a reservoir (a controlled measure for removing sediment from water storage reservoirs) can be estimated with the following equation (White 2000):

$$W_{fc} = 12.8\ Q_f^{\ 0.5} \tag{5}$$

where W_{fc} is the channel width in [m] and Q_f is the flushing discharge given in [m^3/s].

Figure 6 : Satellite image of the Mount Polley tailings storage facility and the surrounding area one day after the breach occurred (Source: Google Earth)

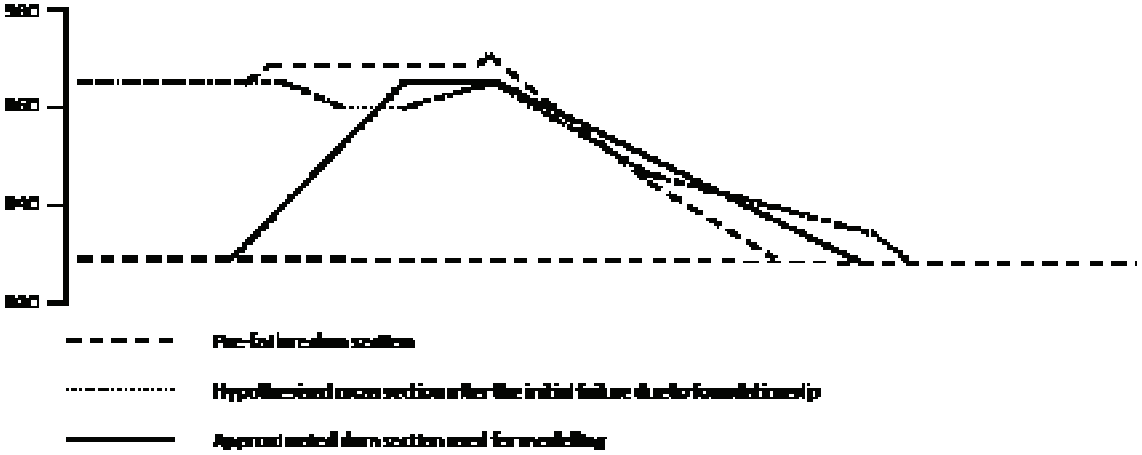

Figure 7 : Mount Polley dam sections: Pre-failure, hypothesised after initial foundation fail-ure (after BCMEM 2015) and the approximated dam section used for modelling

If the initial overtopping discharge (630 m^3/s) estimated from the head above the crest and the width after the foundation failure is used the resulting width is 320 m. If the average flow through breach (about 1200 m^3/s, see results in Figure 8) once it is scoured, the width is 440 m. The median value of the crest length and the two predictions was chosen for modelling (360 m).

EMBREA-MUD estimated an outflow volume of tailings as mudflow of 15.06 million m^3 and an outflow in suspension of 510,000 m^3, totaling 15.57 million m^3. This is slightly above the observed outflow of tailings and interstitial water (estimated between 11 and 15 million m^3) however it does include the eroded dam material as well. Hydrographs of outflows from the dam are shown in Figure 8.

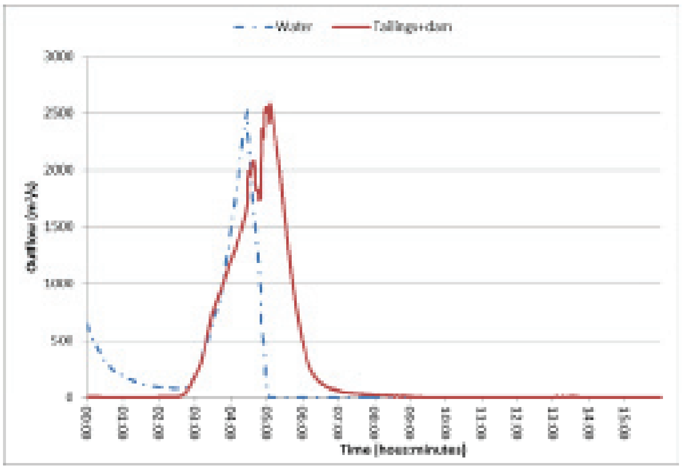

Figure 8 : Outflow hydrographs for water and tailings

For the comparison of the model results to the narrative of the observations in the literature (BCMEM 2015), it was assumed that the failure occurred instantaneously at around midnight.

The first description of what was happening was possible after dawn when light started to ap-pear at 4:25. A V-notch of 80-100 m wide at the top of the tailings dam around 30 m deep was observed. The modelled profile at a simulation time of 4:30 is presented in Figure 9. It shows a breach depth of about 26.4 m (or 29.7 m if measured from the pre-failure crest top) in the sec-tion at station 27.2 m. The modelled width of this section is 27 m. The modelled width of the crest sections (i.e. top of the dam) is between 32 m at the upstream end of the dam and opens up to 47 m at the downstream end, which would have been visible by observing from outside of the dam. The lower top width in comparison to observation (which was 80 to 100 m) is probably a result of the model assumption that the sides are stable until vertical, which is likely too steep.

With respect to the hydrographs, it was observed that the pond was empty after five hours, although a high outflow of muddy water was also reported at that time. If the pond had been completely empty of water there should have been no water outflow, only mudflow. This de-scription could therefore be interpreted as water having been limited to the channels scoured in the tailings, while the rest of the pond area was dry. EMBREA-MUD model predicted that wa-ter became limited to channels at 4:48 from the start of simulation, while water release ended at 5:04 (the pond was empty of water at this time). Mud outflow was at its highest (between 1500 and 2580 m^3/s) in the period from 4:22 to 5:32 am. The EMBREA-MUD model predictions fit the mentioned narrative.

After 6.5 hours, the simulated outflow of mud reduced to about 130 m^3/s, which fits the ob-servation of small outflow, compared to the peak outflow rate that was twenty times higher. Be-tween 10 and 14 hours, the predicted mud outflow varied between a few hundred l/s and a few m^3/s. After 14 hours, the outflow dropped to 5 l/s and by 16 hours to 2 l/s. On the other hand, the observers recorded that at 12:00 (roughly 12 hours after the breach) there was still some out-flow which then ceased by 16:00.

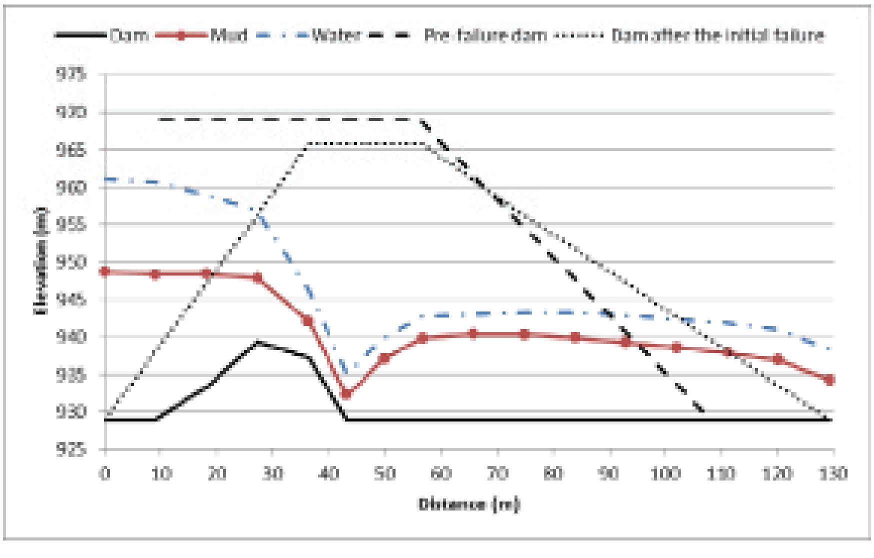

Figure 9 : Breach profile after 4.5 hours

The final breach width at the narrowest section was 40 m (BCMEM 2015), while the simulat-ed width in the narrowest section was 56 m. The observed width in an average cross section was 92 m, while the simulated width varied between 56 and 76 m with an average of 65 m. These differences may be due to the fact that the EMBREA-MUD model did not take into account the variability in the tailings dam's properties but used an average erodibility coefficient. In spite of some differences between the observed and predicted dimensions, the EMBREA-MUD model was able to predict the overall volumes and chronology reasonably well. No particular calibra-tion of model parameters was needed in this case.

5. CONCLUSIONS

EMBREA-MUD, a physically-based numerical model for simulation of tailings dam breach-ing has been developed. It predicts the outflow rates of water and tailings and growth of the breach opening as a result of flow erosion. EMBREA-MUD considers the interactions between three layers: water (Newtonian fluid, corresponding to supernatant water stored above tailings), mud (non-Newtonian fluid, corresponding to liquefied tailings) and the dam itself (subject to erosion by the other two components). For water flow and dam erosion, the model shares the formulation and implementation of the EMBREA model that has already been extensively test-ed (Mohamed et al. 2002). EMBREA-MUD testing against laboratory experiments showed a good agreement with the observed dam-break type flow for the non-Newtonian component.

The model has then been applied to Mount Polley dam failure reported in the literature, where overtopping and flow erosion played an important role in dam failure and could therefore be modelled with EMBREA-MUD that able to predict the overall volumes and chronology rea-sonably well. No particular calibration of model parameters was needed in this case.

REFERENCES

BCMEM (2015) Mount Polley Mine Tailings Storage Facility Breach. Investigation Report of the Chief Inspector of Mines, British Columbia Ministry of Energy and Mines, 30 November 2015. www.gov.bc.ca/mountpolleyinvestigation. Accessed: 12 July 2019

Chen S, Peng S, Capart H (2007) Two-layer shallow water computation of mud flow intrusions into quiescent water. Journal of Hydraulic Research 45(1): 13-25, https://doi.org/10.1080/00221686.2007.9521739

Hanson GJ, Hunt SL (2007) Lessons learned using laboratory jet testing method to measure soil erodibility of compacted soils. J Appl Eng Agr (ASABE), 23(3):305-312.

ICOLD (2001) Tailings Dams - Risk of dangerous occurrences, lessons learnt from practical experiences, Bulletin 121.

IEEIRP (2015) Report on Mount Polley Tailings Storage Facility Breach. Independent Expert Engineering Investigation and Review Panel, Jan 30, 2015. https://www.mountpolleyreviewpanel.ca/sites/default/files/report/ReportonMountPolleyTailingsStorageFacilityBreach.pdf. Accessed 5 August 2019

James M, Al-Mamun M, Small A (2017) Summary of the 2014 and 2015 Tailings Dam Breach Workshops of the Canadian Dam Association. Canadian Dam Association Annual Confer-ence, Kelowna, 16-18 October, 2017.

Jeyapalan JK, Duncan JM, Seed HB (1983) Investigation of Flow Failures of Mine Tailings Dams. J Geotech Eng 109(2):172-189.

Liu H (2018) An experimental and numerical study of runout from a tailings dam failure. PhD Diss, Univ Western Australia. https://doi.org/10.4225/23/5ac6e5ef2b0f4

Mohamed, M.A.A.H., Samuels, P.G., Morris, M.W. and Ghataora, G.S. (2002) Improving the accuracy of prediction of breach formation through embankment dams and flood embank-ments. Proc of Int conf fluvial hydraulics (Riverflow 2002), 3-6 September 2002. Louvainla- Neuve.

Morris MW, Hassan MAAM, Vaskinn KA (2005) Conclusions and Recommendations from the IMPACT Project WP2: Breach Formation. EC Research Project: EVG1-CT2001-00037. Available at: www.impact-project.net/wp2_technical.htm

Morris MW (2011) Breaching of earth embankments and dams. PhD Diss, The Open Univ UK.

van Niekerk HJ, Viljoen MJ (2005) Causes and consequences of the Merriespruit and other tail-ings dams failures. Land Degrad Dev 16:201–212, https://doi.org/10.1002/ldr.681

Puri VK, Kostecki TR (2013) Liquefaction of Mine Tailings. Int Conf Case Histories in Ge-otechnical Engineering. http://scholarsmine.mst.edu/icchge/7icchge/session04/16. Accessed 11 July 2019

White R (2000) Evacuation of sediments from reservoirs. Thomas Telford Publishing, London, UK, https://doi.org/10.1680/eosfr.29538