Proceedings of the 7th International Young Geotechnical Engineers Conference – Scott (Ed.)
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Tailings dam breach analysis: Lessons learned from released volumes of recent environmental catastrophes.

Analyse de ruptures de digues à résidus miniers : les enseignements tirés des écoulements lors de catastrophes environnementales récentes.

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ABSTRACT: Current regulatory frameworks typically require a tailings dam breach assessment (TDBA) to define design criteria and inform risk management of tailing storage facilities (TSFs). Dam breach analyses are also a key input to emergency preparedness plans in defining the extent of potentially flooded areas. In the last decade (2010-2020), two TSF failures caused catastrophic human and environmental disasters: Fundão (Brazil, 2015) and Feijao (Brazil, 2019). Among the numerous variables within a TDBA, the combination of the release volume and the solids content of the materials released comprise the most significant variables that explain the outflow distance. State of the practice procedures include simplified mathematical expressions, such as those by Rico et al. 2008 and Tocher et al. 2014 for estimating these variables as a function of key features of the TSF such as embankment height and impounded volume. The analysis from the outflow characteristics of the TSF failures occurred in Brazil in 2015 and 2019 reveals an underestimation of up to 40% of the release volumes and solids contents obtained from using the abovementioned simplified mathematical expressions. This paper proposes recommendations on the estimation of the release volume of large storage facilities (>10 Mm^3) by comparing to values proposed in the literature. These recommendations are based on the analysis of the consequences of the Fundão and Feijao disasters.

RÉSUMÉ : Les cadres réglementaires actuels exigent généralement une analyse de rupture de digues à résidus miniers (ARDRM) pour définir les critères de conception et informer la gestion de risques d'une digue à stériles. Les analyses de rupture de digue sont également un élément clé des plans de préparation aux situations d'urgence par la définition de l'étendue d'inondations potentielles. Au cours de la dernière décennie (2010-2020), deux ruptures de digue à résidus miniers ont provoqué des catastrophes humaines et écologiques: Fundão (Brésil, 2015) et Feijao (Brésil, 2019). Parmi les nombreuses variables d'une ARDRM, la combinaison du volume de l'écoulement et de la teneur en matières solides de l'écoulement constitue les variables les plus importants expliquant l'étendu de propagation de la crue de rupture. Les procédures d'analyse actuelle comprennent des expressions mathématiques simplifiées, comme celles de Rico et al. 2008 et de Tocher et al. 2014, pour estimer ces variables en fonction de caractéristiques clés de la digue à résidus miniers, telles que la hauteur du barrage et le volume retenu. L'analyse des caractéristiques d'écoulement des ruptures de digues résidus à miniers survenues au Brésil en 2015 et 2019 révèle une sous-estimation allant jusqu'à 40 % des volumes écoulés et des teneurs en solides obtenus en utilisant les expressions mathématiques simplifiées susmentionnées. Cet article propose des recommandations sur l'estimation du volume d'écoulement de digues à résidus miniers de gros volume (>10 Mm3) en comparant aux valeurs proposées dans la littérature. Ces recommandations sont basées sur l'analyse des conséquences des catastrophes de Fundão et Feijao.

KEYWORDS: TDBA, tailings dam breach, release volume, solids content

1 INTRODUCTION

The devastating human and environmental disasters that occurred in the state of Minas Gerais, Brazil, in the last decade at the Fundao dam in 2015 (Fonseca et al., 2017) and the Feijao dam in 2019 (Rotta et al., 2020) from the release of the impounded tailings and water following dam failure has been thoroughly reported in several investigations into the causes of the failure and the design flaws. Expert review panels were assembled by private and public institutions to assess the conditions and triggers of the sudden failure mechanisms of the Fundao dam (Morgenstern et al. 2016) and the Feijao dam (Robertson et al. 2019). In both cases it was concluded that static liquefaction of the tailing materials was the failure trigger mechanism, but with differing origins.

1.1 *Fundao*

The Fundao expert panel (Morgenstern et al., 2016) compiled the historical filling and dam raise sequence, which proved to be a key component in understanding the causes of the failure. The tailings that were delivered to the TSF from the Samarco process plant were differentiated into two types. The first type consisted of tailings sands with free draining capacity and the second type consisted of wet, plastic silt-clay materials (slimes) with a low drainage capacity. The original design concept included an initial construction of a rockfill headwall (Dike I) with upstream raises with compacted sand material and a base drainage system. The sandy tailings would be discharged into the area adjacent to the embankment and the slimes would be discharged behind the sandy tailings at a controlled distance from the top of the embankment. As tailings production increased and the area of the flooded impoundment increased, two galleries were incorporated at the abutments to collect water from the impoundment and release it downstream of the embankment. Inadequate construction of the base drainage system caused internal erosion issues that were observed on the embankment slope, the solution of which included a shallow blanket drain that would divert seepage flow that would otherwise daylight on the slope of the embankment, further reducing stability. The sandy materials below the blanket drain would remain saturated, as would much of the slime materials behind it. To improve the above condition, it was decided that a setback embankment was to be constructed upstream of the left abutment, which resulted in future raises of the embankment being supported on an interspersed zone of saturated slimes and sands that were previously separated from the embankment materials. As the embankment continued to grow, seepage continued to be observed on the slope.

Lateral extrusion was deemed to be the triggering mechanism, related to the ability of the tailings to deform. Horizontal spreading of the softer slimes due to vertical loading induces elongation in the overlying sands. The expert panel investigated whether stress changes in the sandy materials, above the plastic silt-enriched layer, when deformed can generate a stress path in the sands that leads to collapse and static liquefaction. As the structure increases in height, the silts are loaded vertically, but tend to extrude or spread laterally. In doing so, the overlying sands tend to move with the slimes, but lack ductility. As a result, stress changes arise that tend to reduce the lateral confinement of the sands. This mechanism induced the collapse of the saturated sandy materials in the Fundao dam and the development of cracks in the unsaturated materials.

1.2 *Feijao*

Laboratory testing of the Feijao tailings showed a loose behavior of the tailings materials, with the ability to experience creep (the ability to accumulate deformation before failure over an extended period of time) under shear stress. When a deformation threshold was reached, the strength dropped sharply, reflecting a brittle nature. This brittle nature may be explained by cementation that was generated from the oxidation of the grain particles in presence of water.

Robertson et al. (2019) indicate that the tailings filling plan was an interbedding of coarse and fine tailings layers. The embankment materials were characterized as having low permeability, which prevented proper drainage to the foot of the dam. This resulted in saturation of the impoundment, with the water level located near the crest. The Feijao expert panel (Robertson et al., 2019) concluded that there was no single cause of the sudden failure of the Feijao dam; rather, the Panel suggested that the failure was caused by a systemic problem. The Panel concluded that the failure scenario was due to a combination of accumulated creep deformations and reduced shear strength of the materials due to the rainy seasons. Water infiltrated into unsaturated zones of the embankment, which lead to a decrease in the suction matrix in the tailing materials, that lead to a sharp reduction in the strength due to deformation.

1.3 *Current Developments*

These environmental disasters caused be the failures explained above forced changes within the mining industry to review the design and operation of TSFs, one of which initiatives concluded in the development of updated standards for design, operation and closure of tailings facilities included in the "Global Tailings Review" (ICMM, 2020). A key change indicated by this new standard is the development of a Tailings Dam Breach Analysis (TDBA) to establish project design parameters based on the consequences of failure. The Canadian Dam Association (CDA, 2020) compiled much of the contributions and advances that have been made over the past decades related to dam break studies and published a Bulletin which is widely accepted by dam break professionals.

This paper presents a TDBA of the Fundao and Feijao dams, developed using Flo-2d software. Parameters indicated by the official technical reports of each TSF will be used. Design parameters from recommended statistical equations are compared with the results and calibration of the parameters. The study is intended to provide input for design and model input parameters. An improvement in the adjustment of the design parameters will assist in defining improved estimations of the potential flooded area and, in turn, a more adequate dam risk classification.

2 GEOLOGY AND FEATURES OF THE TSF FAILURES

The Fundao and Feijao TSFs are located in the south-central zone of the state of Minas Gerais, Brazil, the area with the highest iron production in the country named the "Quadrilatero Ferrífero" (QF) as shown in Figure 1. The QF contains five main lithostratigraphic units (Alkmim, and Marshak, 1998):

- *Archean crystalline basement*: Basement crystalline rocks include a 2.9–3.2 Ga gneiss/migmatite complex
- Rio das Velhas Supergroup (2.86–2.6 Ga): This unit consists of greenstone (basalt and komatiite), rhyolitic lava and intercalated sedimentary rock
- *Paleoproterozoic Minas Supergroup:* The Minas Supergroup is a metasedimentary unit that unconformably overlies the Rio das Velhas Supergroup
- *Post-Minas intrusives* Thin, undated, pegmatite veins cut Minas rocks
- *The Itacolomi Group:* a unit consisting of coarse sandstone and polymict conglomerate containing Banded Iron Formation clasts

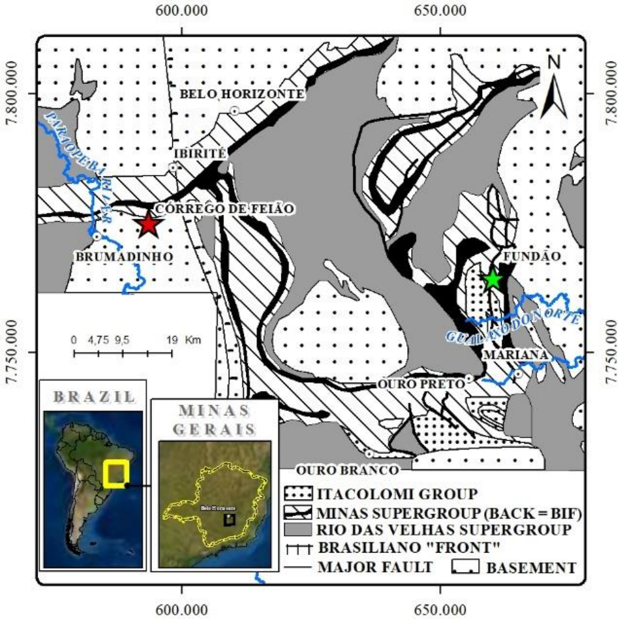

Figure 1. Quadrilatero ferrifero (QF) location and geology (modified from Alkmim and Marshak, 1998)

The Fundao TSF began construction in 2008, with an upstream raise method using compacted sand material and an overall slope in its final configuration of 7H:1V. Upstream and downstream of the middle plateau it is characterized by two embankments with overall slopes of 2.0H:1.0V (see Figure 2). The dam reached a maximum height of 110 m (its crest had reached El. 900 m) and a crest length was approximately 600 m long (considering a setback that increased the initial total length). At the time of failure in November 2015, the impounded volume reached 56.4 Mm^3, and discharging 43.7 Mm^3 (http://www.csp2.org/tsf-failures-from-1915) in a time period of 0,42 hr. (from seismic records Agurto-Detzel et al., 2016). The flood wave reached the downstream town of Bento Rodriguez and subsequently the Gualaxo do Norte river.

Feijao was a TSF that began construction in 1976. The design embraced 10 stages of raise using the upstream method. The overall slope was 2.0H:1.0V, with compacted material consisting of fine residual soils (clays or silts) and tailings (see Figure 3). At the time of the failure, the embankment reached a maximum height of 86 meters (crest El. 942 m) and a length of the crest of approximately 700 m. The impounded volume was 12.0 Mm3 and 9.57 Mm3 was discharged (http://www.csp2.org/tsf-failures-from-1915); the video coverage showed that the release of materials occurred in about 5 minutes (Lumbroso et al., 2020).

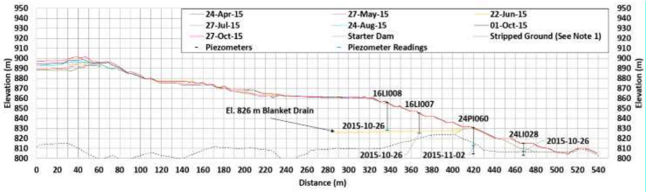

Figure 2. Typical section Fundao TSF (Morgenstern et al., 2016)

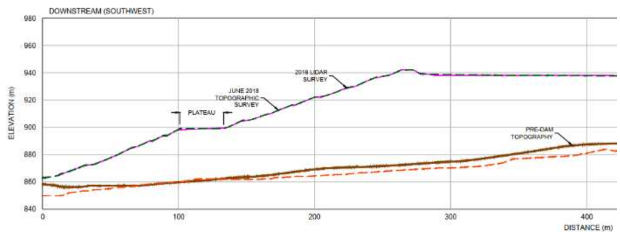

Figure 3. Typical section DAM I, Feijao (Robertson et al., 2019)

3 STATE OF ART AND METHODOLOGY

The procedure used for the development of the TDBA is consistent with the guidelines set forth in CDA (2020). This study seeks to provide additional background on aspects that remain subject to the Professional's judgment and experience in developing a TDBA, and thus, this study contributes to the discussion through the learnings observed.

It has become common in current practice to complete dam break studies to provide information for developing emergency plans or dam classification. Therefore, it is key in a preliminary instance to discuss the extent of critical infrastructure that would be flooded from the release of tailings materials. This assessment can help in establishing the objectives of the study.

An important stage of a TDBA is to understand the topography of the site and find preferential directions that may cause the tailings flow to reach a greater distance. Watershed tributaries and the natural channel slopes produce a larger slurry impact area. Because of this it is necessary to understand which downflow locations may be potentially affected. In the Brazil case studies, it was expected that the tailings flow would reach the Paraopeba and Gualaxo rivers and then the Atlantic Ocean, as it finally happened.

The outflow hydrograph is one of the most relevant aspects to be defined in a TDBA. The hydrograph is the manner in which the release volume is to be input into the computational models. The mobilized tailings volume is estimated by a geometric approximation to an inverted truncated cone behind the embankment. The first step in defining the release volume is to perform a credible TSF failure mode and effects analysis (FMEA) (CDA, 2020). Depending on a selected failure mode, there will be different geometric features associated with the half-cone to calculate the release volume (Fontaine and Martin, 2015). The Fundao (Morgenstern et al., 2016) and Feijao (Robertson et al., 2019) expert panels indicated that static liquefaction was the failure mechanism.

Tailings shear strength plays a fundamental role in the geometric characterization of the inverted cone slope. For a liquefaction failure mechanism, characterizing the cone angle from the residual undrained behavior ($Su/\sigma'v$) is standard practice, using the relationship $\tan(\alpha°) \sim Su/\sigma'v$. Blight (2010) reviewed several failure events, showing that the residual angle was in the range of 2° to 5°; this indicates a limited range of the residual angle. In Fundao at the height of the wall axis, angles between 2.2°-4.5° were observed as residual slope. The calculated residual angle from the liquefied undrained resistance (Morgenstern et al., 2016), $\tan^{-1}(S_u/\sigma'_v)$, was equivalent to $\tan^{-1}$ ([0.045-0.07]) =2.6°-4.0°. In the case of Feijao, the residual angles observed in the surroundings of the dam axis were between 2°-3°. In comparison, the calculated residual angle obtained from the liquefied undrained strength (0.04-0.06) (Robertson et al., 2019) yields a residual angle between 2.3°-3.4°. The comparison confirms that the simplified expression for estimating the residual angle is appropriate to express the post-failure slope of the remaining materials within the impoundment area and although the post-failure surface does not have a unique slope, but is rather better represented by a stepped geometry, the simplified unique slope approach is observed to be appropriate to characterize the semi-cone volume.

In the last decades, there have been great advances in statistical regressions to propose design parameters in the characterization of the release cone, duration, maximum outflow from the hydrograph and the outflow distance. Rico et al. (2008) compiled a database of water reservoir and tailings storage facility failures, which has proven to be a significant contribution in terms of the statistical work, becoming one of the most cited studies in this field. Subsequently, there have been several researchers who have improved the statistical regressions of Rico et al. (2008) by incorporating new data and increasing the number of parameters that may describe the release volume (Larrauri and Lall, 2018; Quelopana, 2019). A comparison of the release volume obtained from different statistical regressions has been performed with the case studies, the results of which are shown in Table 1. The results reveal an underestimation of approximately 40% when estimating the release volume for the case studies studied using the simplified expressions. Most of the data that make up the domain of the statistical expressions are characterized by having storage volumes with as much as orders of magnitude lower than the Brazilian failures reported in this study, which may be an underlying issue explaining the underestimation observed.

Table 1. Comparison of release volume (Mm^3) from statistical regressions at the Fundao and Feijao TSFs

Statistical regression	**Fundao**	**Feijao**
Rico et al. (2008)	24.0	4.57
Tocher et al (2014) (upper bound)	8.45	6.17
Larrauri & Lall (2018)	15.4	3.73
Quelopana, (2019)	20.7	5.36
Official technical report	43.7	9.70

The release volume is included as an input to the modeling software by means of a hydrograph. The characterization of the hydrograph is also part of the Professional's judgment, typically defined based on the recommendations available in the technical literature to calibrate the shape of the hydrograph. Froehlich (1995; 2016) compiled a large database of failures due to overtopping and internal erosion, with statistical regressions proposed to estimate the discharge peak and hydrograph duration time, among others. Subsequently, there have been studies in water dams that have incorporated other TSF features in the estimation of the hydrograph shape, from geometric features to degrees of embankments erosion (Wahl, 2004; Xu and Zhang, 2009; Pierce et al., 2010 and Wahl, 2010). The liquefaction failure database does not yet provide a substantial part of the statistical data regressions. Figure 4 shows the hydrographs used in this study for both TSFs, using the data shown in section 2.

Mud flooding is characterized by behaving as a hyper-concentrated flow, i.e., flows with properties between fluvial flow and debris flow (O'Brien, 1985), who introduced the concept of tailings transport mechanics as a function of the solids concentration, Cv, of the fluid to classify the different flow types. This classification was incorporated in the CDA 2020 guidelines. Liu & Henderson (2020) show that the volume solids concentration (Cv) for Fundao and Feijao was approximately 50% and these are the values used in this study.

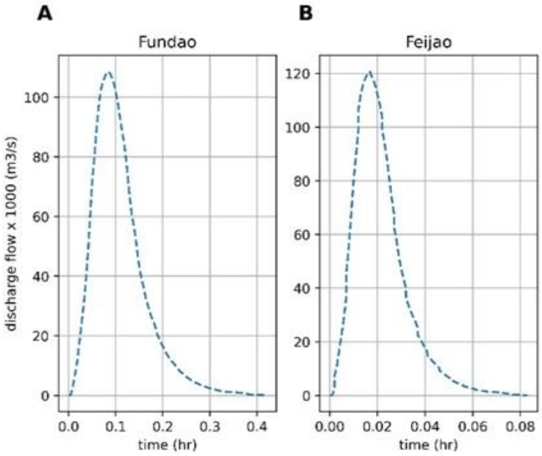

Figure 4. Outflow hydrograph (a) Fundao, (b) Feijao

Flo 2d software used in this study solves the quadratic equation of motion and therefore the non-Newtonian rheological characterization of the hyperconcentrated fluid (non-Newtonian flow), i.e., yield stress and dynamic viscosity, are required as input. For Fundao, the curves indicated by Machado (2017) have been adopted where tests were performed with tailings material obtained downstream of the failure. Magalhães & Oliveira (2021) performed tests to study the rheology of different tailings materials located in the QF (iron quadrilateral) of Minas Gerais; in the absence of rheological tests in Feijao, these results were used in the model. The rheological characterization for both TSFs is shown in Figure 5, and only a unique curve fit was used. It is important to highlight that the iron tailings produced from the ore within the QF area are characterized by a specific gravity (Gs) of about 4.0.

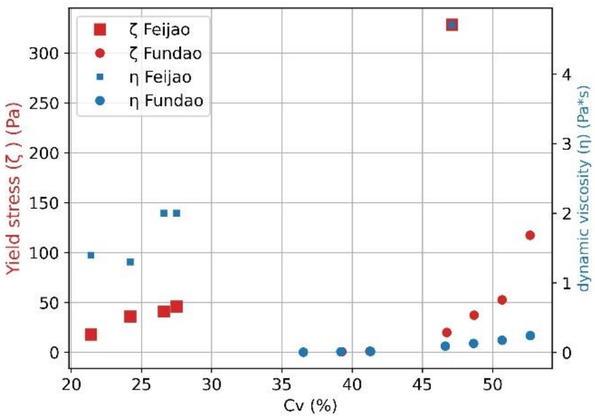

Figure 5. non-Newtonian Rheology tailings

The topography used in the modeling was processed from the data obtained from the ALOS PALSAR satellite (NASA's Alaska Satellite Facility), which has a resolution of 12.5 m.

4 RESULTS

The TSF failures in Brazil have been extensively studied owing to the significant environmental damage caused. The website idesisema.meioambiente.mg.gov.br provides public access of the areas of impact generated by the tailings outflow from the facilities, which were used in the study model. There are still no official values for the arrival times of the flood wave at the locations downstream of the rivers, but some accepted values have been used in the study model. In cases where no official source has been found, newspaper reports have been consulted to define the flood arrival times; these values were compared with results from the study model. Due to the uncertainty of the arrival times, it was established that the end point of the modeling for Fundao is the locality of Paracatu downstream of the Gualaxo River to the north; in the case of the Feijao dam, the entry at the Paraopeba river was chosen.

Manning's roughness coefficients play an important role in the models as they can accelerate or slow down the flood wave; Flo-2d software (Flo2D, 2018) recommends values of roughness coefficients that were used in the modeling. In the case of Fundao, a value of 0.15 was assigned to the area between the TSF and the town of Bento Rodriguez and a value of 0.10 in the area of the Gualaxo channel. In the case of Feijao, a value of 0.15 was assigned for the area between the TSF and the Paraopeba river.

The modeling results are shown in Figure 6 and Table 2 for Fundao and in Figure 7 and Table 3 for Feijao. At key points of interest both models were compared with arrival times and final flow heights. The Fundao modeling covered almost 35 km downstream of the embankment. Modeling results show a good relationship between flooded area and official arrival time. The Feijao model results show consistency of the flooded area compared to the official area. Some differences are observed in the area near the embankment, which can be attributed to the fact that the model utilizes the topography without consideration of the erosion generated by the downstream flow.

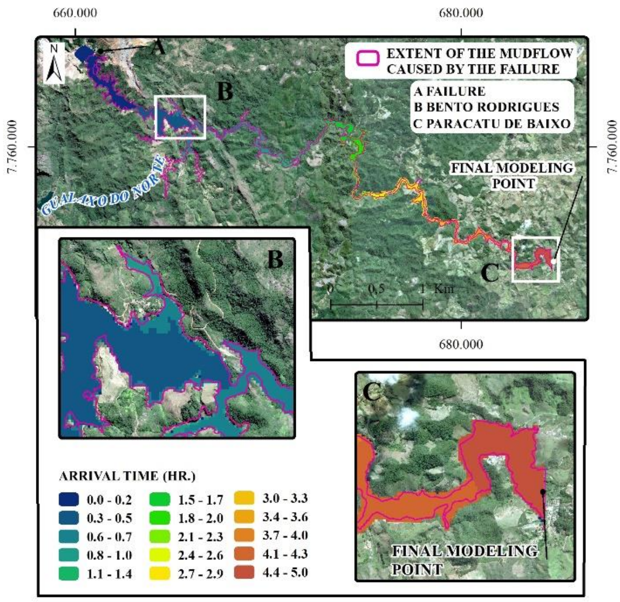

Figure 6. Fundao mudflooding modeling

Table 2. Fundao arrival times of mudflow (local time)

Arrival time	Official Report	Model
Start Failure	15:45-16:20	--
Bento Rodriguez	16:15-16:50	16:15
Paracatu	20:10	20:25

Feijao is the first dam break where the failure is documented on video footage; therefore, the duration time of the failure generates great consensus. This information helps characterize the duration of the outflow hydrograph and is the reason why the modeling required little effort for parameter calibration unlike Fundao. This water input affects the concentration of the mud that continues to travel downstream. The maximum solids content (C_v) of the release hydrograph had to be corrected to 47% to observe arrival times at the Paracatu location as indicated by the information collected.

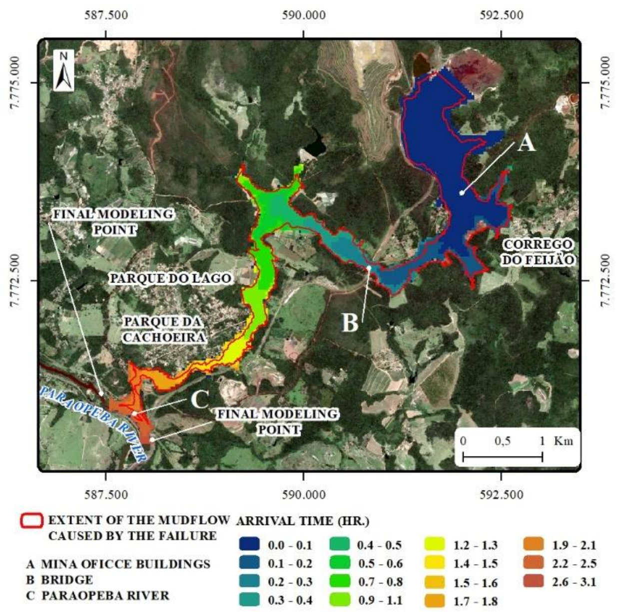

Figure 7. Feijao mudflooding modeling

Table 3. Feijao arrival times of mudflow

Site	Arrival time	Final Depth(m)	Final Depth(m) official
Mine office building (A)	4 min	0.8	1.0
Bridge (B)	15 min	1.8	2.0
Paraopeba river (C)	2 hr:12 min	5.1	5.0

By looking at the failure database at http://www.csp2.org/tsf-failures-from-1915. and filtering the tailings deposit failures where the embankment height was reported, the volume storage and the release volume can be plotted as shown in Figure 8. The ratio of volume released to storage volume has been plotted on the vertical axis. The dams that failed in Brazil appear as outliers in these cases. This reflects that Fundao and Feijao do not have close proximity to the previous failures and that the estimation of release volume is a more complex issue.

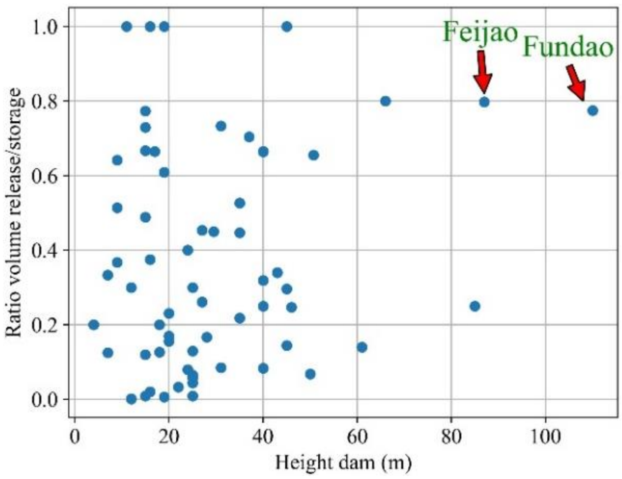

Figure 8. Comparison data base failure dam tailings

5 CONCLUSIONS

Embankment failures in the recent TSF failures in Brazil have presented TSF's stakeholders with major challenges in recent years, from a broader understanding of the geotechnical phenomena involved to more rigorous design guidelines.

The TDBAs of Fundao and Feijao have been performed. The models show a good agreement between the flooded areas with the official information reported. In the Fundao TDBA, the maximum solids content of the released tailings had to be decreased to find a better similarity between the model and the official reported values.

Statistical regressions for the calculation of the outflow volume show an underestimation of the values, attributed to the fact that the database used in the statistical regressions consider limited records of TSFs with a large storage capacity and were triggered by tailings liquefaction. In today's increasing mill throughput scenario, the mining industry is constructing larger and larger TSFs and it is therefore more relevant to generate models that can characterize the outflow volumes in these types of deposits. One of the key recommendations is to define the failure model parameters based on reference parameters from an actual failure of a facility most similar to the TSF to be designed. Calculating the outflow volume by means of the previous geometrical design of the semi-cone is more appropriate.

Another aspect is the failure mechanism to estimate the emptied volume; static liquefaction, as observed in the case studies in Brazil, generates larger displacement of the deposit than other types of mechanisms. Statistical regressions for the release volume that can incorporate properties such as topography on which the TSF is built, as well as the failure mechanism, are expected to improve the estimation of the result.

Rheological studies of tailings in the iron quadrilater (QF) show a high specific gravity > 4 and a high sensitivity in the yield stress and dynamic viscosity curves. This demonstrates the importance of having rheology testing of the tailings materials when performing TDBA.

The failures in Fundao and Feijao generated great concern in society due to the uncertainty that similar events may occur. In addition, the background reflects that in the last decades there has been an increase of TSF failures. Therefore, it is critical to generate TDBA models to obtain better approximations to the potentially affected areas and thus generate emergency plans to avoid fatalities as much as reasonably possible.

6 ACKNOWLEDGEMENTS

This work was completed thanks to the collaboration of Knight Piésold, with invaluable comments from Violeta Martin, PhD.

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