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REVIEW ARTICLE

Content analysis of dam break studies for tailings dams with high damage potential in the Quadrilátero Ferrífero, Minas Gerais: technical weaknesses and proposals for improvements

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Abstract

Tailings dams are civil structures that have an intrinsic potential risk of failure that, if poorly managed or neglected, can lead to severe societal, environmental, and economic damage. Studies of dam breaks make it possible to anticipate these damages and plan appropriate contingency actions for critical situations. In this context, the present work presents the analysis of 86 dam break studies of mining tailings dams in the important Brazilian mineral province called the Quadrilátero Ferrífero, or Iron Quadrilateral, in the state of Minas Gerais, Brazil. The analysis involved verifying whether the studies complied with legal requirements, met international guidelines, and addressed the minimum parameters reported as critical in the literature. We found that all studies analyzed present these components: hydrological studies, the definition of the failure mode and rupture hydrograph, and propagation of the flood wave and mapping of the effects of the rupture in the valley downstream of the dam structure. However, the dam break studies showed deficiencies, such as the weakness of the hydrological studies, lack of specific criteria on the volume of tailings that are supposed to mobilize in a possible rupture, and the failures to consistently model tailings as non-Newtonian fluids. These deficiencies found in the dam break studies present in Emergency Action Plan affect the predictive capacity of the rupture models and thus the accuracy of the flood maps they generate, negatively influencing preparation actions in an eventual emergency. In the absence of guidelines and the regulation about the minimal content of the dam breach studies, we suggest that a possibility for solving this deficiency in the short run is to have technically trained professionals from inspection and control agencies audit the content of the dam break studies.

Keywords Dam break · Tailings dams · Flood modeling · Emergency management

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1 Introduction

Dams are structural barriers built mainly for storing water or industrial waste and processing minerals (Rico et al. 2008). A tailings dam, a particular type of dam used by mining companies that use a wet process for ore extraction, is a way of disposing of materials discarded in the process. These dams are commonly used worldwide by mining companies, mainly due to the low cost associated with this waste disposal technology (Santamarina et al. 2019). In recent years, safety failures in this type of structure have caused harmful technological disasters, among them, the rupture of the tailings dams of Fundão, in Mariana (on November 5, 2015) and of the B1 dam, in Brumadinho (on January 25, 2019), both in the state of Minas Gerais, Brazil. The first caused 19 deaths, pollution, and degradation of properties and preservation areas along 670 km of rivers extending to the mouth of the Doce River in the Atlantic Ocean, in the state of Espírito Santo, while the second caused 253 deaths in addition to polluting and degrading 250 km of the Paraopeba riverbed (Carmo et al. 2017; Freitas et al. 2019; Morgenstern et al. 2016; Owen et al. 2019; Sánchez et al. 2018; Santamarina et al. 2019). Figure 1 shows the cumulative number of deaths and the accumulated volume of tailings released in disasters with dams in Brazil in recent years.

Another tailings dam disaster that deserves to be highlighted in terms of the damage caused is that of Ajka in Hungary, which occurred in 2010. This disaster caused ten deaths in addition to flooding an area of 800 hectares (a large part of which was cropland) with red mud (chemically dangerous tailings from processing of bauxite) (WISE 2014).

In this context, dam break simulation studies (studies of flooding) are of critical importance in the prediction of societal, environmental, and economic damages resulting from possible ruptures of dams, and these studies are fundamental components of Emergency Action Plans (EAPs) (Bernedo et al. 2011). The EPA is a document that integrates the preparation and execution of response actions in an emergency situation in order to safeguard the population downstream of the dam and the environmental, patrimonial, and economic assets of the region (FEMA 2013).

For a tailings dam break study to be most consistent with a real potential situation, some parameters and hypotheses adopted in a confined material propagation model (that is, a mud wave model) must be adjusted, such as dimensions of the rupture gap, volume of solids mobilized by the rupture, and tailings flow parameters (e.g., considering them as non-Newtonian fluids) (Bernedo 2011; Machado2017; Moon et al. 2019). It is noteworthy that there is no standardized methodology for drafting dam break studies; the required models and their parameters are generally derived from the expert knowledge and practice of dam engineering specialists.

That being said, the present study analyzes the main parameters and criteria for dam rupture modeling, propagation, and flood wave mapping adopted in 86 studies of mining dams located in the Quadrilátero Ferrífero, or Iron Quadrilateral, region of Minas Gerais; the study also aims to indicate the approaches improvement, the parameters of the modeling, and the greater mapping precision of the flood wave in ruptures, and thus show the greater effectiveness in actions of prevention and preparation of emergencies involving mining dams.

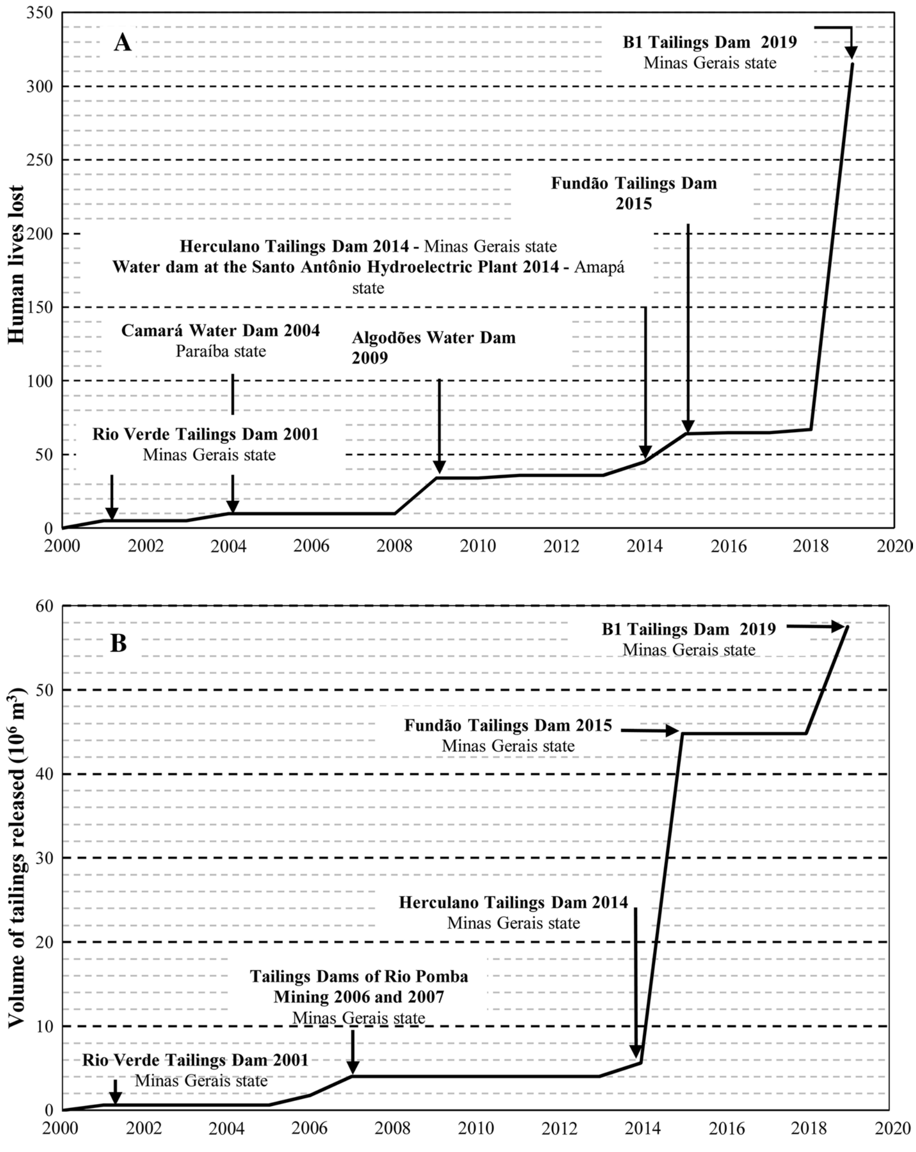

Fig. 1 **a** The cumulative number of deaths associated with disasters with water dams and tailings dams in Brazil in the last 20 years. **b** The accumulated volume of tailings released by recent disasters with tailings dams in Brazil in the last 20 years

2 Materials and methods

2.1 Study area and selection of dam break studies

The Quadrilátero Ferrífero (QF) region of Minas Gerais was chosen because it is one of the largest mineral provinces in the country and is internationally known for its rich

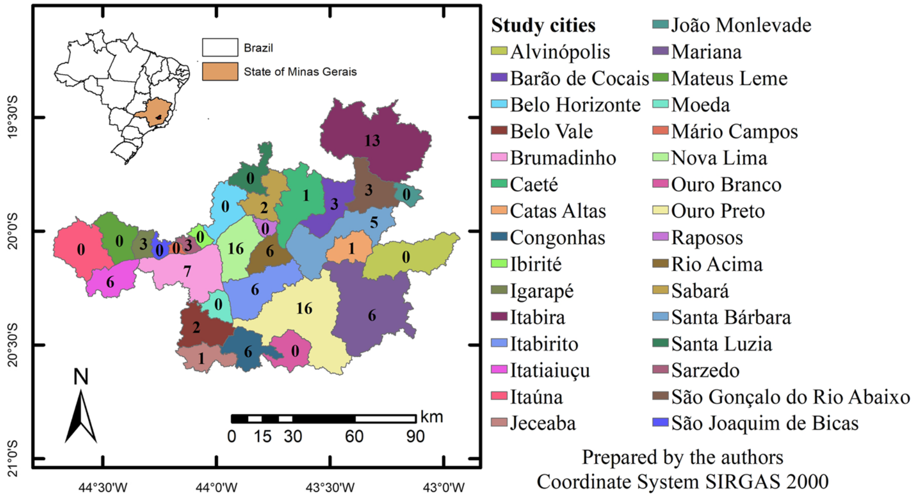

Fig. 2 The Quadrilátero Ferrífero region of Minas Gerais and the municipalities where the dams with high potential associated damage (DPA) are located

reserves of iron ore and other important minerals, such as bauxite, gold, manganese, and topaz. It is a region of more than 7000 square kilometers extending between the old capital of Minas Gerais, Ouro Preto, to the southeast, and Belo Horizonte, the current capital, to the northwest, and covering the mining municipalities of Itabira, Caeté, Ouro Preto, João Monlevade, Mariana, Rio Piracicaba, Santa Barbara, Itabirito, Sabará, Belo Horizonte, and Itaúna, among others, and it was an important area for gold ore at the time of the Ciclo do Ouro, Brazil's gold rush, in the seventeenth and eighteenth centuries (Roeser and Roeser 2013). The existence of large deposits has driven the implementation of mineral extraction projects and, consequently, construction of dams to dispose of tailings or to accumulate water for use in mineral processing.

According to Roeser and Roeser (2013), the QF, a geological region whose shape resembles a square, is the southern continuation of Serra do Espinhaço, a mountain range in the state of Minas Gerais. Its basement rock and surrounding areas are composed of tonalitic–granitic gneisses of Archean age (> 2.7 billion years). Above this crystalline basement are three units of supracrustal metasedimentary rock: the Archean supergroup Rio das Velhas, the Proterozoic supergroup Minas, and the Proterozoic group Itacolomy. The QF region is now made up of 32 municipalities located in the center-south of the state of Minas Gerais, Brazil (Fig. 2).

Based on the Inventory of Dams of the State of Minas in 2018, carried out by the State Environment Foundation (FEAM) in 2018, we identified the dams installed in the municipalities of that region, and of the 690 dams in the state of Minas Gerais, 307 are located in the QF (FEAM 2018). Of the 307 dams in the region, 106 are classified as being of high potential associated damage (DPA); that is, an eventual malfunction and rupture of these dams could cause loss of human lives and potential social, economic, and environmental impacts (ANM 2017). It was from this selection of dams that we selected dam break studies for this study.

2.2 Identification of sources and acquisition of dam break studies

Dam break and inundation studies are a required part of one of the chapters of Brazilian Emergency Action Plans (EAPs) for dams. When developed for mining dams, the EAP is called the Emergency Action Plan for Mining Dams (EAPMD). According to article 31 of Ordinance No. 70.389/2017 of the National Mining Agency (formerly the National Department of Mineral Production, or DNPM) and the sole paragraph of article 12 of the National Dam Safety Policy (PNSB), the places that must have a physical copy of the EAPMD, in addition to the mining undertaking itself, are city halls and local Civil Defense units.

Therefore, we chose to identify and request copies of the EAPMDs from the Civil Defense offices of the municipalities in the QF region, and in cases where the municipalities did not have a Civil Defense post, the EAPMD was obtained from the city hall of the municipality in which the dam was built. There was no attempt to request EAPMDs directly from the companies that own the dams, due to difficulties in contact and because it was easier to obtain them from the official public agencies that hold the documents. In addition, visiting the Civil Defense bodies allowed us to verify the level of service by mining companies to the specific legislation in force with respect to making the EAPMD available and accessible to the appropriate authorities, in keeping with article 12 of the National Dam Safety Policy, Federal Law No. 12,334 of 2010.

Visits to Civil Defense offices to obtain EAPMDs and thus have access to dam break studies took place between September 4 and October 17, 2019.

2.3 Analysis and treatment of EAPMD inundation studies of dam breaks

After acquiring the relevant dam break studies for the selected dams, we analyzed the parameters and models (the software) used in the construction of these simulations and their final product, the inundation map. We sought to compare the parameters with international guidelines and to identify the limitations and advantages of dam break studies prepared by consultancies for mining companies in Brazil and the international practices adopted.

Another reference for our analysis of dam break studies was Ordinance No. 70,389/2017 of the National Mining Agency, which, if compared to the ordinances that preceded it—Ordinances No. 416/2013 and No. 526/2014—presents changes regarding minimum EAPMD components and the content of the inundation study of a hypothetical dam break scenario.

The analysis was carried out using a checklist composed of the main components required by Brazilian legislation and components and parameters required by other leading countries in the planning and management of dam emergencies, namely Portugal, Spain, Australia, and Canada, among others.

In addition to legislation items, parameters considered sensitive in retro analysis surveys of dam rupture disasters were chosen, such as the Machado (2017) and Palu and Julien (2020) surveys for the disaster with the Fundão dam, which point out the parameters for the flow of hyper-concentrated fluids (rheological parameters) and 1D- or 2D-type models as items that influenced the vertical precision of the flood wave. And also, researches like the one of Antonio et al. (2019), for the disaster with the B1 dam, where it was found that in addition to the rheological parameters, the topography mesh (Digital Terrain

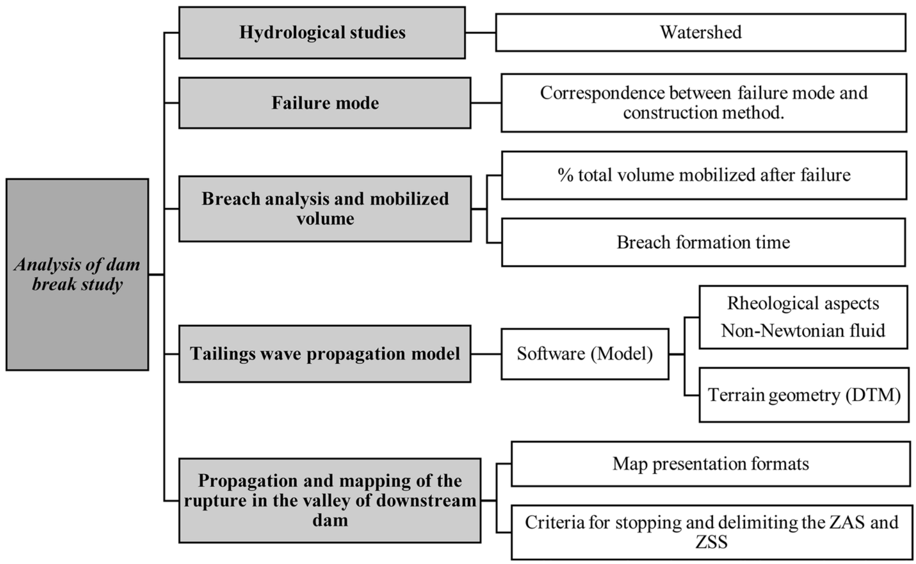

Fig. 3 Flowchart of analysis of dam break studies: Digital Terrain Model (DTM); Self-Rescue Zone (ZAS); Secondary Rescue Zone (ZSS)

Model—DTM) was used to represent the terrain where the wave would propagate, influenced on horizontal resolution and accuracy of the vertical wave.

Another research that was an indication for determining the parameters of analysis was the Moon et al. (2019) review, which points to the estimate of the launched volume and the main rheological parameters of the launched tailings as important characteristics of the tailings wave propagation models.

Figure 3 shows the main parameters of analysis within each of the components that make up the dam break study.

3 Results and discussion

In the Civil Defense offices of the municipalities of the QF, 86 of the 106 EAPMDs of the high DPA dams built in the QF region were found—that is, 81.13% of the total plans sought. Of the 20 plans not found (18.87%), three were being updated; five were joint plans (that is, a single EAPMD was prepared for more than one dam installed in the same mining complex); five were not at the Civil Defense office on the day of the search (and of these, two were at the Civil Defense service post and three were in another sector of the city hall); and seven, about 6.6% of the total EAPMDs, had not been filed with the municipal Civil Defense agencies; therefore, their existence could not be confirmed. In all, the plans studied are for mineral enterprises present in 19 municipalities of the Minas Gerais QF with high DPA dams, namely Ouro Preto (16 dams), Nova Lima (16), Itabira (13), Brumadinho (7), Itatiaiuçu (6), Congonhas (6), Mariana (6), Itabirito (6), Rio Acima (6), Santa Bárbara (5), Barão de Cocais (3), Igarapé (3), Sarzedo (3), São Gonçalo do Rio Acima (3), Belo Vale (2), Sabará (2), Caeté (1), Catas Altas (1), and Jeceaba (1).

It is worth noting that in Brazil, with the National Dam Safety Policy in force, an Emergency Action Plan has been required by law since 2010; nonetheless, there are mining companies from the QF of Minas Gerais that have been delinquent in drafting the EAPMD, as evidenced by the seven dams that did not have the required EAPMD document filed with the local Civil Defense as of the day of our on-site visit. Dams that did not have the document filed are located in the municipalities of Ouro Preto, Brumadinho, and Mariana.

3.1 Analysis of dam break studies

In general, all EAPMDs analyzed (86) are in accordance with the requirements of National Mining Agency Ordinance No. 70.389 of 2017, presenting, at a minimum, the inundation maps including the delimitation of two flood reach zones in a possible rupture accident, as established in Brazilian legislation—namely, the Self-Rescue Zone (ZAS) and the Secondary Rescue Zone (ZSS).[1] Although the ordinance was clear in requiring the delimitation of the ZAS and the ZSS, we observed that although all plans indicated the ZAS, only 13 of the 86 plans studied explicitly indicated the ZSS. Even though ZSSs are all areas that are not classified as ZASs, delimiting their boundaries is also important for planning and preparing for an emergency.

Regarding the content of the inundation studies (dam break studies) of the selected dams, all presented at least the following components: hydrological studies, the definition of the failure mode of the rupture (that is, the reason for the rupture) and the rupture hydrograph, and propagation and mapping of the effects of the rupture in the valley downstream of the dam built.

A considerable number of the hydrological studies analyzed were theoretically weak because they did not consider the regional particularities of the hydrographic basins where the dams are located. About the watershed where these dams localized, 66% of the documents of the study dams belong to an important federal hydrographic basin of the São Francisco River and to the state hydrographic basins of Rio das Velhas and Rio Paraopeba. It is known that the Rio das Velhas is responsible for 70% of the water supply of Belo Horizonte (the capital of the state of Minas Gerais) and for half of its metropolitan region, and the Paraopeba River is responsible for supplying 53% of the population of the metropolitan region of Belo Horizonte (CBH Rio das Velhas 2019; PDRH Paraopeba 2019).

As seen in the recent disasters with Samarco's Fundão dam in Mariana and Vale's B1 dam in Brumadinho, water use was severely compromised due to the large inflow of sediments and suspended solids launched in the event of these ruptures, leading to an immediate and extraordinary increase in water turbidity, in addition to the intense silting of the river channel and its banks and the contamination by heavy metals. It is noteworthy that the inflow of sediments and suspended solids is a characteristic impact of iron ore dams, which make up 89% of the dams in this study (Morgenstern et al. 2016; Sánchez et al. 2018). Furthermore, these events caused a series of water crises with direct implications for the quality and cost of water treatment supplying communities, in addition to impacts on biodiversity and human activities that require the use of water.

[1] Self-Rescue Zone (ZAS): "region of the valley downstream of the dam in which the warning notices to the population are considered to be the responsibility of the entrepreneur, as there is not enough time for the competent authorities to intervene in emergencies, and greatest of the distances for its delimitation: the distance that corresponds to a time of arrival of the flood wave equal to thirty minutes or 10 km. Secondary Rescue Zone (ZSS): Flood Map region, not defined as ZAS" ANM (2017).

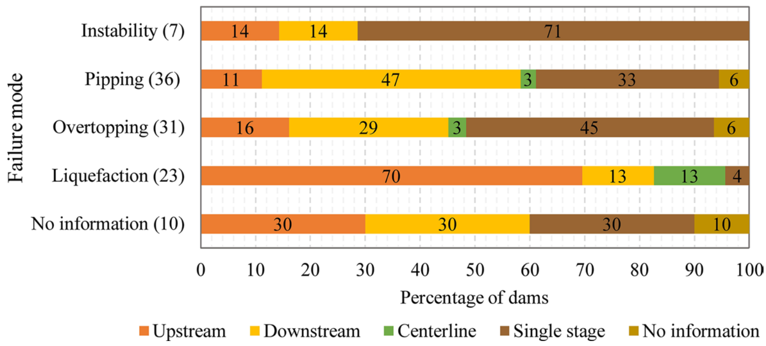

Fig. 4 Failure modes and dam construction methods used in the analyzed dam break studies

Also on this topic, an item that deserves attention is whether the study adopts a rainy day scenario or a sunny day scenario. Of all 86 studies analyzed, 85 consider the hypothesis of a dam break happening on a rainy day. This choice is considered reasonable given that on a rainy day there is an increased inflow in the reservoir due to precipitation, which would lead to a more damaging scenario than a rupture on a sunny day.

3.2 Defining failure mode and analysis of breaches

Figure 4 shows the most common failure modes in the analyzed dam breaks simulations. We found that failure due to internal erosion (also known as piping) is the most recurrent cause in failure simulations (present in 42% of studies, or 36 cases), followed by overtopping (31 cases), liquefaction (26), and instability (7), respectively, while no information was available in ten cases.

In Fig. 4, although internal erosion appears in greater numbers, overtopping was the most used failure mode in dam break studies. The greater number of failures due to internal erosion is justified because many consultancy companies simulated two or more rupture scenarios, always considering the hypothesis of rupture by overtopping (most recurrent) and the hypothesis of rupture by internal erosion. The result found is in agreement with the dam failure analysis reported in ICOLD documents and scientific articles, which also point out that worldwide one of the most recurrent types of failure in dams is overtopping (CIGB/ICOLD and UNEP/PNUE 2001; Rico et al. 2008).

In the EAPMDs analyzed, the hypothesis of overflow as the failure mode was adopted in cases when the flood flow capacity of the dam would be less than the additional flood volume or when the flood would exceed the designed capacity of the dam spillway. Regarding the failure mode of the dam being due to internal erosion, in the literature there is no standard for its occurrence. In a simplified way, internal erosion is associated with problems of water infiltration in the dam and consequent soil removal from its structure (Fusaro et al. 2017).

The second largest cause of failure in tailings dams in the world is liquefaction (CIGB/ICOLD and UNEP/PNUE 2001; Rico et al. 2008), but in the plans analyzed, liquefaction was the third most common failure mode to be adopted in the simulations used in the studies. It was found in the plans analyzed that this failure mode was adopted mainly in ruptures of dams built by the upstream construction method, which is justified because they are more susceptible to this failure mode. Of the 86 dams in the QF, 27% (23 of the

86) were constructed by the upstream method, and of these, 70% (16 of the 23) had their rupture simulated by liquefaction. The analysis of these EAPMDs and the last two major disasters with tailings dams in Brazil show a relevant relationship between the liquefaction failure mode and the upstream construction method.

Knowing the failure mode of the dam allows for estimating the time for formation of the breach and thus estimating the arrival times of the flood wave of mud or tailings. Detailed knowledge of these variables is of fundamental importance for planning the evacuation of populations downstream of the dam. Thus, for each of the failure modes presented, we determined what would be the average time for formation of the breach.

Overtopping failures have longer breach formation times, averaging 41 ± 21 min according to the plans studied. For the internal erosion failure mode, the analyzed plans averaged 20 ± 13 min. Both failure times reflect a more conservative approach, since these failure events can develop over hours or even days (Saliba 2009; Silva 2016). In all simulated disruption scenarios using liquefaction, the failure time was considered instantaneous, in view of this mechanism developing in most cases abruptly, as experienced in the most recent disasters that had this failure mode (Santamarina et al. 2019).

Of course, the faster the formation of the breach, the shorter the response time available to Civil Defense, the mining company, and the populations in an imminent dam break emergency. Planning for shorter breach times is more conservative, and it can be beneficial to adjust the target times for training and emergency drills with the population to account for this to ensure greater integrity of lives vulnerable to disruption.

Regarding the definition of the breach geometry, about 66.3% of the plans (57 of the 86) used the formulations proposed by Froehlich (1995), (2008), and (2016). Another 3.5% of the plans (3 out of 86) defined the breach formation geometry using the document of Dam Analysis Breach (2010). The remaining 30.2% (26 of the 86) did not provide information on how the breach geometry was determined. Most of them, 69.8% of the plans, used formulations in the literature to estimate the geometry and the time for breach formation, which we consider to be positive because these formulations are largely disseminated in the technical area.

To estimate the percentage of mobilized tailings in the event of a dam failure, 63% of the plans (54 of the 86 plans) used the empirical relationship established by Rico et al. (2008). According to Rico et al. (2008) on average, one-third of the tailings and dammed water are released during the failure of the dam. In those 54 plans we analyzed, the average value was 35.4% ± 1.3%. Another 7% of the plans (6 of the 86) considered that 100% of the tailings from the dam would be mobilized at the rupture, 2% (2 of 86) considered that 70% of the tailings would be mobilized, and another 1% that 50% of the tailings would be mobilized. Studies that adopted 50%, 70%, and 100% of mobilized tailings justify the adoption of these values because they seek to be more conservative. Note that the specialized literature, such as that of Rico et al. (2008), can provide a forecast closer to reality and that does not overestimate the volume of mobilized waste.

The precision of the rupture parameters, such as breach width, time of breach formation, and volume to be mobilized, is crucial for the greater fidelity of the rupture model in a real situation. In cases where the rupture parameters cannot be predicted with reasonable precision, a more conservative approach may be necessary, which results in an increase in associated costs (Wahl 1997). These costs are due, for example, to the larger areas to be signaled and prepared for emergency situations and to greater investments in structuring Civil Defenses.

With all the EAPMD data including the hydrological study, the failure mode, the rupture breach dimensions, and the percentage of tailings volume to be mobilized, it is possible to

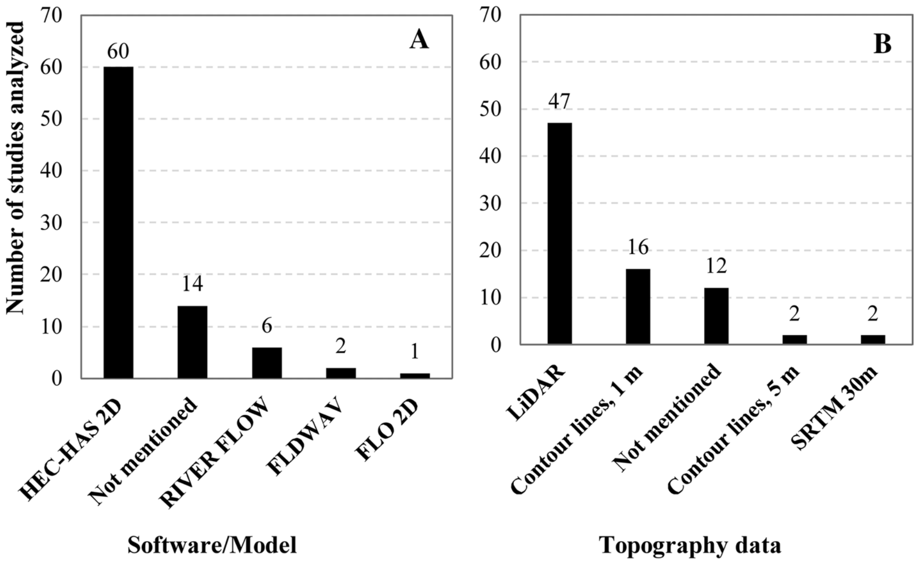

Fig. 5 **a** Main software used to model the flood wave propagation of the study tailings dams; **b** main topographic meshes used in the models for construction of the terrain geometry

determine the rupture hydrograph, which shows the variation of the tailings wave flow over time. The rupture hydrograph provides input data for the model to be used in order to predict the flow rates of the post-rupture tailings wave.

3.3 Tailings wave propagation model

As for the most used models for the propagation of the tailings wave, we found that about 70% of the plans used the HEC-HAS 2D software to simulate the propagation of the flood wave (Fig. 5a). This can be explained by the fact that River Analysis System (HEC-RAS) is free software developed by the Hydrologic Engineering Centre of the US Army Corps of Engineers and has guides and manuals, with highly disseminated models. Another possible explanation for the greater use of this software as compared to other options is the delimitation of the study area (the Quadrilátero Ferrífero).

Many of the dam break studies analyzed here were prepared by the same consulting company, which led to a greater use of this software. At this point, it is emphasized that although all dam break studies must be signed by a technical manager, who works in consulting companies, there is no way to assess the quality of the inundation studies and the propagation mapping of the rupture wave. This surely is a weakness, given that the studies are only checked for compliance with legal requirements, and there is no effective way of assessing the parameters and approaches used in the modeling.

Although HEC-HAS is the most frequently used software among the studies analyzed, it has some limitations for modeling hyper-concentrated fluid flows, given that its equations are proposed for fluids with a low concentration of sediments (Machado 2017). In order to ensure the correct implementation of HEC-HAS, most of the dam break studies we analyzed used the similarity principle, which adjusts the dimensionless coefficients of the equations that deal with the water flow, adapting them to the hyper-concentrated flow as a function of the kinematic viscosity of the fluid (Machado 2017).

Despite this limitation in the use of the HEC-HAS software for fluids with a high concentration of solids, its use for modeling rupture of tailings dams with the appropriate methodological adjustments seems to be an accepted practice in the literature, as can be seen in the literature (US EPA 2014; WEST Consultants 2011; Machado 2017).

The softwares RIVERFLOW 2D, FLO 2D, and DAMBRK are commercial, and all have add-ons for mudflow simulation (Mudflow). FLDWAV, however, was developed by the US National Weather Service and is widely used by the US Federal Emergency Management Agency (FEMA). According to FEMA (2015), FLDWAV replaces in its functions other models such as DAMBRK.

The models used for the prediction of wave propagation were models ruled by 1D flow equations, such as FLDWAV and DAMBRK, and 2D flow equations, such as HEC-RAS 2D, RIVERFLOW 2D, and FLO 2D, suggesting that the Brazilian consultants working with this type of modeling are within the market standards, due to the fact that these are the types of models most widespread internationally.

One-dimensional models have simpler calculation and implementation procedures and require less computational demand than 2D models; however, when it comes to the propagation of a wave beyond the river channel (unconfined flood plains), 2D models can show better flood wave accuracy (India 2018; Palu and Julien 2020).

Given this greater precision of 2D models for the rupture of dams flow, the Brazilian National Mining Agency published the Resolution n ° 32 in May 2020, which requires that dam break studies for mining dams consider minimally the 2D models contemplating the addition of materials and sediments that the rupture wave will carry in its displacement (ANM 2020).

It is noteworthy that no consulting company that prepared these studies used 3D modeling. According to Moon et al. (2019), tailings propagation models will evolve to use 3D modeling in the coming years.

We found that 20% of EAPMDs did not mention in the dam break study which software was used to simulate the flooded spot. The omission of this information can affect the analysis of the results obtained in the study and thus the identification of components that may be revised or updated in the model, making future evaluations or audits of the content of the dam break study impossible.

An important item of modeling and one of the main sources of errors in the models is the definition of the terrain geometry, including its relief and drainage. The quality of the topographic mesh of the terrain is essential for precision in terms of flood wavelength and height (Cook and Merwade 2009; Kumar et al. 2017; Teng et al. 2017).

Figure 5b shows the main topographic meshes used for the construction of the terrain geometry for the flow simulation. It was found that 54% of the dam break studies present in the EAPMDs we analyzed used a topographic grid derived using light detection and ranging (LiDAR) to generate the geometry of the flood model.

It is known that the topographic grid obtained through the LiDAR sensor is one of the most accurate and serves as a reference in guides and guidelines of several countries, such as India (India 2016, 2018). In urban areas of Portugal, the UK, and Spain, the topographic scale considered is required to be more detailed, ranging from 1:25,000 to 1:10,000 (DEFRA and Babtie 2006; Ministerio de Medio Ambiente 2001; ANPC and INAG, 2009).

It is noteworthy that some authors relate the quality of the topographic mesh and the precision of the flood mapping, and in all these studies, LiDAR is classified as the topographic mesh with the most adequate precision for the generation of flood areas.

Sanders (2007) when comparing digital topographic meshes such as those from LiDAR and Shuttle Radar Topography Mission (SRTM) data concluded that the former is the best source of terrain data due to its good horizontal resolution and vertical accuracy. Similarly, but with the addition of the comparison of the 1D and 2D analysis, Cook and Merwade (2009) observed that smaller areas of flooding could be found when using data from LiDAR.

Tschiedel and Paiva (2018) took another approach to topographic mesh analysis. They tested sensitivity factors in flood propagation modeling and found that, depending on the valley studied, lower resolution topographies can be used to estimate peak time in some sections. In other words, they showed that despite having less accuracy, the SRTM mesh can present a good estimate of the peak flow in some sections, and in certain cases, it can replace the LiDAR mesh without compromising the quality of the flooded area.

Despite this finding in the study by Tschiedel and Paiva (2018), in general, research shows that the SRTM mesh has a lower horizontal resolution than the LiDAR mesh, and this directly affects the definition of the boundaries of the flood envelope. Because of this, the two dam break studies that use the SRTM mesh may have flaws in their flooding envelopes and thus fail to define the target zones (ZAS and ZSS).

Another item that can be considered one of the most important in the modeling of rupture of a tailings dam is the consideration that the tailings disposed in the dams are non-Newtonian fluids (or hyper-concentrated fluids); this is the main difference between a water flow and the disposal of tailings (Machado et al. 2017).

Of the 86 EAPMD dam break studies analyzed, six assumed a flow composed only of water. Of these, four are in fact water accumulation dams and the other two are sedimentation basins, and after analyzing the volumetric concentration of solids, their flow can be considered aqueous. Another three plans adopted water drainage in their dam break study, even though they deposit iron ore tailings, demonstrating a gross error in the adoption of modeling parameters, an error that can lead to mistaken predictions about the flooded area. The other plans (77) all described how they addressed the flow of waste and water.

Research by Bernedo et al. (2011) and Moon et al. (2019), who compared the flow of tailings and water to the same dam, showed that by assuming that the tailings *run off* flow as a Newtonian fluid, the rupture wave travel times are faster and the depths are greater.

This shows that modeling tailings as if they flow like water shows conservative results in terms of travel times and depths of the flood wave. But from the point of view of prevention and planning for emergencies, overestimated results result in higher expenditures on structural measures, and when it comes to the evacuation of populations, a false alarm is created, hindering future Civil Defense relations and actions with these populations.

Also in the context of the disposal of tailings, another fundamental aspect that affects the flow of water and tailings is rheology. This important property allows us to know the deformation and flow characteristics of the tailings, parameters that are fundamental for more accurate modeling of the extent and depth of flooded areas.

Many of the analyzed EAPMDs considered in their dam break studies the rheology of tailings in modeling of the flooded areas. The data show that about 78% of the dam break studies do not mention or address the rheological aspects of the tailings, another 10% treat the rheological aspects in a theoretical way, that is, through references to values in the literature, and only 12% consider rheological parameters obtained through geotechnical testing with the dam's own tailings.

Several kinds of research and guidelines by authors from Australia and Canada cite the importance of rheology in tailings dam studies and how these characteristics can influence the extent of the flooded area (Martin et al. 2015; Moon et al. 2019).

3.4 Propagation and mapping of rupture effects in the valley downstream of the dam

All the dam break studies analyzed showed the delimitation of the flooded area and in general included the following information: indication of the location of the dam; hydrography and reference sections; access ways; locations of cities or population centers; landmarks of distance and time of arrival of the rupture wave; indicator of reaching the stop criterion of the simulation; flooded area; Self-Rescue Zone (ZAS); alert system; and indication of escape routes and meeting points.

Most of the maps presented, in addition to the flood area, the sections used in the modeling and in each one of them presented the following information: reference description, distance in relation to the dam axis, maximum depth reached in the section (m), maximum elevation reached in section (m), and maximum speed achieved in section (m/s). These same items identified in the analyzed dam break studies are required in countries of reference for dam safety, such as the USA, Portugal, Spain, and the UK, showing that despite the lack of a specific methodology for the dam break studies, for the flood maps, there is a standard that has been adopted internationally.

The format of the presentation of flood maps was also analyzed. Most EAPMDs, 70%, have maps printed in A1 formats, with maps in larger sizes that facilitate reading and interpretation. Some of these maps were even available in the KML format, an extension of Google Earth. In countries such as Australia, India, and the UK, emergency management agencies are required to receive flood envelope maps in digital formats for GIS software, such as a shapefile and extension for Google Earth (Government of Queensland 2002; DEFRA 2006; India 2018).

3.5 Contributions to improvement of the deficiencies found in the analyzed dam break studies

The approaches and methodologies of dam break studies, mainly for tailings dams, are being improved in order to make these studies more realistic and thus more efficient in planning emergency preparedness and response involving dams (ICMM; UNEP; PRI 2019).

Besides its potentialities, this study pointed out some theoretical and technical aspects such as the input parameters when it comes to tailings flow that must be improved in the elaboration of dam break studies in Brazil. Despite this, it is suggested that future research should deepen in these aspects to improve the execution of dam break studies and thus the quality of its products.

For terrain topography issues, research is suggested that deepens the effects of the Digital Terrain Model (DTM) on the vertical precision of the flood wave in an integrated and systematic way with other modeling parameters, such as the type of runoff. There are many studies on the influence of this aspect in isolation, but a systematic sensitivity analysis of its influence and factors such as type of flow has yet to be improved.

As for the flow-type issues, considering the particularities of the tailings, such as the high concentration of solids, was one of the aspects mentioned in this study, as well as in other research on the subject, but it requires more detailed attention in further studies, to contribute to the understanding of the most appropriate rheological parameters to be inserted in the propagation models, and how they influence the behavior of the flood wave.

It is understood that these improvements, which are still necessary, tend to consolidate more specific guidelines on the content and execution of dam breaks by the bodies and agencies regulating dams, but this is only possible based on technical and theoretical knowledge and consistent technical information provided by the scientific community.

4 Conclusion

Our content analysis of the inundation studies for dam breaks showed that, in general, all studies included hydrological studies, the failure mode of ruptures simulated, rupture hydrographs, and mapping of the propagation of the rupture wave.

As for the failure modes adopted in the rupture simulations, these were shown to be consistent with the method of construction, as in the cases of failure by liquefaction for upstream dams. In the case of simulating more than one failure mode, the choice of these also proved to be consistent with the adoption of the most damaging scenario, which follows the legal requirement of National Mining Agency Ordinance No. 70.389 of 2017.

The adoption of the LiDAR topographic grid in 54% of the plans proved to be a positive aspect of the analyzed dam breaks, as it achieved greater horizontal resolution (greater fidelity in the extent of the flooded area) and vertical precision (greater precision in the depth of the wave), ensuring greater precision of the inundation maps and in the definition of the areas to be reached.

Most of the plans (70%) use the HEC-HAS software to model the rupture and propagation of the flood wave. However, it is known that, although it is widely used for modeling flooding with water, HEC-HAS has limitations for modeling the flow of fluids with high concentrations of solids (hyper-concentrated or non-Newtonian fluids). Despite this, adjustments in the parameters of the HEC-HAS model to approximate the flow of water to the flow of tailings seem to be well accepted in the literature.

In addition to HEC-HAS, other software that has specific complements for mudflow, and thus provides a better forecast of the flow of tailings, was also used in a smaller number of the studies. This software includes RIVERFLOW 2D, FLD WAV, FLO 2D, and DAMBRK. In these models, one of the most important parameters is the tailings rheology, which was neglected in 78% of the plans analyzed. Not considering the rheology of the tailings can compromise the prediction of the extent of the flooded area and thus affect the preparation for a possible disruption by the entities involved in emergency management.

The omission of information about the premises and assumptions adopted in the preparation of these dam break studies, as was verified in some plans, is a weak point of these documents, even in cases where only a summary is presented (without a detailed record). In the event of an inspection, the lack of this information would make it difficult to review and understand the variables that could affect the quality and accuracy of the inundation maps and in turn the delimitation of the areas of coverage.

On the basis of this work, we suggest that future research should seek to deepen understanding of the methodological issues around modeling the flow of mining tailings, considering them to be hyper-concentrated, non-Newtonian fluids, with the objective of improving flood modeling for this type of fluid in situations involving overflow accidents. Another suggestion is to evaluate the role of the inspection agencies in the auditing of EAPMDs, mainly of their dam break studies, in order to assess how these agencies evaluate and validate the studies and the flood envelopes derived from them.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Consent to participate The Civil Defenses and the researchers signed a term guaranteeing that the documents used in this research would be used only for scientific purposes and would not be passed on to third parties.

Consent for publication The authors authorize the publication of this manuscript.

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