SIMULATION OF THE RUPTURE OF AN INDUSTRIAL FERTILIZER TAILINGS DAM IN ARRAIAS, TOCANTINS, BRAZIL

SIMULAÇÃO DE ROMPIMENTO DE UMA BARRAGEM DE REJEITOS INDUSTRIAIS DE FERTILIZANTES EM ARRAIAS, TOCANTINS, BRASIL

SIMULACIÓN DE RUPTURA DE UNA PRESA DE RELAVES INDUSTRIALES DE FERTILIZANTES EN ARRAIAS, TOCANTINS, BRASIL

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ABSTRACT
Dams are versatile structures used for various purposes, including tailings containment resulting from mining activities. In recent years, the rupture of these structures has become a recurring fact in Brazil, especially the disasters that occurred in the cities of Mariana and Brumadinho, in the State of Minas Gerais, Brazil, which caused irreversible environmental impacts and loss of hundreds of human lives. This demonstrates the relevance of computer models for predicting dam failure scenarios, which can be very useful in anticipating the consequences of dam breaks and guiding emergency action plans of dams. In the study conducted for the Itafós Arraias Mineração e Fertilizantes S.A. tailings dam was used the HEC-RAS software, which incorporates non-Newtonian fluid dam break modeling, combined with ArcGIS, ALOS PALSAR digital elevation model and other biophysical data regarding the area affected by the dam were used. Simulation of the flood wave behavior was by piping-type break, with the results indicating a flood area of 484.02 ha, maximum depth of 19.78 m, maximum wave propagation velocity of 13 m/s and maximum flow of 2,619.25 m3/s (Section 1), in addition to possible interference/impacts on natural landscapes, areas of anthropic use and public works.

Keywords: HEC-RAS. Dam Break. Flood Wave Simulation.

RESUMO
Barragens são estruturas versáteis utilizadas para diversas finalidades, inclusive a contenção de rejeitos decorrentes da atividade de mineração. Nos últimos anos, o rompimento dessas estruturas se tornou um fato recorrente no Brasil, com destaque para os

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desastres de Mariana e Brumadinho, que acarretaram impactos ambientais irreversíveis e perda de centenas de vidas. Isso vem mostrando o quanto a aplicação de modelos computacionais para prever cenários ocasionados pelo rompimento de barragem, é muito apropriada para antecipar as consequências do rompimento de barragens e balizar os planos de ação de emergência de barragens. No estudo realizado para a barragem de rejeitos da Itafós Arraias Mineração e Fertilizantes S.A., utilizou-se o HEC-RAS que incorpora a modelagem do rompimento de barragens de fluidos não newtonianos, combinado com o ArcGIS, modelo digital de elevação ALOS PALSAR e outros dados biofísicos da área de influência da barragem. A simulação do comportamento da onda de cheia foi por rompimento do tipo piping, com os resultados mostrando uma área de inundação 484,02 ha, profundidade máxima de 19,78 m, velocidade máxima de propagação da onda de 13m/s e vazão máxima 2.619,25m3/s (Seção 1), e as possíveis interferências/impactos em paisagens naturais, áreas de uso antrópico e obras públicas.

Palavras-chave: HEC-RAS. Rompimento de Barragem. Simulação de Onda de Cheia.

RESUMEN

Las presas son estructuras versátiles utilizadas para diversos fines, incluida la contención de relaves derivados de la actividad minera. En los últimos años, el colapso de estas estructuras se ha convertido en un hecho recurrente en Brasil, con destaque para los desastres de Mariana y Brumadinho, que ocasionaron impactos ambientales irreversibles y la pérdida de cientos de vidas. Esto ha demostrado que la aplicación de modelos computacionales para prever escenarios ocasionados por el rompimiento de presas es muy apropiada para anticipar las consecuencias de estos eventos y orientar los planes de acción de emergencia para presas. En el estudio realizado para la presa de relaves de Itafós Arraias Mineração e Fertilizantes S.A., se utilizó el HEC-RAS, que incorpora la modelación del rompimiento de presas con fluidos no newtonianos, combinado con ArcGIS, el modelo digital de elevación ALOS PALSAR y otros datos biofísicos del área de influencia de la presa. La simulación del comportamiento de la onda de crecida se realizó considerando un rompimiento del tipo piping, con resultados que mostraron un área de inundación de 484,02 ha, una profundidad máxima de 19,78 m, una velocidad máxima de propagación de la onda de 13 m/s y un caudal máximo de 2.619,25 m³/s (Sección 1), además de las posibles interferencias/impactos en paisajes naturales, áreas de uso antrópico y obras públicas.

Palabras clave: HEC-RAS. Rompimiento de Presa. Simulación de Onda de Crecida.

1 INTRODUCTION

Phosphate rocks are widely used as raw materials for fertilizer production, detergent production, animal feed supplements, among others. During the processing of phosphate ores, about 30-40% of the ore mass is disposed of as tailings after beneficiation operation (GNANDI et al., 2005). Tailings dams are structures used by mining companies as a way of storing the waste extracted after this processing (SANTOS et al., 2020).

With the increase in the number of dams of this nature in the country, there is also a growing concern about the safety of their structures, which consists of maintaining their structural and operational integrity, and the preservation of life, health, property and the environment (BRASIL, 2010). It was only in 2010 that the topic became part of the Brazilian policy agenda with the creation of the National Policy on Dam Safety (BRASIL, 2010), although it had already been the subject of discussion among engineering and geotechnical professionals since the 1980s (FRANCO, 2008). Brasil (2010) establishes responsibilities for the inspection of dam safety for several environmental agencies that are part of the National Environment System (Sisnama). The National Mining Agency (ANM) is responsible for the regulation and inspection of mining dams and the National Water and Basic Sanitation Agency (ANA), considering other types of dams, is responsible for coordinating water security, aiming to ensure the safety and inspection of structures and people.

As observed for the cases of Mariana and Brumadinho, the rupture of tailings dams has drastic consequences for all those involved in the vicinity of a dam. According to Amaral (2017), regardless of whether the rupture occurred due to poor inspection, failure in materials or construction methods, inconveniences are inevitable when there is no evacuation plan for the population or mitigating measures. If the dam were to break, there is irreversible damage to communities, cities (Wang et al., 2021) and the environment (Garcia et al., 2025). In the case of tailings dams, this damage is intensified by the contaminants present in the fluid, which can modify the physicochemical characteristics of the water sources (Kütter et al. 2023, Islam & Murakami, 2021). Simulations of dam failures have been carried out in Brazil and in other countries, with emphasis on the work of Derdous et al. (2015), Neves, Rodrigues and Cabral (2019), Raman and Liu (2019), Santos et al. (2020), Lee and Liu (2020), Psomiadis et al. (2021), Gibson and Sánches (2021).

Observing the Brazilian framework on the study of mining tailings dams and the importance of simulations of dam failure, this work proposed to carry out a case study for the Tailings Containment Dam of Itafós Arraias Mineração e Fertilizantes S.A., in Arraias, Tocantins. According to ANM (2022a), this is the only mining tailings dam in DPA condition – classification B in activity in the State of Tocantins that is included in the National Dam Safety

Policy – PNSB (Brasil, 2010), with high associated potential damage, which currently falls under the alert level. For the dam failure simulation study, the HEC-RAS - *Hydrologic Engineering Centers River Analysis Systems software*, from the *US Army Corps of Engineers* (BRUNNER, 2022) combined with the ArcGIS geographic information system, is used.

The main objective of the case study was to simulate the dam rupture by *piping*, determining the scope of the flood area, depth, maximum velocity of the tailings sheet and flow and the possible potential interferences/impacts caused along the flood area.

2 METHODOLOGY

2.1 DATA

A geographic database was set up in ArcGIS with public data available in a web environment. In terms of biophysical data, soil, relief, geology, climatological data, and vegetation cover and land use information plans were inserted from the geoportal data of the Secretariat of Planning of the State of Tocantins (SEPLAN, 2021). The database was complemented with altimetry data from the digital elevation model of the ALOS PALSAR satellite acquired from the *Japan Aerospace Exploration Agency* – JAXA website (JAXA, 2022). For the characterization of the reservoir, public data obtained from the National Mining Agency – ANM (ANM, 2022b) are used.

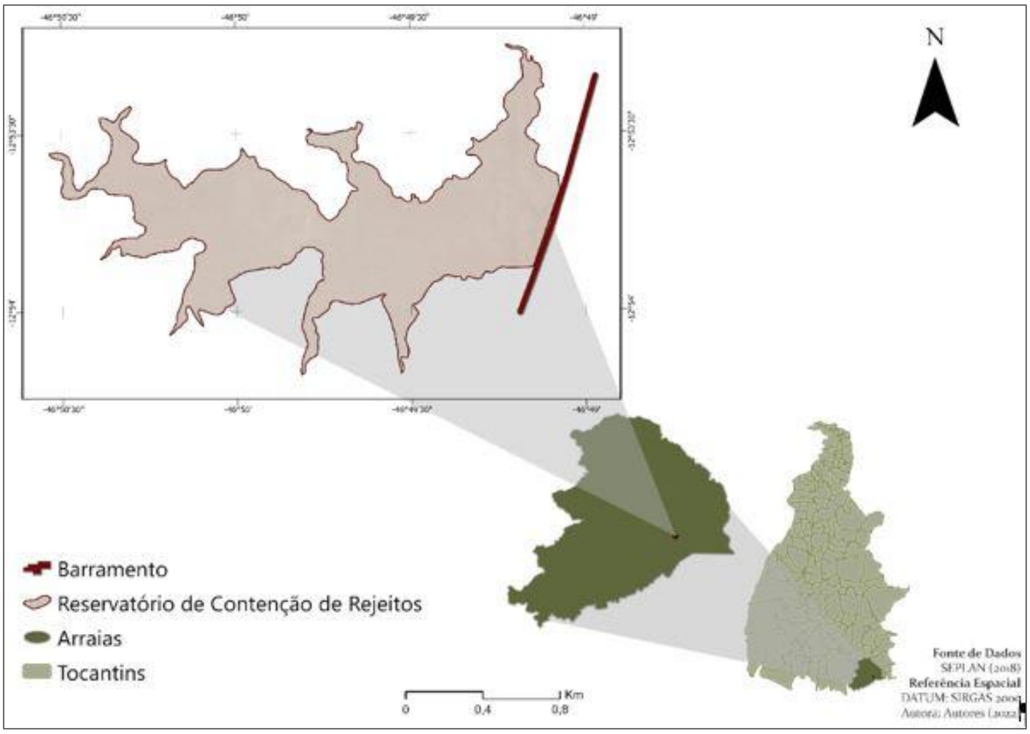
2.1.1 Tailings dam of Itafós Arraias Mineração e Fertilizantes S.A

The tailings dam of Itafós Arraias Mineração e Fertilizantes S.A., installed in the municipality of Arraias-TO, near the border with the north of the state of Goiás, between the coordinates of west longitude 46°50'00" and 46°48'00" and south latitudes 12°55'00" and 12°52'00". The main purpose of the dam is the controlled disposal of tailings generated during the phosphate ore processing process. Figure 1 shows the location of the tailings containment reservoir, its geometry and dam.

According to the ANM (2022b), the dam has been active since 2013 and has an expected useful life of 30 years. It was built in the valley of the Bezerra stream with an initial height of 20 m and can reach a maximum height of 30 m. The current height of the dam is 22 m, with the reservoir having an area of 71 ha and a volume of 4,136,059.54 m3 and the projected of 7,500,000 m3. The type of dam is homogeneous earth, with a foundation in residual/alluvial soil, and a construction method of raising downstream, with continuous type of raising. In terms of state of conservation, the civil structures are well maintained and in normal operation, with percolation fully controlled by the drainage system, with no deformations and settlements with the potential to compromise the safety of the structure. On the other hand, there are failures in the protection of slopes with the presence of shrub vegetation.

Figure 1

Location map of the tailings dam in Arraias, Tocantins, Brazil



Source: elaborated by the authors.

The type of tailings stored in the reservoir is due to the processing of phosphate ore, a raw material for the production of simple superphosphate (SSP), used as an input in agricultural activity, with a 2.5% phosphate pulp inserted in the tailings (ANM, 2022).

The dam has an emergency action plan, but according to ANM (2022b), copies of the PAEBM have not yet been delivered to city halls and municipal and state defenses, as required by Ordinance no. 70,389/2017. In terms of environmental impact assessment, the project has a significant impact, of medium intensity, and affects downstream, in the event of a dam failure, a number below 100 people (ANM, 2022b).

2.2 METHODS

It is noteworthy that one of the main forms of dam failure occurs when water overflows the dam wall, overtopping, and burrows through it due to the loss of freeboard, a situation more likely in old tailings dams that have been filled, vegetated and abandoned (HANCOCK. COULTHARD, 2022).

To study this hypothesis, the process of simulating the rupture of the tailings dam of Itafós Arraias Mineração e Fertilizantes S.A. began with the elaboration of the rupture hydrograph. For this, hydrologic modeling was used in the HEC-HMS (*Hydrologic Modeling System*). It provided, from the use of altimetry data and the rainfall hyetogram (calculated by the Huff method, 1967), the delimitation of the hydrographic basin, drainage stretches, water balance and, finally, the project hydrograph obtained by the method developed by the Soil *Conservation Service* - SCS (current *Natural Resources Conservation Service* - NRCS). performing this hydrological modeling at HEC-HMS, it was observed that there would be no overtopping from the flows found, since the dam's overflow systems are capable of pouring the flow from the maximum precipitation for a return time of 10,000 years. Thus, the rupture simulation was not associated with a precipitation event, but with collapse by *piping* or overtopping.

In the HEC-RAS environment, the altimetry component of the terrain was inserted, using the ALOS PALESAR digital elevation model, with a 12.5 m grid, an interval sufficient to generate a computational mesh with appropriate cells for analysis. Then, the roughness coefficient of Manning's equation was assigned to quantify the flow resistance (MANANDHAR, 2010). The calibration of the Manning roughness coefficient was based on land cover and land use data (Table 1).

Table 1

Manning coefficient values used

Uso da Terra	Coeficiente de Manning
Terra estéril	0,03
Arbustiva	0,05
Pastagens e terras cultivadas	0,035
Rio	0,04

Source: adapted from chow (1959).

Still in the hec-has, the following boundary conditions of the model were used: (a) the volume of the reservoir upstream and (b) the normal depth with a slope of the channel bottom of approximately 0.4% downstream.

THE next step is to perform the calibration of the HEC-RAS MODEL (version 6.1) considering that the flow behavior of the material resulting from the rupture of the phosphate ore tailings dam is more similar to non-Newtonian fluids, such as Bingham fluids, which have specific rheological properties. For the dam in question, the results of BARREDA ET AL.,

(2021) were also used for the maximum value of yield stress or elastic limit stress of 300 Pascal and 50 Pascal for 73% and 65% of solids mass, respectively.

And, finally, the final geometry of the tailings dam rupture breach was defined, according to the empirical model proposed by Froehlich (2008).

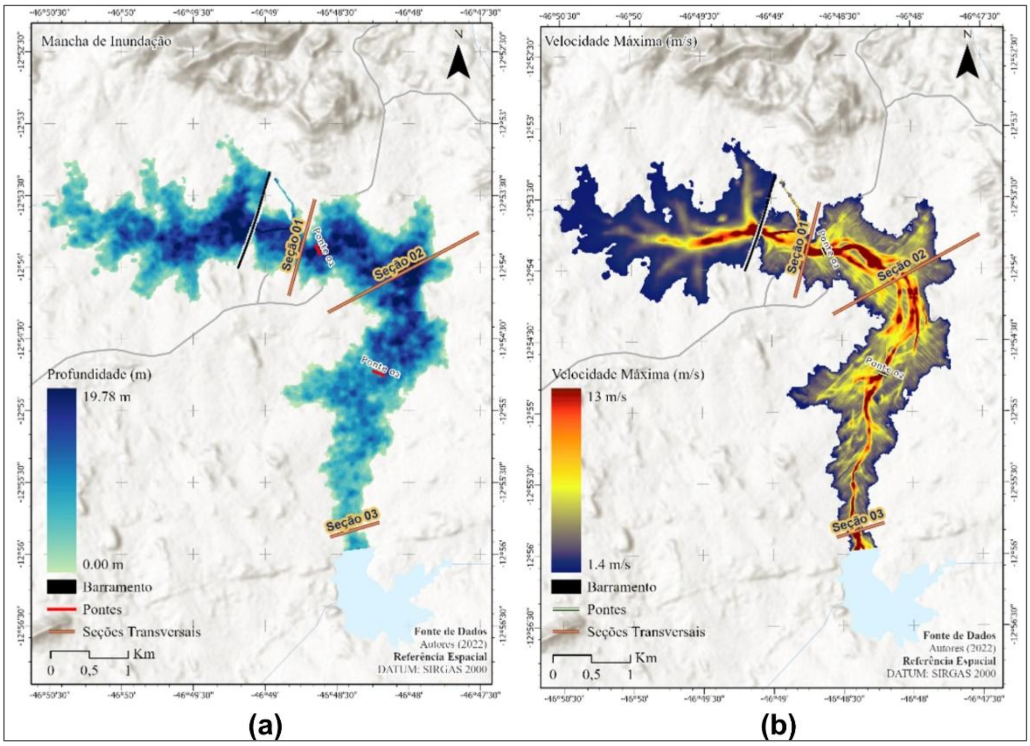
3 RESULTS AND DISCUSSION

3.1 FLOOD AREA

Figure 2 shows the flood spot in the critical situation, that is, when it reaches the largest area. The slick covers an area of 484.02 ha and a maximum depth of 19.78 m. The maximum velocity of the flood wave reached is 13 m/s, reaching Section 3 in 4.33 hours after the rupture.

Figure 2

Flood Spot formed (a) and velocity reached in m/s (b)



Source: elaborated by the authors.

The data collected in the three cross-sections, maximum speed reached, maximum elevation, and flow hydrograph along the wavefront path are shown in Table 2.

Looking at Table 2, it can be seen that Section 1 is 0.63 km, Section 2 is 1.88 km and Section 03 is 5.82 km away from the dam. Among the three sections, Bus-S1, S1-S2 and S2-S3, Table 2 shows that the maximum level of tailings reduces 31 m in height, due to the elevation levels of the land. For the S1-S2 section there is a reduction of only 6 m, while in the S2-S3 section, there is a 25 m high decay due to the retention of tailings in this interval.

Table 2

Flow, tailings level, depth and velocity data for each section considering maximum values

	Barramento -S1	S1-S2	S2-S3
Distância do barramento (km)	0,63	1,88	5,82
Nível máximo de rejeito – cota (m)	623	617	592
Profundidade máxima (m)	12,35	17,60	3,15
Vazão máxima (m^3/s)	2.619,25	2.452,84	374,54
Velocidade máxima (m/s)	2,51	1,46	4,05

Source: elaborated by the authors.

For the depth of the wave, it can be seen that in the S1-S2 section there is an increase of 5.25m in relation to the Barramento-S1 section, while in the S2-S3 section there is a sharp decline in depth of 14.45 m. These variations can be justified by the observation that, for the first section, Section 1 presents a higher flow when compared to Section 2, and also, that in the latter there is an increase in accumulated material and little loss of energy due to the short distance traveled, resulting in greater depth. Between S2-S3, the depth reduces slightly, since there are losses of matter and energy along the way. In addition, the last section has a higher speed of propagation of the flood wave and lower flow when compared to the others, so the cross-sectional area (depth x width) is also reduced.

The maximum flow rate between S1-S2 is reduced by 166.41 m^3/s, due to the loss of energy during the thalweg. For S2-S3 this decrease is more pronounced, there is a reduction of 2,078.30 m^3/s, justified by the greater distance traveled.

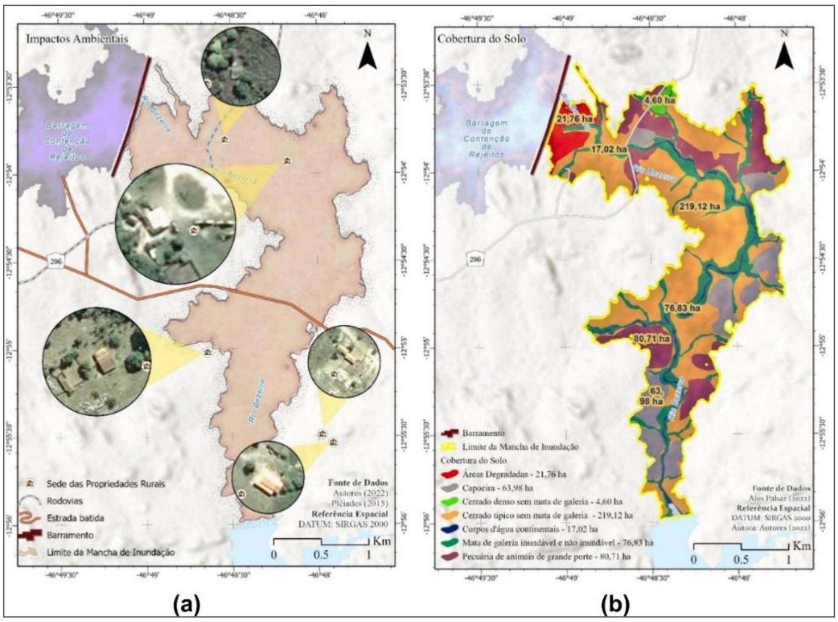
Finally, with regard to the maximum speed, between S1-S2 there is a reduction of 1.05 m/s, because there is a small slope and distance in this section, and also, the width of the flow increases along the stretch, allowing greater passage of matter and reducing the speed to the control surfaces. Between S2-S3, the velocity increases drastically, it is the maximum observed, since the valley is quite narrow. Despite all the loss of energy and flow, with the slight decrease in the control surface area, there is an intense increase in speed. There are lower velocity and flow at 5km away from the dam when compared to the work of Santos et al. (2020), however these values depend on the area, height of the dam, slope of the terrain, among other factors.

3.2 ENVIRONMENTAL INTERFERENCE

Along the path of the wavefront, it is verified that it impacts improvements in the rural area and transport infrastructure, pasture areas and native vegetation, and probably the local fauna (Figure 3). Khalkho et al. (2020) report the loss of infrastructure due to dam rupture and highlight the importance of flood maps for the preparation of the Emergency Action Plan (EAP) for disaster management.

Figure 3

Environmental interference (a) and land cover and use affected by the flood area (b)



Source: elaborated by the authors.

Figure 3(a) shows two rural property headquarters that will be buried by the tailings flow, as well as two bridges, one on the TO-296 highway and the other on a side road that connects the industrial unit of Itafós Mineradora and the tailings dam. At the end of the wavefront's route, it is noted that it reaches the water collection dam that the industry uses to maintain its production process.

Figure 3(b) shows that 80.71 ha of pastures with the use of large animal husbandry are affected by the flooding and that 364.54 ha of native vegetation are also buried and destroyed. Of this total, 63.98 ha are for capoeira, 4.60 ha represent dense cerrado without gallery forest, 219.12 ha correspond to typical cerrado without gallery forest and 76.83 ha are equivalent to floodable and non-floodable gallery forests. In addition, there are 21.76 ha of degraded area and 17.02 ha of buried watercourse. These results, in a more summarized form, are presented in Table 3.

IN relation to fauna, there is no capacity to measure affected individuals, however, based on information from the Environmental Impact Study - EIA (AMBIENGER-PROMINER, 2010), there is an indication of possible losses and scares of mastofauna, avifauna, ichthyofauna and herpetofauna, and loss of aquatic and terrestrial habitats. The flood area would also bring as negative consequences the loss of natural landscapes, housing structures and infrastructure by burial, loss of livestock areas and native/anthropized vegetation by runoff or burial by waste, alteration of water and soil quality and visual impact.

Table 3

Areas of cover and land use affected by the flood area

Cobertura e uso da terra	Área (hectares)
Áreas degradadas	21,76
Capoeira	63,98
Cerrado denso sem mata de galeria	4,60
Cerrado típico sem mata de galeria	219,12
Corpos d'água continentais	17,02
Mata de galeria inundável e não inundável	76,83
Pecuária de animais de grande porte	80,71
Total	**484,02**

Source: elaborated by the authors.

4 CONCLUSIONS

The flood map generated in the HEC-RAS software by combining the ALOS PALESAR digital elevation model, Manning's coefficient with biophysical data provided by SEPLAN-TO, structure characteristics provided by ANM (2022) and the piping breach assumptions according to Froelich (2008) allowed a representation of the flood wave behavior from structural collapse. Additionally, it is perceived that the use of the computational mesh for the 2D model is suitable for application in studies with sinuous watercourses, such as the Bezerra stream, making the modeling more accurate.

Carrying out dam rupture studies is extremely important to determine the coverage of the impacted area, speed reached by the wave and depth. These factors are the ones that will guide the preparation of the emergency action plan with greater assertive possibility and the environmental impact studies. This is because they allow a better observation of the problems arising from the rupture and the force of the wave, that is, its mechanical impact and the identification of buried places where chemical impacts can be triggered due to the type of tailings superimposed on the soils.

It is considered that the results and practicality of the modeling obtained in this case study through the combination of geoprocessing tools with HEC-RAS (public domain software), should be a procedure used for the analysis of tailings dam failure, which strengthens the recommendation of the National Water Agency. In addition, it is of great value for the preparation of the emergency action plan for mining tailings dams

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